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MODELLING AND SIMULATION ON RECYCLING OF ELECTRIC VEHICLE BATTERIES – USING AGENT APPROACH

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Abstract
This study investigates electric vehicles battery recycling problem. In this study, based on Agent theory and Anylogic platform, Agent model of battery recycling is built. We have done simulation for electric vehicle batteries recycling: this paper analyses the influence that factors (battery renovation rate, quantities of electric vehicles, electric vehicle lifetime, battery lifetime, battery renovation time) have on recycling (quantities of wasted batteries, quantities of reused batteries, optimal quantities of batteries). Through simulation, this study shows that factors' influence on recycling depends on the relative life RL greatly. When renovation rate changes in the interval [0.7, 0.8], the results fluctuate greatly, such as optimal quantities of batteries will decrease about 10 %, quantities of reused batteries can increase about 30 %, and quantities of wasted batteries will have a sharp decline by about 40 %; the model is optimal until battery renovation times are increased to three.
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Key Words: Electric Vehicle, Battery Recycling, Agent, Modelling, Simulation

1. INTRODUCTION

Automobile industry is an important pillar industry in the national economy. Meanwhile, energy crisis and environmental protection problems will come together. By the virtue of use of clean energy and reduction of total emissions, electric vehicles become the new requirements in response to a low-carbon economy in China's auto industry. Based on vehicle driving principle, electric vehicles can be divided into pure electric vehicles (PEV), hybrid electric vehicles (HEV), and fuel cell electric vehicles (FCEV). This study focuses on PEV. Specifically, this paper studies lithium-ion batteries according to their characteristics. However, the development of electric vehicles will also face with some problems, for example, the end-of-life batteries. Spent lithium-ion batteries contain lithium and other dangerous metal materials. So if they are not effectively tackled with, there will be not only a vast waste of resources, but also serious environmental pollution. Early in 2005, Hicks et al. [1] proposed environmental problems generated by wasted products; Wen et al. [2] pointed out that a large number of end-of-life batteries would bring enormous pressures on our living environment with the popularity of electric vehicles; Zdenek et al. [3], Notter et al. [4] thought that large amounts of CO_2 can come together with battery production. Under these circumstances, the problems of processing spent batteries need to be solved urgently. Recycling of spent batteries can decrease the mining of metal energy as well as reduce battery production costs [5-7]. And because of relevant laws, social responsibility, economic interests and people's awareness of environment and resource protection, recycling of spent batteries is put forward.

It is undeniable that battery recycling has a good future. How to manage battery recycling and to know which factors can affect battery recycling, as well as their impact on battery recycling, will have a serious bearing on electric vehicles industry development and environmental protection. Based on the findings from existing literatures, we found that existing studies discuss the recycling process, the recycling methods and modes, the

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influencing factors of recycling, etc.

Caraman et al. [8] came up with a predictive controller model for wastewater treatment, and Vilanova et al. [9] also described a digital control model for wastewater treatment; so it needs predictive control model for spent batteries too. So the research questions in this study are: which factors can affect battery recycling and how they do it. At present, the aforementioned problems have not been resolved yet in related research works. In this study, we propose the Agent model to illustrate the problems of battery recycling with the help of Anylogic simulation platform. We organize this paper as follows: in the following section, we present a comprehensive review, which forms the theoretical foundation of this study. In section 3, we introduce the Agent method, which provides the base for battery recycling conceptual model. In section 4, we present the simulation models with Anylogic. In section 5, we discuss the simulation results and verify the model. Finally, we conclude the study.

2. LITERATURE REVIEW

With the increasing of electric vehicles, spent batteries will come in abundance. Even though there are conventional disposal methods for e-waste, these methods have disadvantages in economics and environment. As a result, new e-waste management options need to be considered, that is, recycling [10]. The reasons that spent batteries should be recycled can be attributed to three aspects: firstly, protecting environment. Spent batteries contain lithium and other metal materials, which will cause not only a waste of resources, but serious environmental pollution if they are not effectively recycled [7]; secondly, conserving resource. The reused batteries can reduce the mining of metal ores, save the use of metal ores [5-7]; thirdly, decreasing cost. The reuse of recycled batteries can reduce the demand of raw materials so as to decrease production cost [11].

Because of the importance of battery recycling, it has been widely studied in literature. Generally speaking, spent batteries are included in the WEEE (waste electrical and electronic equipment), solid waste, etc., so recycling of spent products is confronted with the similar problem. Findings from existing literatures indicate that the researches discuss the recycling process, methods, modes, and influencing factors, etc.

Recycling process is the basis. Ishihara carried out an analysis on environmental burdens of lithium-ion batteries during production, collection, recycling and waste disposal under the assumption of mass production [12]. Based on battery recycling closed-loop logistics system (disposed, recycled, reused or remanufactured), Kannan et al. [13] established a multi echelon, multi period, and multi product mathematical model, then explored the genetic algorithm to solve the model, at last, analysed economic efficiency of the recovery system; On the background of end-of-life products recycling, Duta et al. [14, 15] thought an essential criterion for a performing disassembly system is the benefit it brings, and decreased by the cost of their retrieval, the author solved the NP-hard disassembly system problem based on genetic algorithms in the end. Hischier et al. [16] developed MFA (the material flow analysis) and LCA (life cycle assessment) to evaluate spent electronic products recycling process' impact on environment.

Different recycling methods and modes can be used in recycling process. A mixed-integer-linear-programming (MILP) model for integrated disassembly and bulk recycling was developed, implemented and solved by Ploog and Spengler [17]. The bulk recycling, disassembly recycling, and smelter recycling were also introduced by Sodhi and Reimer [18], and based on different recovery modes, the corresponding mathematical model (setting benefits as the objective) function was developed to explain battery recycling problem; Nagurney and Toyasaki [19] depicted resources, recyclers, processors and demand market, which constituted the electronic product recycling system, followed by mathematical functions to describe the behaviour of main bodies in recovery process and explored the corresponding algorithm in the end; Savaskan et al. [20] addressed the problem of choosing appropriate reverse channel structure for the collection of spent products from customers, and summarized three options for collecting such products:(1) collecting them herself directly from the customers, (2) providing suitable incentives to an existing retailer to induce the collection, or (3) subcontracting the collection activity to a third party. And authors found that (2) is the most effective undertaker of product collection activity for the manufacturer.

There are common factors in different modes. Wen et al. [2] surveyed that collection rate played an important role in the recycling of electronic products; Väyrynen and Salminen [21] pointed out that the global capacity of industrial-scale production of larger lithium-ion battery cells may become a limiting factor in the near future, so increased lifetime combined with a higher recycling rate of battery materials was essential for a sustainable battery industry; thus Sidiquea et al. [22] analysed the factors (expenditure variable / recycling programs / income / demographic characteristics) that affected recovery rate by utilizing county-level panel data; Schaik and Reuter [23, 24] pointed out product design and recycling technology can affect recycling and environment based on System Dynamics; Zackrisson et al. [25] thought improvements in battery technology, especially related to cycle life, had decreased production phase environmental impacts almost to the level of use phase impacts.

Meanwhile, people have paid attention to specific factors analysis, in particular, these factors' impact on battery recycling, that is, what-if analysis. Schiffer [26] formulated a combined performance and lifetime model, so that different operating profiles (depending on system sizing and operation strategy) can be analysed with regard to their impact on battery lifetime. System Dynamics had been developed to sensitivity analysis of waste management [27-30]. System Dynamics method is applicable to specific issues-oriented modelling, but inadequacy of the method is the assumption of individual homogeneity.

To sum up, existing literatures mainly focus on the recycling process, methods, modes, and influencing factors. Based on a comprehensive literature review, we find that there is much room for improvement regarding the influencing factors problems in battery recycling. Further study on 'factors' impact on the recycling is necessary to provide insights for practitioners and academics. Based on Agent, we analyse quantities of electric vehicles (number of cars, below), electric vehicle lifetime (car lifetime, below), battery lifetime, battery renovation rate, battery renovation times' impact on battery recycling (including quantities of wasted batteries, quantities of reused batteries, optimal quantities of batteries).

3. THE METHOD AND CONCEPTUAL MODEL

The recycling model of electric vehicles batteries focuses on factors' impact on the recycling. Different objects (vehicle and battery) are involved in the model, so Agent is introduced.

An agent is defined as autonomous, computational entities that can be viewed as perceiving its environment through sensors and acting upon their environment through effectors, and a few common properties that can be assigned to an agent are autonomy, co-operativity, reactivity, pro-activeness and learning; Multi Agent is a relatively new specialization of Distributed Artificial Intelligence that helps in developing complex systems with concurrent behaviour [31]. The definition of an agent depends heavily on what we take as the environment, and on what sensing and acting mean. If we define the environment as whatever provides input and receives output, and take receiving input to be sensing and producing output to be acting, every program is an agent. Thus, if we want to arrive at a useful contrast between agent and program, we must restrict at least some of the notions of environment, sensing and acting. Meanwhile, domain-specific ontology is needed in Agent-based systems [31].

To describe an autonomous agent, we must describe its [32]:

- Environment;
- Sensing capabilities;
- Actions;
- Drives;
- Action selection architecture.

That is also described as:

$(Action_i a)$: Agent i will take action a;

$(Bel_i \varphi)$: Agent i will take belief φ;

$(Achieve_i a\varphi)$: φ is Agent i's belief, so Agent i will take action a to achieve it;

$(Can_i \varphi)$: Agent i can achieve φ;

$(Can_i \varphi) \xrightarrow{def} (Achieve_i a\varphi) \bigcup (Action_i a) \bigcap (Can_i \varphi)$: Agent i can achieve φ directly; Agent i can indirectly achieve φ after Agent i has taken action a;

$(Commit_i \varphi)$: Agent i has commitment on φ;

$(Commit_i \varphi) \xrightarrow{def} (Bel_i \Box((Achieve_i a\varphi) W Exception))$: Agent i will always take action a to achieve φ except the accident.

The electric vehicle battery recycling model relates to car Agent, battery Agent, as well as message. Each Agent's action depends on the environment, the condition of itself and the state of other Agent. Each Agent has information communicating and self-running ability. Based on the documents, car Agent includes four states: production, normal driving, battery replacement and vehicle scrapped, and battery Agent includes five stages: waiting, working, replacing, refurbishing and scrapping. Electric vehicles battery recycling model is shown in Fig. 1.

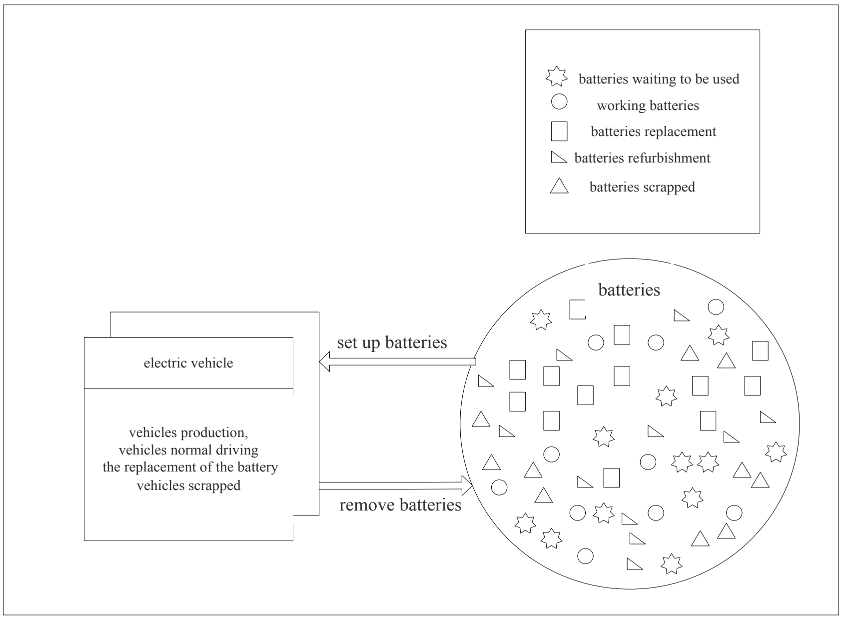

Figure 1: The conceptual model.

Based on conceptual model and literature, in this paper we analyse number of cars, car life, battery life, battery renovation rate and battery renovation time' impact on quantities of wasted batteries, quantities of reused batteries, optimal quantities of batteries, so that the simulation model can be established.

4. MODELLING WITH ANYLOGIC

Electric vehicle battery recycling model involves car Agent, battery Agent, as well as message model. The modelling platform is AnyLogic 6 University edition which belongs to XJ Technologies, programming language is Java.

4.1 Message model

Message model is required to realize the communication between car Agent and battery Agent, including installing battery, removing battery, replacing battery and discharging battery. The foundation of excellent communication mechanism in multi-agent system is of much significance, which enables each agent to comprehend with one another in semantic level, for the purpose of structuring an organic whole to accomplish the task together through cooperation. Furthermore, the communication mechanism is supposed to support synchronous and/or asynchronous communication, and one-to-one, one-to-many and broadcast communication. The mechanisms consist of 'timeout', 'rate', 'condition', 'message' and 'agent arrival' in AnyLogic, in this paper we adopt 'message'. Agent communication is in the basic ABSFSim (Agent-based shop floor simulator), not the developed one [31, 33].

Message model should include car ID, battery ID, and message content.

The code in AnyLogic is as follows:

```
 public class Msg implements java.io.Serializable {
  int carID;
  int batID;
  String txtMsg;
public Msg(){
    }
public Msg(int parcarID, int parbatID, String partxtMsg){
        this.carID = parcarID;
        this.batID = parbatID;
        this.txtMsg = partxtMsg;
    }
   @Override
     public String toString() {
        return
             "carID = " + carID +" " +
             "batID = " + batID +" " +
             "txtMsg = " + txtMsg +" ";
             }
    }
```

The message process is designed in Fig. 2. If car Agent sends a message, battery Agent will generate a trigger condition, and then answer car Agent automatically; similarly, battery Agent gives the message, car Agent will generate a trigger condition, automatically answering battery Agent. Therefore, communication is completed between car Agent and battery Agent, and car Agent can cycle to normal operation until car Agent or battery Agent is used up.

4.2 Battery Agent

In this paper, we explain and define battery Agent in battery ID and battery state.

(1) Battery ID

Set the distribution and number for battery Agent, so each battery Agent can get an ID. More detail is as follows:

```
int i;
for(i=0;i<batteryNumber; i++)
{
batteries.get(i).batID=i;
}
```

Battery Agent can send message and respond to car Agent automatically.

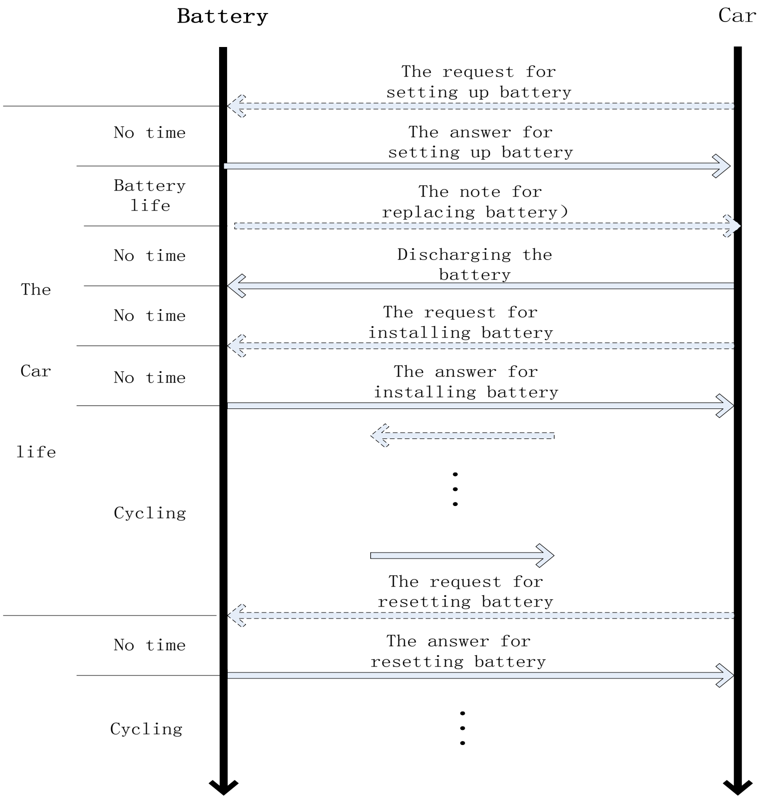

Figure 2: Message model.

(2) Battery state

Set battery's state 'false' when it is in use (batteries.get(i).state=false); Set its state 'true' when it is unused (batteries.get(i).state=true). All of these can ensure the batteries are not being used at the same time. In addition, the total amount of batteries:

$$N = \sum (Iu + Rp + Rf + Ws) \tag{1}$$

where Iu, Rp, Rf, Ws are quantites of batteries in different stage (in use, replaced, refurbished and wasted); and when the Agent model stops,the total amount of batteries is:

$$N = \sum (Iu + Rp + Rf + Ws) = \sum Ws \tag{2}$$

Then quantities of wasted battery are got. Many factors need to be considered during the process of battery recycling, such as battery life L, battery renovation rate r and battery renovation time t.

(3) Battery life

Lifetime is the decisive factor that affects battery recycling, that is:

$$B(k) = \begin{cases} 0, \text{ if } L(k) < L_{MAX}(k) \\ 1, \text{ if } L(k) \geq L_{MAX}(k) \end{cases} \tag{3}$$

where k is battery ID, $B(k)$ is battery recycling condition (0 means in use,1 means recycling), $L(k)$ is battery life, and $L_{MAX}(k)$ is the maximum of battery life. Considering battery renovation time t, the whole lifetime can be prolonged, that is:

$$L(k) < t \cdot L_{MAX}(k) \quad (4)$$

where $t > 0$.

(4) Battery renovation rate

When $L(k) \geq L_{MAX}(k)$, spent batteries can be recycled for reusing. The distribution of battery renovation affects quantities of reused batteries directly. We assume that it obeys Bernoulli distribution:

$$F = \text{Bernoulli}\ (\beta) \quad (5)$$

where β is renovation factor (renovation rate r, below). Spent batteries are renovated on basis of the probability of β and are scraped in the probability of $1 - \beta$. Recycling rate is set to 1.

(5) Battery renovation time

Spent batteries can be renovated to be reused, but time of battery renovation is limited by M (maximum time of renovation). Only when $t < M$, spent batteries can be renovated, or scraped.

Battery Agent is shown in Fig. 3.

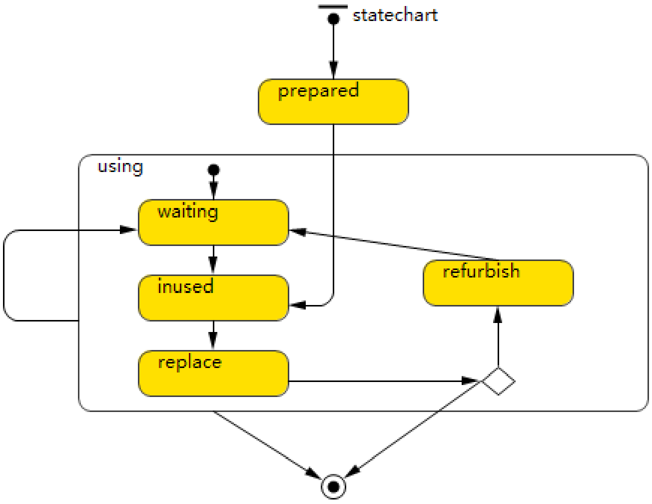

Figure 3: Battery Agent.

Description of symbols in Fig. 3:

statechart and •: battery initial state; ⟶: flow of battery; ◇: selection; ⦿ batteries are scraped;

prepared: producing battery; inused: setting up battery; replace: replacing battery; refurbish: renovating battery; waiting: inventory battery.

Firstly battery is charged in prepared state, when receiving the message 'setting up battery' sent by new car, battery is in use, meanwhile battery is in an unusable state (state=false). Battery needs to be replaced when $L(k) \geq L_{MAX}(k)$, at the same time, it will notice car of replacing battery, meanwhile battery is in an unusable state (state=false). Spent batteries can be handled in two ways, one is directly scrapped in probability $1 - \beta$, the other is to be renovated based on the probability β, meanwhile battery is in an unusable state (state=false). After the renovation cycle, battery re-enters the system, meanwhile battery is an unusable state (state=true), and time of renovation is calculated. The discharging battery also re-enters the system when the car is scraped. When receiving the message 'installing battery' issued by car, battery will be in use, meanwhile battery is in an unusable state (state=false). When reaching the certain time *M*, battery will be directly scraped instead of being renovated, meanwhile battery is in an unusable state (state=false).

4.3 Car Agent

Car Agent has close relations with battery Agent. To be specific, the demands of car directly determine the production of battery, and car life affects battery needs. So the triple explains and defines a car Agent:

$$C(c(d), c(n), c(l)) \tag{6}$$

where $c(d)$ is car ID, $c(n)$ is car number, and $c(l)$ is car life.

(1) Car ID

Set the distribution and number for car Agent, so each car Agent can get an ID. More detail is as follows:

```
int i;
for(i=0;i< carNumber;i++)
{
cars.get(i).carID=i;
}
```

So car Agent can send message and respond to battery Agent automatically.

(2) Car number

The production of battery N depends on the quantities of car $c(n)$, that is, $c(n) = F(N)$, where F is a math function. If quantities of batteries are enough for car running, optimal quantities of batteries are got, which are $Mn(N)$. Therefore, quantities of batteries can neither be too big (leading to a waste of resources and environmental pollution) nor be too small (bringing about the slow development of electric vehicle industry).

(3) Car life

On one hand, car life has a direct impact on quantities of wasted batteries, quantities of reused batteries and optimal quantities of batteries; on the other hand, the longer car life is, the bigger M is, that is:

$$M = e \cdot F(c(l)) \tag{7}$$

where e is the coefficient ($e > 0$), F is a math function.

Car Agent is shown in Fig. 4.

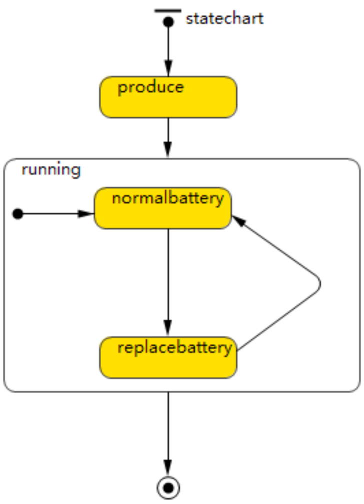

Figure 4: Car Agent.

Description of symbols in Fig. 4:
produce: car production; normalbattery : normal battery; replacebattery : the abnormal battery (needs to be replaced); the others are the same as at the battery Agent.

Firstly car is in production. The message 'setting up battery' will be sent before new car running. When $L(k) \geq L_{MAX}(k)$, abnormal battery needs to be discharged from car after receiving the message 'replacing battery'; at the same time, car will request for installing battery. If battery is normal, car will not stop until reaching $c_{MAX}(l)$ (maximum of car's life). When car is scraped, the message 'resetting battery' can be sent by car, and then the battery could be reused or recycled.

Simulation research is carried out based on conceptual model and simulation model.

5. SIMULATION

The simulation platform is AnyLogic 6 University version which is the simulating tool developed by the XJ Technologies. The software is written in Java, the simulation program can be compiled to Java Applets and supports working on a Web page.

5.1 Settings of simulation

Settings are as follows in AnyLogic 6 University:

Environment environment , car Agent cars [..] , battery Agent batteries [..] , and Agents are in the same environment;

Parameters batteryPopulation and carPopulation , which are number of batteries and number of cars respectively;

Variables reusedbattery and batfalse , which are quantities of reused batteries and quantities of unusable batteries respectively;

Event event , and the codes in AnyLogic are as follows:

```
int i;
reusedbattery=0;
batfalse=0;
   for(i=0;i<batteryNumber;i++)
 {
   if(batteries.get(i).recycle>1) reusedbattery++;// quantities of reused batteries
   if(batteries.get(i).state==false) batfalse++; // quantities of batteries which are unusable.
 }
```

Quantities of wasted batteries can be got when the simulation ends up.

The time of replacing/setting up/installing of batteries is ignored, recovery rate is 1, the other parameters settings are seen in Table I.

5.2 Simulations

Based on Agent model, this paper analyses number of cars, car life (the mean $c / 2$ is used in simulation, the same below), battery life (the mean $b / 2$ is used in simulation, the same below), battery renovation rate and battery renovation times' impact on quantities of wasted batteries, quantities of reused batteries and optimal quantities of batteries.

(1) Change battery renovation rate

Take the average of 30 simulation results (other parameters settings are shown in Table I), quantities of wasted batteries, quantities of reused batteries and optimal quantities of batteries are got in Fig. 5 a.

Table I: Parameters setting.

Parameters (unit)	**Value**
Number of cars (ones)	200
Number of batteries (groups)	535
Cars production time (month)	2
Car life (month)	Uniform distribution: $U(0, c)$, $c > 0$ and $c = 240$
Battery life (month)	Uniform distribution: $U(0, b)$, $b > 0$ and $b = 72$
Battery renovation cycle (month)	2
Battery renovation time (times)	3
Renovation rate (%)	$ß = 0.6$
Simulation time (month)	200

T-test for simulation results. Take '58' (quantities of wasted batteries) for example：

Based on the Law of Large Numbers, it is considered that samples of 30 obey Normal distribution. The confidence interval of *T*-test is (95 % confidence):

$$(\bar{x} - t_{(\alpha/2,\, df)} \frac{s}{\sqrt{n}},\ \bar{x} + t_{(\alpha/2,\, df)} \frac{s}{\sqrt{n}}) \quad .(8)$$

where: $\bar{x}$ is sample mean, t is a statistical value, α is risk, df is degree of freedom, s is sample standard deviation, and n is sample number.

The confidence interval is [57, 59]. It explains that 95 % of simulation results locate in the interval [57, 59]. Sample mean ($\bar{x} = 58$) is served as the simulation value (the same below).

It can be seen in Fig. 5 a, with the improvement of renovation rate, quantities of wasted batteries and optimal quantities of batteries decrease continuously, but quantities of reused batteries will increase. Use 0.7 as the benchmark, when renovation rate rises 10 %, optimal quantities of batteries can decrease 10 %, quantities of wasted batteries will be reduced by 40 % correspondingly, and quantities of reused batteries will increase by 30 %; when the renovation rate drops 10 %, optimal quantities of batteries may increase 7 %, quantities of wasted batteries will increase by 30 %, and quantities of reused batteries will be reduced by 20 %.

(2) Change number of cars

Take the average of 30 simulation results (other parameters settings are shown in Table I). When the number of cars is 220, optimal quantities of batteries are 535; 300 cars require 790 batteries at least. Then the demand balance curve of car-battery is got. The curve above is about saturation area, meaning that the production of batteries exceeds the actual needs; the curve below is about shortage area, meaning that the production of batteries is less than the actual needs. Concrete information is shown in Fig. 5 b.

Similarly, when parameters change, the corresponding demand balance curve can also be obtained, which can be found in Fig. 5 b. Number of cars is the independent variable N, while the number of batteries is the dependent variable $c(n)$ which has closed relations with N, and the relations can be calculated resorting to $c(n) = F(N)$.

(3) Change battery life

Take the average of 30 simulation results (other parameters settings are shown in Table I), quantities of wasted batteries, quantities of reused batteries and optimal quantities of batteries are shown in Fig. 5 c.

It can be seen from Fig. 5 c that with increasing of battery life, quantities of wasted batteries, quantities of reused batteries and optimal quantities of batteries change reversely.

The change is especially big when battery life is prolonged from 12 months to 24 months: quantities of wasted batteries will be reduced by 65 %, quantities of reused batteries have as much as 60 % reduction, and optimal quantities of batteries decease about 40 %. Considering base number, the change is very large absolutely; while the change is normal in other cases.

(4) Change car life

Take the average of 30 simulation results (other parameters settings are shown in Table I), quantities of wasted batteries, quantities of reused batteries and optimal quantities of batteries are shown in Fig. 5 d.

It can be seen from Fig. 5 d, when car life is prolonged from 96 months to 108 months, quantities of wasted batteries are unchanged (the same with quantities of reused batteries and optimal quantities of batteries); Use "156 months" as the benchmark, quantities of wasted batteries will increase by 38 %, quantities of reused batteries may increase by 40 %, optimal quantities of batteries can increase by 11 % with car life increased by every three years; Quantities of wasted batteries will decrease by 23 %, quantities of reused batteries may decrease by 56 %, optimal quantities of batteries can decrease 10 % with car life decreased by every three years.

(5) Change battery renovation time

Take the average of 30 simulation results (car life is 195 months, other parameters settings are shown in Table I), quantities of wasted batteries, quantities of reused batteries and optimal quantities of batteries are shown in Fig. 5 e.

In Fig. 5 e, the outcomes change more obviously when time of battery renovation increases from 2 to 3. In that circumstance, quantities of wasted batteries will be reduced by 35 %, quantities of reused batteries will increase by 13 %, and optimal quantities of batteries will be reduced by 14 % correspondingly. However, the outcomes remain unchanged with increasing of renovation time.

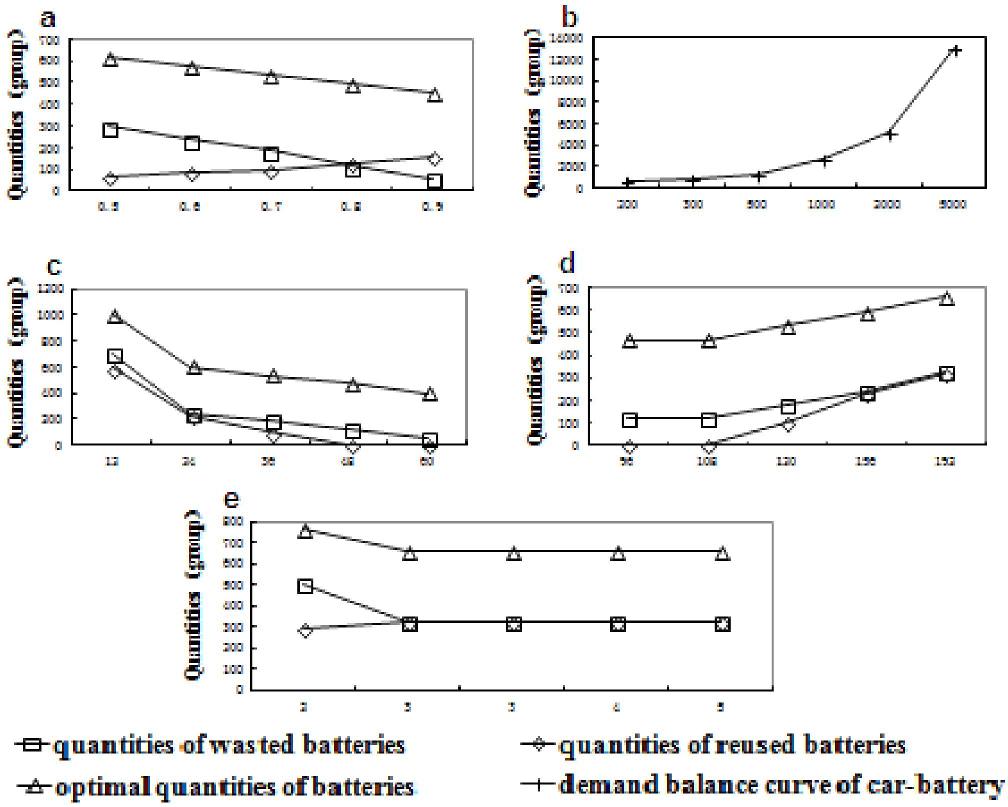

Figure 5: Factors and battery recycling.

Number of cars and car life belong to exogenous factors, affecting the simulation results indirectly; while battery life, battery renovation rate and time of battery renovation are endogenous factors, affecting the simulation results directly. Due to the difference between endogenous and exogenous factors, their impact on simulation results will be different.

6. CONCLUSION

Large quantities of spent batteries will come along with the development of electric vehicles in the future, so we should take batteries recycling into consideration. This requires the knowledge about which factors can affect battery recycling and how much influence they have. In this study, the modelling and simulation of recycling of electric vehicle batteries is carried out based on agents. We can get the conclusions as follows:

(1) Battery renovation rate has the big impact on simulation results; (2) Actual battery production should be in accordance with the demand balance curve of car-battery strictly, or it will bring about batteries supply shortage or waste of resources; (3) Battery life's impact on the simulation results depends on the relative life *RL* ($RL = L_{MAX}(k) / c_{MAX}(l)$). In car life, the bigger *RL* is, the more times battery needs to be renovated, the greater battery life's impact on the simulation results is; and vice versa. And car life's impact on the simulation results can also be constrained by *RL*; (4) Time of battery renovation is a state of equilibrium, take this simulation for example, the optimum is three. At last, modelling and simulations are developed to realize the influencing factors analysis in electric vehicles battery recycling.

However, this paper has certain limitations and deficiencies. To simulate recycling of electric vehicle batteries requires a lot of raw data, but electric vehicle industry is still in the initial stage. Therefore, the simulation lacks original data. Consequently, the simulation studies are carried out based on laboratory data instead of raw data.

7. ACKNOWLEDGEMENTS

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