Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-021-17061-w

Optimal recycle price game theory model for second-hand mobile phone recycling

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Received: 1 December 2020 / Accepted: 11 October 2021

Abstract
Human societies develop rapidly through the advancement of technology; however, with these advancements, many problems are emerging. The topic chosen for this study surrounds the e-waste, which has become a major problem around the world. Second-hand and unused mobile phones are a big part of globally generated e-waste. If these devices are properly recycled, they can generate substantial economic and resource value. Yet if they are indiscriminately discarded, they cause a profound environmental impact. Given the current low recovery rate of mobile phones, an increase in recovery rates becomes critical in lessening economic and environmental impacts. Based on the status quo of second-hand mobile phone recycling processes in China, this article analyzes the behavior of individuals and recyclers through a comprehensive static information game theory and finds ways to increase the recycling rate of second-hand mobile phones. The study helps the customers, to clearly identify the recycle price. In case of market, the government policy can be introduced with a reward and punishment mechanism. Furthermore, under the ideological guidance of game theory, this paper also establishes a corresponding price model of second-hand mobile phone recycling based on best response dynamics like search, variable neighborhood search, and hybrid meta-heuristic method. This model shows that the recovery time differences have a significant impact on the recovery price. Moreover, to an extent, this model can promote the possibility and initiative of customers choosing cell phone recycling.

Keywords Second-hand mobile phone · Recycling · Noncooperation and cooperation · Two-player game · Static games of complete information

Introduction

Current situation about electronic waste

One of the critical global issues in the modern era is the growing quantity of e-waste and its toxic effect on the environment and people (Hidasan et al. (2014); Arı and Yılmaz (2016a)). In 2019, a total of 53.6 Mt of e-waste was generated globally, calculated to 7.3 kg per capita. This figure is expected to increase to around 74.7 Mt by 2030 (Forti et al. (2020)). Mobile phones are large part of e-waste products. According to Deng et al. (2017), due to mobile phones' short service life, which is usually less than 2 ~ 3 years, the production of waste mobile phones is considerable. Although consumers have a general awareness of the importance of recycling electrical and electronic equipment including mobile phones, their awareness has not been fully transformed into recycling behavior (Ylä-Mella et al. (2015)). Compared with traditional household waste, mobile phones contain highly toxic substances and valuable materials, such

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Published online: 29 November 2021

as copper, silver, gold, and palladium all which can be recycled. Therefore, recycling mobile phones has a dual value of environmental protection and resource conservation.

From the perspective of saving resources and protecting the environment, solving the problem of how to increase the recycling rate of mobile phones is essential.

Moreover, as the world's largest exporter of electrical and electronic equipment and importer of used electrical and electronic equipment, China plays a crucial role in the treatment of electronic products (Chi et al. (2011)); thus, this article attempts to analyze how to improve the recycling of second-hand phones in the nation..

Hicks et al. (2005) pointed out that in China and other developing and industrial countries, waste is viewed as a resource and income-generating opportunity. Therefore, the market hopes that consumers and recyclers can actively participate in recycling used mobile devices. However, how to effectively manage e-waste in China is imminent. E-waste management is a multi-stakeholder problem. To solve the problem effectively, this article applies game theory in used mobile phone recycling.

Analyzing the structure of closed-loop supply chains: a game theory perspective

Game theory is a field of applied mathematics used to analyze complex interactions between entities (Hadzic et al. (2013)). Game theory's focus is on multi-intelligent rational decision-making regarding conflict, competition, and cooperation. Moreover, it is a useful tool for obtaining their corresponding benefits from each other by analyzing each factors' behavior and the information known (Myerson (2013)). Cooperative games and non-cooperative games are two primary situations involved in game theory. These include theories of interpersonal interaction, also known as people and economic behavior. Cooperative game theory studies how people distribute the benefits of cooperation through cooperative strategy and negotiation among the various agents and various income distribution problems. Cooperative game theory promotes both parts' interests in the game and the whole of society's interests through cooperation. Thus, cooperative game theory emphasizes collectivism and collective rationality. On the other hand, non-cooperative game theory emphasizes individualism and individual rationality; it is the study of how people choose to maximize their interests in situations where interests affect each other, that is, the problem of strategic choice. At present, the two sides, consumer and company, are in a state of non-cooperation, which is also the root of the serious e-waste problem in China. Therefore, how to change this situation becomes very important.

For the second-hand mobile phone recycling, a good strategy should not only promote the interests of both consumer and company, but also advance the interests of the whole society. Therefore, we hope to turn the previous non-cooperation between the two parties to cooperation through the game theory and build an optimal recycle price model to increase the number of second-hand mobile phone recycling and raise consumers' awareness of recycling.

This paper is organized with a background study in the "Background" section. The "Application of game theory for recycling" section mainly focuses on analysis and the literature work about the meta-heuristic algorithms and game theory which plays an important role in the recycling models. In "The ORPGT model of second-hand mobile phone" section, our proposed method for finding the optimal recycle price (ORP) uses game theory, and the experimental results and discussion is elaborated upon in the "Experimental results and discussion" section. The paper is concluded with our findings in the final "Conclusion" section.

Background

Consumer behavior in second-hand mobile phone recycling

The current research on mobile phone recycling mainly focuses on analyzing consumer behavior and improving the recycling management model. For consumer behavior, the low recycling price and residents' lack of environmental awareness have caused failing recycling (Su (2018); Du et al. (2014)). However, Ylä-Mella et al. (2015) state that consumers are aware of waste recycling systems' importance but that the awareness has not been transformed into recycling behavior. In contrast, Tan et al. (2018) further confirmed the recycling awareness is not the main reason for recycling. It is because financial benefits from recycling for individual customer are too low compared to the original price. Arı and Yılmaz (2016b) found that guidance and motivation can effectively improve housewives' willingness to recycle and increase the recovery rate of mobile phones. Zhang et al. (2019) also ascertained that consumers' personality traits essentially affect phone recycling. Consumer behavior influences second-hand mobile phones recycling, and positive behavior helps to increase the recovery rate.

Recycling model based on game theory

Different researchers have adopted various game theory approaches to improve the recycling management model. Tan et al. (2018) construct a complete information static game to transform recycling pricing into the problem of solving the Nash Equilibrium point in recycling. Liu and Su (2019) used the game method to calculate the government's optimal subsidy pricing and reported that the fund pricing of some kinds of abandoned electrical and electronic products was not reasonable through data simulation. Wang et al. (2020) established a dynamic Stackelberg game mode and found that the reward and punishment mechanism can significantly improve waste products' recovery rate. Furthermore, Shi et al. (2020) proved theoretically that cooperative games could bring more profit to consumers' supply chain and benefits. Nash Equilibrium between cooperative consumers and enterprises is the key to improving the recovery rate of used mobile phones. However, due to the inappropriate pricing of second-hand mobile phones, the game between consumers and enterprises fails to be Nash equilibrium. Previous studies mostly started from theoretical game theory to explore recycling and the government's reward and punishment mechanism to help consumers and enterprises approach Nash equilibrium. This study points out the necessity of second-hand mobile phone pricing balance for recycling through a detailed analysis of consumer behavior, corporate behavior based on game theory, and the government's reward and punishment mechanism. Then it analyzes the decisive factors of second-hand mobile phone pricing based on machine learning. Finally, optimization methods through Tabu Search, Variable Neighborhood search, and hybrid meta-heuristic algorithm are established to achieve Nash Equilibrium recycling price. Recently Shekarian and Flapper (2021) has referred a closed-loop supply chain (CLSC) model that is seen as one of the circular economy's leading approaches for reducing our natural environment load. We will be utilizing this in future in our research.

Application of game theory for recycling

Hawk-Dove game between recycler and consumer

The following parameters are used to analyze the recycling game between consumer, enterprise, and government in Table 1.

For companies, storage, transportation, and labor in the recycling process will incur recycling costs, which are usually challenging to reduce. Consumers are unwilling to share the cost of the recycling process, only 47.9% of consumers agreed to pay for only 0 ~ 5% of the used mobile phone cost (Yin et al. (2014)). Some companies decline second-hand mobile phones' recycling prices to reduce cost and maximize profit. Furthermore, in the pricing of second-hand mobile phones, companies are usually in a dominant position. In the recycling game between individuals and enterprises, recyclers are reluctant to raise recycling prices and regularly hold a non-cooperative attitude.

According to the following Hawk-Dove game (SMITH and PRICE (1973)) between recyclers and consumers, the recyclers have governing control over recycling prices. In the Hawk-Dove model parameters, suppose consumers expect the ideal recovery price to be *Pi*, recycling companies give their best offer to be *Po*. The revenue from recycling phones is *R*. Generally, $Po < R < Pi$.

Table 1 The set of parameter

Parameter	Description
R	Revenue from recycling phone
P_m	TIf both parties are Doves the transaction price
P_i	Consumer ideal recycle price
P_0	Best recycling price that enterprise offers
P_h	Higher payoff for enterprises when the status quo of used mobile phones improves
P_L	Lower payoff for enterprises when the status quo of used mobile phones is not improved
Q	The payoff of the passive participant
q	The payoff of the active participant
D	Rewards for active participant
E	Penalties for passive participant

Table 2 The Hawk-Dove game between recycler and consumer

		Consumer	
		Dove	Hawk
Recycler	Dove	$(R-P_m, R-P_m)$	$(R-P_i, P_i)$
	Hawk	$(R-P_0, P_0)$	(0, 0)

If one is a Dove (compromise) and the other is a Hawk (Hardliners), the transaction price is the Hawk offered, so that the price will be Po.

If both parties are Doves, both make concessions, and then the transaction price is *Pm*, $Po < Pm < Pi$.

If both parties are Hawks, the transaction cannot be realized, the consumer has no profit, and the companies cannot profit from recycling. Assume the revenue from recycling phones is *R*, and then the model is shown in Table 2.

Given the Dove and Hawk model presented in the foregoing section, the detailed analysis of the work is presented in the following section.

If the consumer chooses the Dove strategy, the enterprise insists that the hawk strategy is the optimal scheme (since R−P> R − Pm). If consumers insist on hawk strategy, enterprises insist on hawk strategy is the optimal scheme (since R − Pi < 0).

Therefore, the best choice for enterprises is to adhere to the Hawk strategy, and when they did, consumers can only choose the Dove strategy. Hence, based on the Hawk-Dove game, the recovery price decision lies with the recycler, which leads to companies' negative attitudes toward cooperation. Besides, even if some companies are willing to benefit consumers,

Table 3 Prisoner's dilemma in recycling used mobile phones.

Company A/Company B	Active participation	Passive participation
Active participation	(P_h, P_h)	(q, Q)
Passive participation	(Q, q)	(P_L, P_L)

they will eventually be affected by other recyclers in market competition.

Prisoner's dilemma gaming in recycling mobile phones

When few recycles enterprises actively participate in recycling, the negative attitude of other recyclers will weaken the recycling. Individual rationality leads to collective irrationalities, like the prisoner's dilemma in recycling.

Recycling has both active participation and passive participation strategies. When the status quo of used mobile phones is significantly improved, the enterprises involved in recycling of used mobile phones will get the same higher payoff: P_h. When the status quo of used mobile phones is not improved, the recyclers of used mobile phones will get the same lower payoff: P_L. When one party A and B participate actively and the other party passively participates, the payoff of the active participant is q, and the payoff of the passive participant is Q. The Table 3 gives a How the participants are classified in the Prisoners dilemma and the notations used.

The mobile phone recycling prisoner's dilemma model has two equilibrium: (P_h, P_h), (P_L, P_L). The (P_h, P_h) Pareto efficiency is better than (P_L, P_L). However, due to the cost of recycling mobile phones, active participation cost is higher than passive participation. The passive party will share the active participant's results without the cost, so $Q > P_h$. A single recycler's active cooperation cannot accomplish the increase in second-hand mobile phones' recycling rate. It requires the association of all mobile phone recyclers. When only a few recyclers actively participate in recycling, the recycling rate will not be improved, and the result of the game is the same as the passive participation of both parties. Because passively participating recyclers bring negative externalities to actively cooperating recyclers, the actively participating party pays higher recycling costs, so $q < P_L$. From the perspective of personal rationality, A and B will both choose to participate passively.

The government reward and punishment mechanism

To turn non-cooperation into cooperation, it is decided to introduce the government to regulate the behavior of

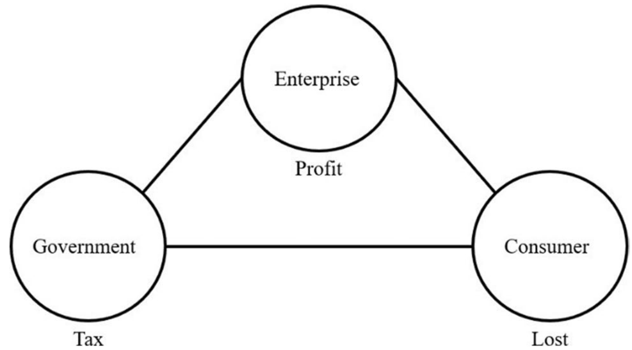

Fig. 1 Three key players in game with and their relationship

enterprises. Therefore, we divide our participants into three main parts: the government, the enterprise, and the consumer. And the key players in the regulatory recovery mechanism are shown in Fig. 1.

Government reward and punishment mechanism refers to the process of administrative management, the government supervises and inspects the assigned tasks and rewards active participants and punishes the less active in the promotion of policy implementation.

Punishment mechanism: When mobile phone recyclers participate passively, the government enforces economic penalties -E. Its standard penalties are irrespective of the mobile phone models or brands.
Reward mechanism: When mobile phone recyclers participate passively, the government issues corresponding rewards D. Table 4 indicates the penalty.

After the reward and punishment mechanism is introduced, active participation is a dominant strategy for recyclers, so the Nash Equilibrium becomes (active participation, active participation)

The ORPGT model of second-hand mobile phone

Human interaction is studied by using some of the bio-inspired algorithms and game theory strategies involving two or more persons. Hence, the paper proposes a method to utilize Nash Equilibrium which is most widely used in the gaming literature. The following figure gives the overall structure of our proposed model for finding the optimal recycle price using the game theory Fig. 2

This part of the paper explains the model that has been used for predicting the price for recycling phones and the parameters that been assumed for implementation. Machine

Table 4 Penalty matrix

Without the reward and punishment mechanism		
Company A/Company B	Active participation	Passive participation
Active participation	D, D	D, -E
Passive participation	-E, D	-E, -E
With the reward and punishment mechanism		
Company A/Company B	Active participation	Passive participation
Active participation	P_h+D, P_h+D	q+D, Q-E
Passive participation	Q-E, q+D	P_L-E, P_L-E

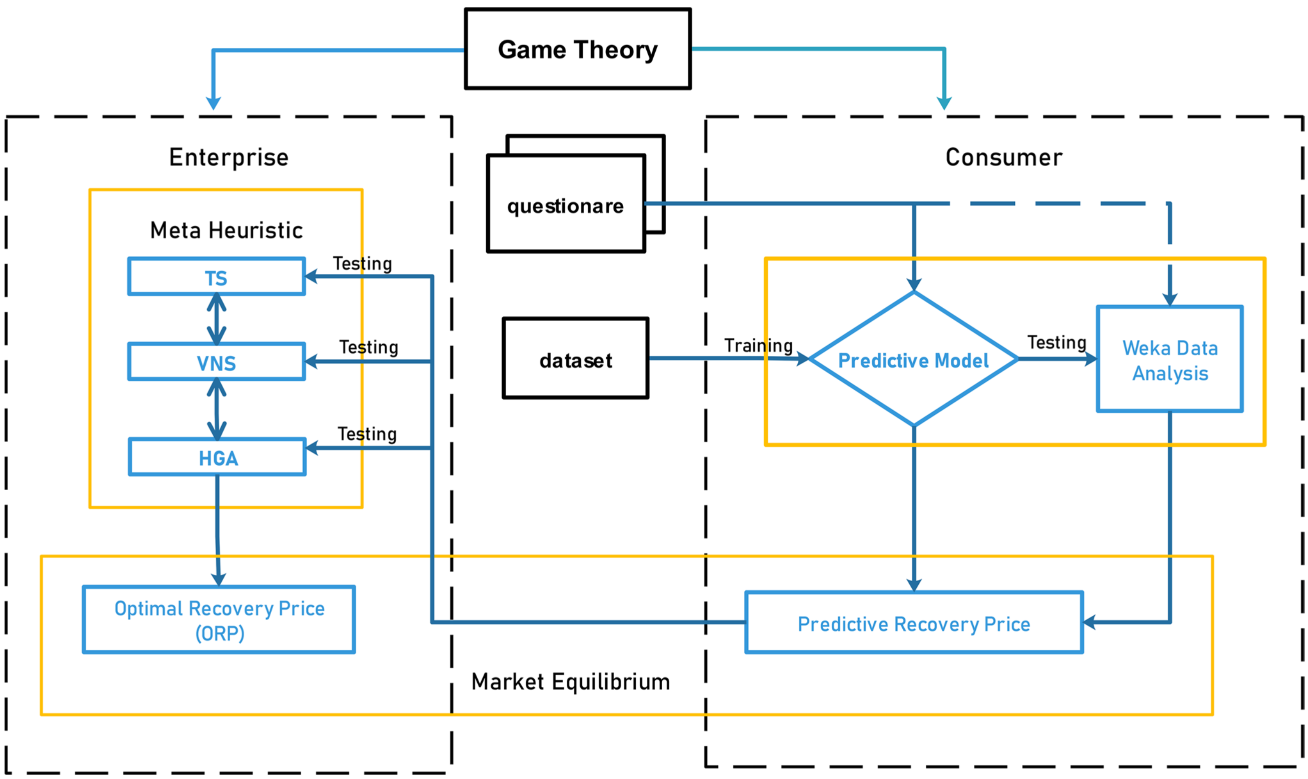

Fig. 2 The overall architecture of our proposed ORPGT model

learning algorithm is used to calculate the utility function for specific phones and conditions.

Model for predicting the recycling price

This research data contains 2275 effective instances of second-hand mobile phones (1022 Huawei and 1253 Apple, 42 Huawei Nova, 28 Huawei Nova 2, 42 Huawei Nova 2 PLUS, 63 Huawei Nova 2s, 63 Huawei Nova 3i, 42 Huawei Nova 3e, 21 Huawei Nova 5, 42 Huawei Nova 5 PRO, 42 Huawei Nova 5i, 84 Huawei Nova 5i pro, 63 Huawei Nova 6, 21 Huawei Nova 6 SE, 84 Huawei P20 Pro, 42 Huawei Mate 20, 42 Huawei Mate 20 Pro, 63 Huawei Mate 20 X, 70 Huawei Mate 30, 105 Huawei Mate 30 Pro, 63 iPhone 7, 42 iPhone 8, 63 iPhone 7 Plus, 252 iPhone 11 Pro, 252 iPhone 11 Pro Max, 189 iPhone 11, 63 iPhone XS, 63 iPhone XS Max, 126 iPhone XR, 63 iPhone 8 Plus, 63 Huawei P30 Pro, and 77 iPhone SE2) and covers 13 attributes like mobile communication technologies (includes 4G and 5G phone), brand name of the company, phone name, version, RAM size, ROM, time difference (length of time between purchase and recycling), CPU, operating system, screen size (inches), screen resolution, and level. The level is fixed with some criteria such as the appearance and physical damages caused during the recycling process. The following are the 6 levels used in game theory for recycling purposes.

Level 1: The appearance is perfect, and the screen is free of scratches.

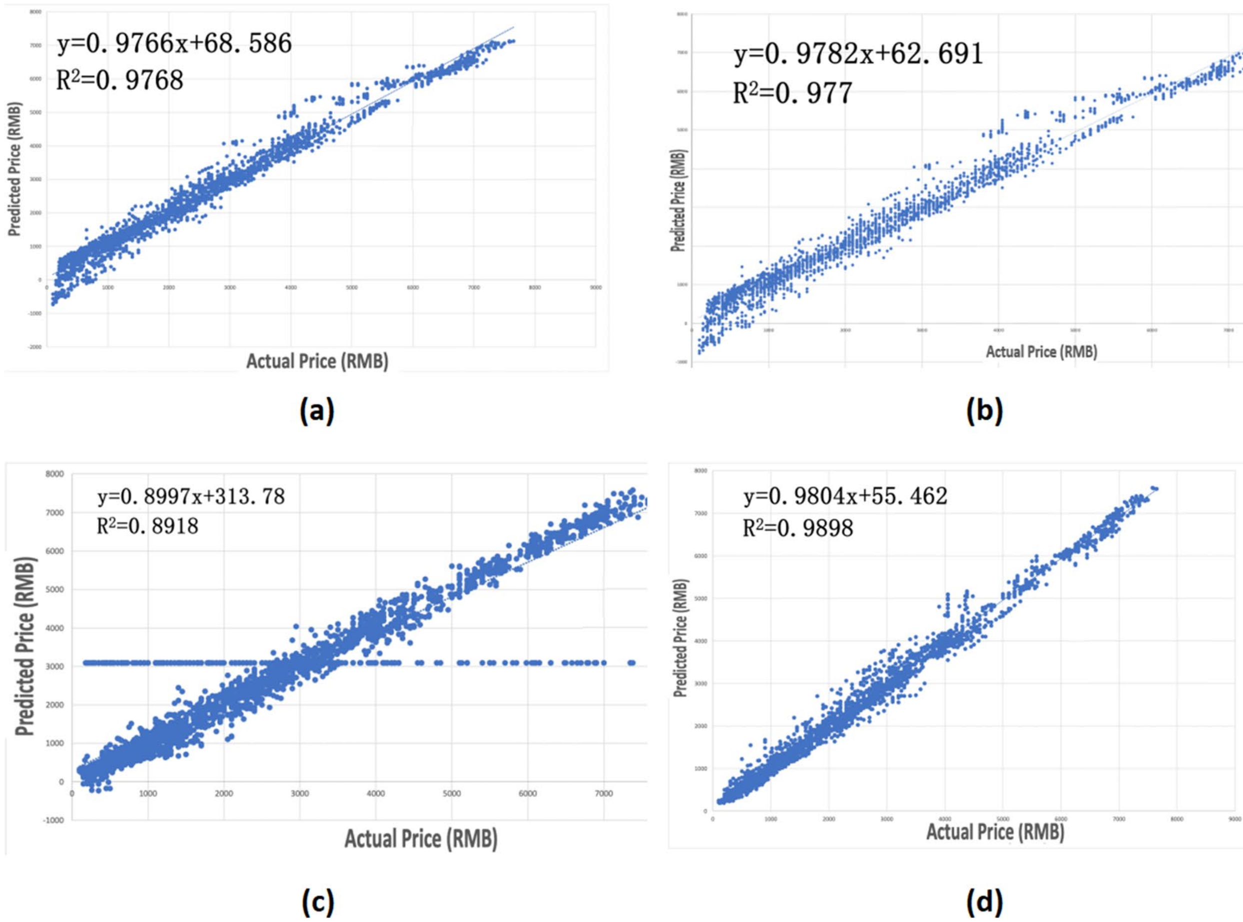

Fig. 3 Scatter chart between actual price and predicted price for different algorithms

Level 2: The appearance is flawless; and there are traces of use but no dents.
Level 3: There are some small scratches, slight dents but , no bending.
Level 4: A few apparent scratches, no bending.
Level 5: Many scratches, but no bending.
Level 6: The display is damaged and aging.

The research was conducted using the Weka[1] tool that employs four machine learning algorithms. These algorithms are readily available machine learning algorithms used in predicting standard pricing. Ultimately, they are used to find the best features and are to be used alongside the Gaussian Processes, the Linear Regression, the Random Forest Tree, and the Multiplayer Perception to predict the recycling price of these mobile phones.

The Gaussian Process and Linear Regression results are similar, and their correlation coefficients and R^2 values are close to 1. The Multiplayer Perception's correlation coefficient is 0.9444, which shows poor performance. The correlation coefficient of Random Forest Tree algorithm is 0.9949, which is the optimal algorithm among the four Fig. 3.

The database is maintained in Excel 2016, and the all the above-mentioned machine learning algorithms were executed with Weka tool. Table 5 gives the time needed (second) for building the model (TM) for each algorithm and their mean square error (MSE), root mean squared error (RMSE), linear prediction function (LPF), linear prediction R^2 (LPR), relative absolute error (RAE), root relative squared error (RRSE) and correlation coefficient (CC). The abbreviations of four algorithms are Gaussian Processes (GP), the Linear Regression (LR), the Random Forest Tree (RFT), and the Multilayer Perceptron (MP).

Meta-heuristic algorithm to find the best-balanced prices for the market

Meta-heuristic algorithms have many applications in different fields. The game theory in concert with meta-heuristic algorithms will improve the efficiency of accurately

[1] Weka 3: An open-source machine learning tool is based on Java and released by GNU. Data mining and visualization are done with it.

Table 5 Result comparison for four available algorithms

Algorithm	TM	MSE	RMSE	LPF	LPR	RAE	RASE	CC
GP	15.24	235.3553	309.2562	$y = 0.9766x + 68.586$	0.9768	13.81%	15.22%	0.9883
LR	0.93	234.0691	307.7538	$y = 0.9782x + 62.691$	0.977	13.73%	15.15%	0.9885
RFT	0.34	143.601	206.2108	$y = 0.9804x + 55.462$	0.9898	8.42%	10.15%	0.9949
MP	134.88	327.368	668.6814	$y = 0.8997x + 313.78$	0.8918	19.20%	32.92%	0.9444

calculating the best-balanced prices for the market. After analyzing the four different types of machine learning algorithms, the results indicate that the efficiency of the random forest tree algorithm is comparative giving better results. Hence, the meta-heuristic algorithm is based on the game theory and the random forest tree algorithm to find the Nash Equilibrium by using the predicted major parameter, the depreciation coefficient (c).

For the experiment featured in this paper, 13 attributes about the phone (from the database) are taken as the input to calculate the depreciation coefficient (c) of the phone. Some of the trade in sites also give the prediction of the recycling prize by comparing them with the current model and the latest rate. This prize is referred as the "standard payout" which helps to maximize enterprise profit of or minimize consumer loss. The model in Fig. 4 shows a simple idea of how both enterprise and the consumers are satisfied with maximum profit and minimum loss, respectively. As shown in Fig. 4, every enterprise has a different cluster of customers. And the quantity of phones that could be recovered from each enterprise will influence recycle prize by its own recovery price provided for consumers along with the competitor's recovery price provided for consumers. For example, the recovery prize offered by the enterprise's is relatively high for their customers when compared to competitors as the enterprise gets new business from customers when they exchange devices in the same market. Hence, this section explains the utility function commonly used by both the enterprise and the consumer. Every group consists of one enterprise and a cluster of consumers, and we define the utility function as $U_e - U_c$. The objective is to find the recovery price sets for each enterprise in the market which could let the total utility function get the maximum value. The result is not only to maximize profits for enterprise, but also to have a higher consumer satisfaction with the recovery price. The total utility function of the whole market is the sum of each group's utility function. Simulation is conducted by Weka with the original data from the market. The traditional methods give the results exponentially, and after several trial and error procedures, three of the meta-heuristic algorithms: Tabu Search (TS), Variable Neighborhood Search (VNS), and a hybrid of the Genetic Algorithm (GA) and VNS are utilized to find an acceptable solution.

Tabu Search (TS)

Tabu Search (TS) is one of many gradient search techniques designed for large, combinational optimization problems. Tabu Search uses an individual serial search method. With the taboo table, the search trajectory and the search direction can be recorded and tracked to prevent "premature convergence" (Gmira et al. (2021)). Tabu Search gives better results with both 2 or 3 permutations that are used. For this research, 2-opt and 3-opt neighborhood structures have been used. Under such structures, large-scale instances would have good scaling capabilities and robustness (Žulj et al. (2018)).

Variable Neighborhood Search (VNS)

Variable Neighborhood Search (VNS) is another meta-heuristic framework that is used for solving (combination) optimization problems. Variable Neighborhood Search is one of the popular local search algorithms for different kinds of neighborhood structures to search alternately, which

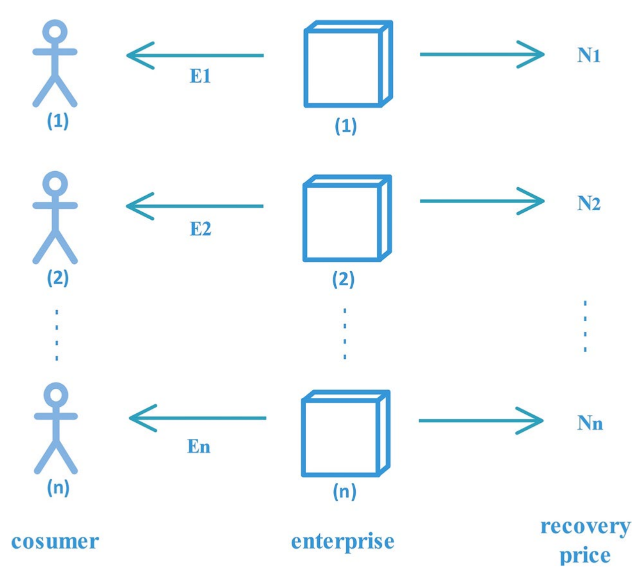

Fig. 4 Relationship between customers and enterprises with different recovery prices for different models

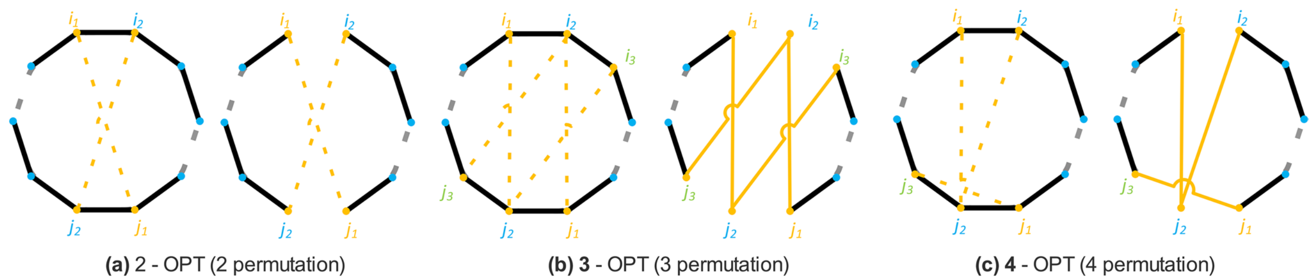

Fig. 5 Neighborhood of structure permutations

achieves a balance between intensification and diversification. VNS identifies what local optimal solutions that are likely to be found in a neighborhood, but not necessarily in a neighboring neighborhood (Hansen et al. (2019) and Djenić et al. (2016)). Moreover, the global optimal solution is the local optimal solution of all possible neighborhoods. As TS was implemented with 2 neighbor structures, VNS was executed though four neighbor structures, i.e., 2-opt, 3-opt, 4-opt, and the insertion.

Genetic Algorithm and Hybrid Meta-heuristic Algorithm (GA and HGA)

In order to enhance the efficiency of results, the hybrid meta-heuristic algorithm may be a more effective optimization in comparison. Considering the steady performance of GA and VNS, they are hybridized to form a hybrid meta-heuristic algorithm for finding better solutions for the optimal recycling price of second-hand mobile phones. Ultimately, the idea of using this hybrid method is to optimize the total utility function better. Fig. 5 shows thee permutation: 3-OPT and 4-OPT, respectively, which is used in the Tabu Search and other proposed meta-heuristic algorithms.

The algorithm HGA is the hybrid genetic algorithm used for finding the optimal recycle price for the second-hand mobile phones and is given below in Fig. 6 to explain the procedure of the proposed hybrid method by using the Genetic Algorithm (GA) and the Variable Neighborhood Search (VNS).

Experimental results and discussion

Problem definition through questionnaire

This work mainly focuses on using game theory for getting ORP. As a part of the preliminary work, we randomly distributed 265 online structured self-administered questionnaires. The respondents come from different provinces across the country, covering distinct age groups and using a wide range of mobile phone brands. SPSS[2] tool is used to analyze the survey data. 71.7% (190 out of 265) of the survey respondents lacked clarity on the recycling price. Among them, 71.6% (136 out of 190) will adopt negative recycling behaviors such as postponing or abandoning recycling. In the remaining 28.3% of the survey respondents who understand the recycling price, nearly half believe that the recycling price is unreasonable. While continuing to analyze negative consumers, 56.6% (150 out of 265) of the survey respondents left their used mobile phones at home. Moreover, 81.8% of the respondents expressed a willingness to recycle that increased as the price of recycling increases. Based on the initial survey, we understand that the price of second-hand mobile phones is unintelligible for consumers, and the lower price limits the recovery rate of mobile phones.

Identify the optimal recycling prize

The following parameters are used to predict the recycling price, and the mathematical functions are also mentioned in Table 6.

Recycling old mobile phones is the first phase of research to maintain customer benefit and the enterprises' profits. When considering the enterprise, the amount spent to buy back used devices is an important factor in overall profitability.

For the enterprise:

$$A = \left(1 + a_1\right)cD \tag{1}$$

Equation (1) represents the expense of a phone that the second-hand recycling company should pay.

$$M = eH \tag{2}$$

Equation (2) represents the total number of recycled mobile phones. It is calculated by the recovery rate and the number of second-hand phones available on the market.

[2] SPSS®:A data analysis software from IBM®

Fig. 6 The code of HGA

Algorithm 1: HGA

Gettotalutility($int[]Evalues$)
for $i \leftarrow 1$ **to** $Evalues.length$ 1 **do**
  $e_i = e + \mathrm{x}_i\mathrm{E}_i + y_i \sum_{K=1}^{n} (\mathrm{E}_i\text{-}E_k)$;
  $M_i = (H/\mathrm{n})\ e_i$;
  $N_i = ETN * \mathrm{E}_i\ \mathrm{B}_i = Z_i(1+a_1)(N_i\text{-}\ E_i)$;
  $U_{ei} = N_i\ (H/\mathrm{n})\ e_i\text{-}(1+a_1)\ e_i(H/\mathrm{n})\text{-}(B_i\ e_i(H/\mathrm{n}) +\ N_i \mathrm{e}_i(H/\mathrm{n})a_2)$;
  $U_{ci} = (D - \mathrm{E}_i)$;
  $U_{Total} = U_{Total} + (\ U_{ei}\ \text{-}\ U_{ci})$;
return U_{Total};
InsertIntoThePopulation($int[]Evalues$)
if *Gettotalutility(Evalues)* $>=$*threshold1* **then**
  Add Evalues into rank[4](crank[4]);
else if *(Gettotalutility(Evalues)* $<$ *threshold1 Gettotalutility(Evalues)* $>=$ *threshold2)* **then**
  Add Evalues into rank[3] (crank[3]) ;
else if *Gettotalutility(Evalues)* $<$ *threshold2 Gettotalutility(Evalues)* $>=$ *threshold3* **then**
  Add Evalues into rank[2] (crank[2])
else
  Add Evalues into rank[2] (crank[1]) ;
Main()
$generation = 10$;
$populationsize = 20$;
VNS = invoke the VNS;
Randomly generate x_i, y_i, z_i (i = 1, 2, ..., n) in x[ ], y[ ], z[ ];
$U_{total} = 0$;
$Count = 0$;
Add noise value for E_i E_i (i = 1, 2,..., n) in E[ ]x (x = 1, 2,..., population size) Initialize parent population = VNS(E[ ]) contains rank[j]x (j = 1, 2, 3, 4) (crank[j] for offspring population);
$Population_i$ = the ith solution in the population;
Insert into the population($E[]_j$);
while $count < generation$ **do**
  while *size of offspring population* $<$ *size of parent population* **do**
    rossrrate cr = random number [0,1);
    mutationrate mr = random number [0,1);
    if $cr \in [0, 0.8)$ **then**
      crossover two pair of parents to get 2 offsprings;
    if $mr \in [1/populationsize, 0.8)$ **then**
      mutate 2 offsprings;
    Insert into the population(offsprings);
  for $i \leftarrow 0$ **to** $populationsize/2$ 1 **do**
    $Ranknum = 4$;
    InsertIntoThePopulation(rank[$Ranknum$]$_i$);
    InsertIntoThePopulation(crank[$Ranknum$]$_i$);
    $Ranknum{+}{+}$;
  $Count{+}{+}$;
for $i \leftarrow 0$ **to** 20 1 **do**
  VNS(populationi)
Output the biggest total unility: Gettotalutility($population_{thebest}$);

Table 6 The set of parameter

Parameter	Description
a_1	Tax on recycling used mobile phones
a_2	Tax rate for sale after the mobile phones refurbished
c	Mobile phone depreciation coefficient
e	Recovery rate
A	The company recovers the expenditure of a second-hand mobile phone
D	The price when the customer buys the phone
M	Number of recycled mobile phones
H	Number of second-hand mobile phones in the market
C	Total revenue
N	Sale price of a second-hand mobile phone after refurbishment
B	The cost of refurbishing a used mobile phone
E	Recycling price received by customers
F_1	Expenses during the recovery phase
F_2	Expenses during the refurbishment and resale phase
Ue	The utility function of the enterprise
Uc	The utility function of the consumer

$$F_1 = AM\left(1 + a_1\right)ecDH \tag{3}$$

Equation (3) represents the enterprise's expenses during the recovery phase, and it equals the product of the recovery price per cell phone and the number of cell phones recovered.

Phase 2: Refurbish and sell.

After buying the second-hand phone, the profit or little margin is fixed by refurbishing the used phone and selling them back on the market as previously owned.

$$C = NM = NeH \tag{4}$$

Equation (4) represents the total revenue, which is the product of the total number of recycled mobile phones and a second-hand phone sale price.

$$F_2 = BM + a_2NM = BeH + a_2NeH \tag{5}$$

Equation (5) represents expenses during the refurbishment and resale phase; it includes the cost per mobile phone in the refurbishment phase and the tax on mobile phones sold.

$$U_e = C - F_1 - F_1 = eH\left[\left(1 - a_2\right)N - B\right] - a_1ecDH \tag{6}$$

Equation (6) represents the enterprise's utility function, which is the total revenue minus the expenses incurred in both the recovery phase and the refurbishment phase.

$$U_c = D - E \tag{7}$$

Equation (7) represents the utility function of the consumer, which is the price when the customer buys the phone minus the recycling price received by customers.

As mentioned above, our approach uses this model to identify the optimal recycling prize (ORP) through which both the customers and enterprises benefit. As per the requirement of the algorithms, the parameter setting and the assumptions made are listed in Table 7 below:

According to Li's (2018) definition of the recovery channel model, for ith enterprise, its recovery rate e_i depends on its own E value and its competitors' E value. Thus, the recovery rate is

$$e_i = e\ x_iN_i + y_ix^n_{i,k-1}N_iN_k \tag{8}$$

For each group, the amount of second-hand mobile phones that each enterprise could recover from the customers are evenly distributed; however, this may be influenced by its recovery rate e_i. The M_i is defined as follows:

Table 7 The assumption of parameter

Parameter	Value
a_1	0.02
a_2	0.03
e	0.75
x_i	$0.25 \times 10^{-4} \pm 0.10 \times 10^{-4}$
y_i	$0.30 \times 10^{-4} \pm 0.10 \times 10^{-4}$
z_i	0.045 ± 0.010
H	10000
ETN	0.93
n	50

Table 8 Parameters for meta-heuristic algorithms

Parameter	Value
Tabu search	
Tabu list length	50
Number of neighborhood structure	2
Stopping criteria	1500
Variable neighborhood search	
Number of neighborhood structure	4
Stopping criteria	1500
Hybrid genetic algorithm	
Population size	20
Mutation rate	$\frac{1}{population\ size} \sim 0.8$
Crossover rate	$0 \sim 0.8$
Generation	10
Hybrid VNS stopping criteria	100

$$M_i = e_i(H \div n) \tag{9}$$

The recovery price that enterprises gives to the customer and the enterprise's selling price is defined as

$$N_i = z_i E \tag{10}$$

Each enterprise's cost depends on the price difference between the second-hand mobile phone recycling and selling price, which is related by z_i. The B_i is defined as follows:

$$B_i = z_i\left(1 + a_i\right)\left(N_i - cD\right) \tag{11}$$

Overall the utility function for the enterprise model can be defined as:

$$U_{ei} = C - F_1 - F_2 = NeH\left(1 + a_2\right) - AeH - Z\left[(1 + a2)N_i - A\right] \tag{12}$$

$$U_{ci} = D - E_i \tag{13}$$

The meta-heuristic algorithms' goal is to maximize the U_{Total}; Equation (14) defines the maximum value as

$$U_{total} = \sum\nolimits_{i=0}^{n} U_{ei} - U_{ci} \tag{14}$$

We randomly selected 20 well-known standard mobile phones as samples to test the meta-heuristic algorithms and compared them to the current state of device recycling. The initialization of the parameters is shown in Table 8 above.

From Fig. 7 above, it's apparent that the traditional total utility values are lower than each total utility value calculated by the meta-heuristic algorithms by using the game theory model. In this paper, the Nash Equilibrium truly could let customers and enterprises reap more benefits compared to the traditional price. As per our analysis, each one of the three algorithms has its advantages when compared with one another depending on the hardware. In the parameter settings of the model because of hardware constrains,

4G/5GModel	Name	Time Difference (Days)	Purchase price	Traditional Recovery Price	UTS	UV NS	UHGA	UTraditional
4G	iphone7	1387	6189	1550	1246.69	1434.07	1010.52	320.72
4G	iphone8	1019	3499	1150	4652.58	3143.47	2482.79	783.87
4G	iphoneSE	98	3299	2000	3921.06	4022.05	3762.82	2757.25
4G	iphoneXR	588	7899	2700	3749.96	3874.10	3485.63	2000.63
4G	iphone11 Pro MAX	298	12699	7100	16513.79	16823.74	15371.79	9297.53
4G	Huawei-Mate20x	590	4499	2000	3340.47	3424.29	3221.76	2157.25
4G	Huawei- Mate20 PRO	616	5499	2100	3119.23	3219.16	2944.41	1878.61
4G	Huawei- P30 PRO	281	7899	2730	3783.23	3957.24	3509.85	2066.22
4G	Xiaomi CC9pro	360	2648	1500	2937.03	3010.33	2707.30	1980.04
4G	Xiaomi CC9pro	360	2699	1650	3233.07	3304.78	3067.43	2286.58
4G	Xiaomi CC9pro	360	3199	1850	3541.13	3618.80	3395.83	2477.25
5G	Xiaomi 10 Pro	240	5499	2900	5577.89	5691.14	5267.51	3641.31
5G	Xiaomi 10 Pro	240	5999	3000	5612.71	5753.21	5323.31	3610.62
5G	VIVO NEX3S	180	5298	3250	6765.88	6907.98	6275.81	4512.48
5G	VIVO NEX3S	180	4998	2900	5782.85	5937.92	5577.53	3891.81
5G	VIVO NEX3	360	5498	3100	6139.15	6322.27	5847.81	4082.48
5G	VIVO NEX3	360	4998	2800	5521.67	5620.93	5148.30	3670.45
5G	VIVO NEX3	180	4998	2250	3816.69	3924.67	3661.00	2459.10

Fig. 7 Results compared with TS, VNS, and HGA

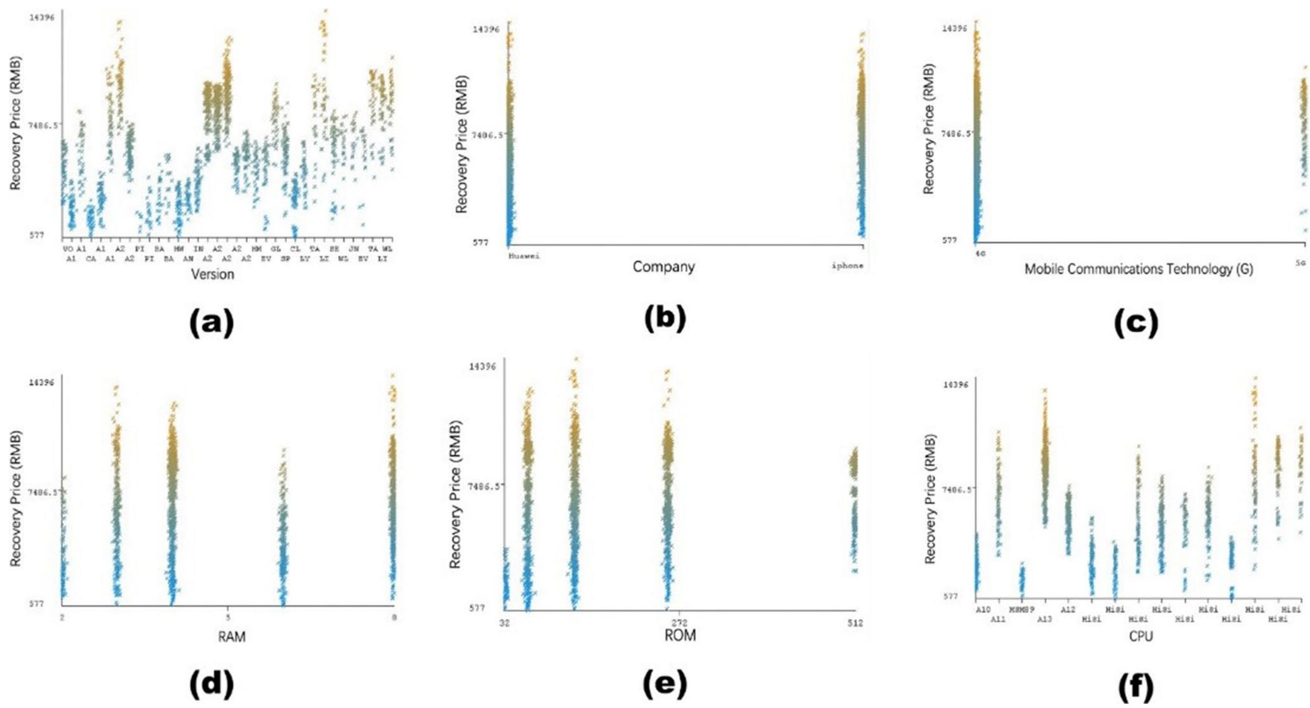

Fig. 8 Recovery price based on some of the attributes like **a** mobile mobile communication technology, **b** company, **c** version, **d** RAM, **e** ROM, **f** CPU

the epochs for the VNS hybrid in the GA are only 100, while the epochs for individual TS and VNS are 1500. Hence, if the parameters for HGA are higher, the results of the HGA may even give us better results. As per observed results, we analyzed the issues found with different attributes. However, we believe that the traditional price can be comparatively enhanced with the proposed model.

Visualization of role of the attributes with recycle price

Fig. 8a shows that the recovery price based on different attributes has been employed for the study. Generally, the price of every brand depends on the following attributes and also affects the price of recycling price. In the People's Republic of China, Apple brand mobile phones are particularly coveted for their special features. As such, the particular features of every phone including its brand name are considered important factors. Furthermore, the recycling price of 4G mobile phones is significantly higher than that of 5G devices. For data collection, 5G technology is only used for high-end mobile phones from Huawei and Apple. It is only promoted in developed areas because the secondary market has apparent limitations. 4G technology is the central mobile phone signal technology currently in circulation, with a broader audience under necessary factors such as the target population and application scope. Therefore, the recycling price will be affected by the applicable population, the communication technology's maturity, and available areas. Fig. 8b shows that the recovery price of an Apple iPhone's is much higher than that of other brands. However, the market shares occupied by Apple and Huawei may change at any given time; thus, this does not have a direct effect on the price of recycling a device. Fig. 8c shows the data is that of a normal distribution tendency. The mobile phone chip version directly affects the recycling price, which is more explicit for Huawei and more implicit for Apple. Fig. 8d shows data of a centrally distributed tendency, and the RAM (random access memory) sizes of devices directly impact the recycling price, which is opposite to that of the purchase price. Fig. 8e shows that for all samples, the recycling price of phones with 32 GB ROM (read only memory) is significantly lower than the standard, while others remain stable and concentrated. The ROM size does not have a regular distribution on the recovery price; hence it has no direct effect on the price of recycling a device. Fig. 8c shows the data is that of a normal distribution tendency. The chip version directly affects the recycling price, which is more explicit for Huawei and more implicit for Apple. Fig. 8d shows data of a centrally distributed tendency, and the RAM (random access memory) sizes of devices directly impact the recycling price, which is opposite to that of the purchase price. Fig. 8e shows that for all samples, the recycling price of phones with 32 GB ROM (read only memory) is significantly lower than the

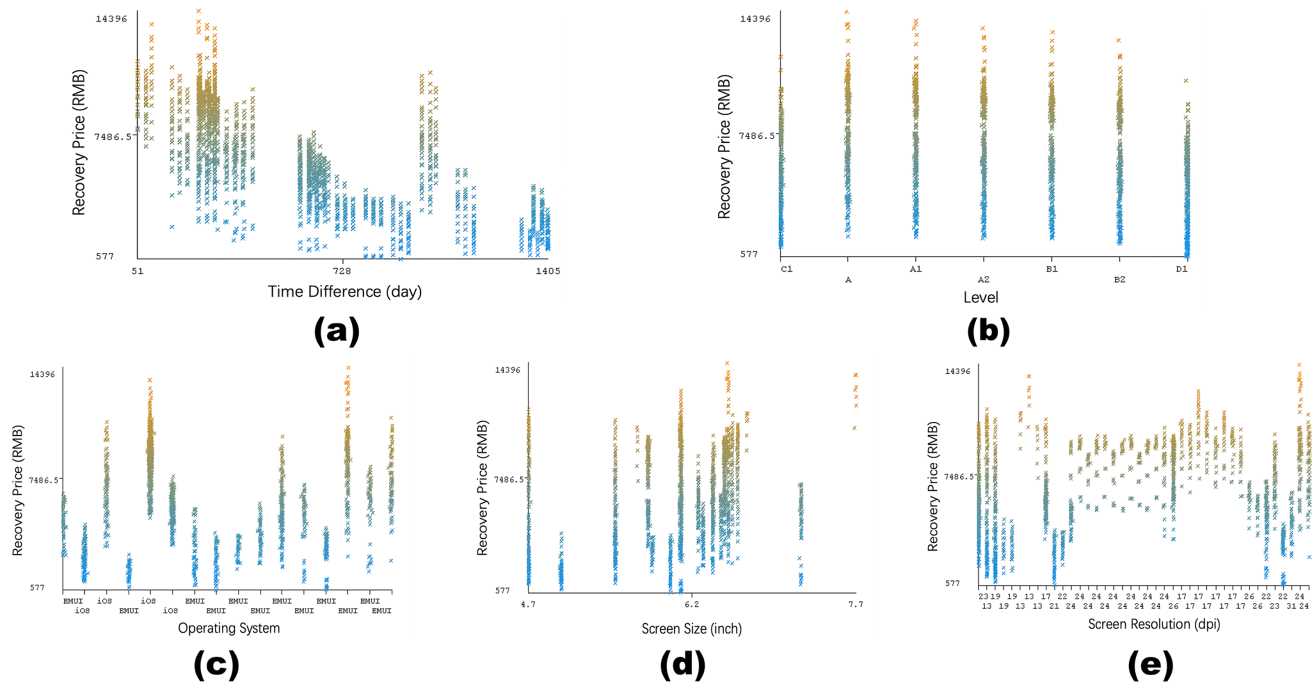

Fig. 9 Recycle price based on the attributes like **a** time difference, **b** level, **c** operating system (OS), **d** screen size, **e** screen resolution

standard, while others remain stable and concentrated. The ROM size does not have a regular distribution on the recovery price; hence it has no direct impact. In Fig. 8f, different CPUs (central processing unit) show a sinusoidal distribution tendency, and the overall data shows an upward trend. Therefore, phones with higher-performing CPUs have a greater recycling value. CPU types have a direct effect on the recovery price of phones.

For Fig. 9a, data presents a sinusoidal distribution and reaches a peak between the interval [200, 500], and the overall downward trend is evident. The recycling price of second-hand mobile phones drops significantly over time. Time difference plays the most explicit role among all attributes. In Fig. 9b, the level is defined by the degree of completeness of the appearance of the second-hand recycled mobile phone. However, the distribution of each unit is uniform and consistent. Hence, the impact of the level on the recovery price can be ignored. Fig. 9c shows the two types of operating systems (OS) involved, IOS (Apple) and EMUI (Huawei), and only discuss the most suitable OS of each sample appearance settings of OS. The IOS operating system shows a paragraph-like upward trend along the time axis, while the EMUI operating system displays a growth wave curve. Since OSs are updated with the timeline, the longer the second-hand phones go before they are sold, the lower the optimal OS version of the device. Fig. 9d shows that screen size (inches) has a centrally distributed trend, peaking at 6.5 inches. The edge data is 4.7 inches and 7.7 inches, in which the recycling price has an explicit downward tendency. Hence, the intermediate size is more comfortable to be accepted by customers. In Fig. 9e, the data distribution has no apparent regularity. First, the recycling prices of different companies are partially concentrated. Second, when the Screen resolution is 24 dpi and 17 dpi, the data is concentrated and stable, but when the screen resolution is 22 dpi and 19 dpi, the recycling price of used mobile phones drops significantly. Overall data, the fluctuation range is implicit, so the mobile phone's resolution level slightly affects the recycling price.

In conclusion, obtained by data visualization analysis through Weka. Among all attributes, time difference has the most explicit impact. It affects recovery prices by influencing other co-factors. The lower the time difference of second-hand mobile phones, the higher the recycling value for consumers.

Data visualization of the data set compares the optimal recovery price derived from the above mathematical model and meta-heuristic. Time difference is the most important factor. The impact of other attributes on the recovery price is also the same. It can be demonstrated that the model and derivation mechanism established in this paper are in line with the actual situation. Cohen et al. (2021) has proposed a model for solid waste recycling to identify difficulties that a municipality and its residents face in building and operating infrastructure for recycling under the extended producer responsibility law. Similar study will be carried out even for market and enterprise resale prize based on the local governing body.

Conclusion

In the analysis of consumer recycling behavior, the questionnaire survey shows that more than 80% of consumers cannot obtain the recycling price of second-hand mobile phones. And more than half of them will passively participate in mobile phone recycling due to that fact. This research has processed and analyzed thousands of second-hand mobile phone recycling price data to make the recycling price of second-hand mobile phones more transparent to consumers. This research establishes a second-hand mobile phone recycling price model based on mobile communications technology, company, phone name, version, RAM, ROM, time difference, CPU, operating system (OS), purchase price, screen size (inches), screen resolution, and level. The data model shows that the recovery time difference significantly impacts the recovery price. This data model reduces the lag of consumers' knowledge of the recycling price and minimizes the possibility of their passive participation. Furthermore, consumers could realize the dramatic impact of recycling time difference on recycling prices through this model. This may then encourage consumers to participate in mobile phone recycling earlier and more actively.

However, this model only collects four mobile phone brands with the largest share in the Chinese market: Apple and Huawei, Xiaomi, and Vivo. Data from other brands such as Samsung and ZTE are missing. In the future, research may focus on comprehensive analysis (that includes other major brands such as ZTE and Samsung.) As mobile phone series are updated quickly and often, future research should analyze more comprehensive and updated mobile phone brand data. And moreover, we would also implement the Shekarian and Flapper (2021) closed loop analysis in future when this paper referring to important configurations of the circular economy (CE) has received considerable attention in sustainability matters. It is composed of characteristics that, when identified, studied, and categorized, help not only to a better understanding of the current contributions in the literature but also lead to formulating new models.

For recyclers, the study analyzes the behavior of recyclers through Hawk-Dove game and prisoner's dilemma. The Hawk-Dove game shows that recyclers are in a dominant position in the market, and they determine the recycling price of used mobile phones. Since second-hand mobile phone recycling requires cost borne by the recyclers themselves through personal rationality and benefit maximization, recyclers tend to provide consumers with lower prices. The recycling of these devices requires the participation of a great deal of mobile phone recyclers. Prisoner's dilemma shows that some recyclers' passive participation will lead to other recyclers' inactive participation. Therefore, the government should participate in the second-hand mobile phone recycling market and regulate recyclers. When recyclers are passively involved in recycling, the government should urge recyclers to increase taxes or face fines as punishment mechanisms.

- When consumers are actively engaged in the process, the government should encourage recyclers by lowering taxes or appropriating funds. This study uses meta-heuristics to analyze the Nash Equilibrium between consumers and recyclers in the commercial behavior of recycling mobile devices.
- The results shows a tendency that to reach the maximum profit in the whole market, the recyclers should provide higher prices compared to the traditional prices for the second-hand mobile phone
- From the data visualization by using machine learning algorithm in Weka, it's clear that the time difference is the core factor that affects the fluctuation of the recovery price.
- However, this research has some limitations: (1) the second-hand mobile phone recycling price model contains only four mobile phone brands with the largest share in the Chinese market: Apple and Huawei, Xiaomi, and Vivo; data from other brands such as Samsung and ZTE are missing.
- The feasibility, necessity of the reward, and punishment mechanism in the process are only discussed at the theoretical level.
- Due to the random factors in the meta-heuristic, the algorithm has the probability to diverge from the local optimal solution and shift to a more global optimal solution. Therefore, fixed input cannot guarantee unified output.
- With the above stated limitation of the mathematical model, some phones whose optimal price estimated by the meta-heuristic algorithm is higher than their new price.

Future research may focus on building a more completed mathematical model based on comprehensive second-hand mobile phone recycling data and take account the higher importance of the time difference factor. As mobile phone series are updated quickly, future research can analyze more comprehensive and updated mobile phone brand data. More practical rewards and punishment are needed to regulate the behavior of recyclers. As Zhang et al. (2020) has mentioned, the game theory model is built here to find out how effective funding is for this recovery and recycling system in China. So the researcher will be exploring more in WEEE.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-021-17061-w.

Acknowledgements We are thankful to the leaders and the management of the institution.

Author contribution Author contributions: Dr Sujatha and Dr Kennedy are the supervisors of this research and guided the scholars. Liu Zixuan designed the mathematical model and algorithms. Yihang Liu collected the dataset, Yang Qiu and Zixuan Liu worked in the software. Yihang Liu and Wanying Dou edited the whole document and initial study was carried out by them and Zixuan Liu. All authors contributed to the study conception and design.

Funding This project is supported by the Institute for Societal and Contemporary computing by Wenzhou-Kean University.

Data availability Code is available; it can be given through git hub link after acceptance.

Declarations

Consent for publication Not applicable

Competing interests The authors decl are no competing interests.

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