System dynamics analysis on remanufacturing of used lithium battery condering inspection errors

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Abstract

In the process of recombination and remanufacturing of used lithium batteries, due to the inspection errors, the profits of collectors and manufacturers are affected, and the consistency of the restructured battery modules is poorer. Based on this question, the system dynamics model of used lithium battery collecting and remanufacturing considering inspection errors is constructed. Through the simulation of the model, the effects of the proportion p of batteries cells of grade II and the inspection error rates c and d on the profits of manufacturers are analyzed. The simulation results show the optimal range of p. Within the optimal range of p, the profit of the manufacturer increases with the decrease of the inspection error rate c and d, and the decrease of the inspection error rate ensures the consistency of the recombination battery module.

Keywords

Used lithium battery, Remanufacturing, System dynamics, Inspection error.

1. Introduction

In recent years, with the promotion of electric vehicles, the number of used lithium batteries has also increased rapidly. Without reasonable collecting, these used lithium batteries will pollute the environment. In 2018, the National Development and Reform Commission and other departments jointly requires enterprises to speed up the establishment of collecting channels for used power batteries and carry out comprehensive applications of different types and levels of used lithium batteries[1]. At present, there are two main methods for collecting used lithium batteries: one is direct material collecting, and the other is echelon use after collecting and remanufacturing of used lithium batteries [2].

The lithium batterysy contain many battery cells. Due to different service environment and length of time, there will be some differences in the performance of each battery cell. In the process of recombination and remanufacturing, these battery cells need to be connected in series or parallel. If you want to give full play to the maximum performance of each battery cell, you need to ensure that the battery cells in series or in parallel have good consistency [3]. The performance of lithium battery module is not determined by a cell, but by multiple cells with the worst performance of each single performance parameter [4].

In the process of consistency screening of used lithium batteries, manufacturers roughly classify batteries according to the capacity of battery cells: batteries with a capacity greater than 60% are called battery cells of grade I, batteries with capacity less than 60% are called battery cells of grade II. However, due to technical or non-technical reasons, some inspection errors are caused. Such as, the battery module that can be used reusable is inspected as non-reusable, and the battery cell of grade II is inspected as battery cell of grade I. This paper will use Vensim PLE to build a system dynamics model of used lithium battery collecting and remanufacturing based on inspection error rates. Through the simulation of the model, the impact of inspection error rates on the profits of manufacturers will be analyzed.

2. Literature review

The relevant literatures include two parts: the research on the recycling of used lithium batteries based on system dynamics and the research on inspection error rates.

2.1 Research on recycling of waste lithium batteries using system dynamics

According to relevant literatures at home and abroad, it is found that Wang used the system dynamics method to build a battery recycling model, analyzed it from the perspective of consumer behavior, and obtained the enterprise recycling and remanufacturing capacity strategies under different situations [5]. Yohannes et al. took electric vehicle batteries as an example, and introduced the main contributing factors and challenges of used battery recycling [6]. Hoyer et al. studied the reverse logistics of used batteries of electric vehicles in accordance with German laws and regulations [7]. Ozceylan et al. took Turkey as an example and proposed a closed-loop supply chain logistics network model for linear programming of used electric vehicle batteries [8]. Wu et al. found that the cost of reengineering and remanufacturing based on battery cells is the highest and the scope of application is wided, which provides a data basis for the economic analysis of recycle and reuse [9]. Wang studied the economy of battery recycle and reuse, and calculated the investment income for recycle [10].

2.2 Research on inspection error

Gu et al constructed the system dynamics model of reverse supply chain, and gave the reasonable range of inspection error rates reduction [11]. Gu et al. studied whether the inspection error rates in the reverse supply chain is worth reducing, so as to help the recycler and the remanufacturer make beneficial decisions [12]. Zhang used system dynamics to build a closed-loop logistics system model with recovery inspection error based on employee training investment [13].

Based on the existing research status of used lithium battery recycling with system dynamics and inspection error rates, this paper studies the recycling and remanufacturing of used battery with inspection errors by using system dynamics.

3. Model construction

3.1 Relevant assumptions

In the reverse supply chain of used lithium battery recycling and remanufacturing composed of single collector and manufacturer, we assumed that: only one recycling and remanufacturing of used lithium batteries are involved. The manufacturer disassembles,detects and sorts the recycled battery modules which are roughly divided into battery cells of grade I, battery cells of grade II and non-reusable battery cells according to the performance of the battery cells. The battery cells of grade II and the grade I do not contain non-reusable battery cells. The manufacturer sells the restructured battery modules of grade I and grade II directly to the consumer market, and the consumer market is large enough.

3.2 Dynamic model of the recycling and remanufacturing system for used lithium batteries

The dynamic model of used lithium battery recycling and remanufacturing system is shown in Figure 1. In the model, the collector is responsible for recycling used lithium batteries which is divided into "reusable battery modules" and "non-reusable battery modules". Since the collector can only conduct preliminary test, there may be some inspection errors, such as the "reusable battery modules" contains part of the non-reusable battery modules. The greater inspection errors, and the greater the loss of the manufacturer when the collector sends the "reusable battery modules" to the manufacturer. For "non-reusable battery modules", it means that "non-reusable battery modules" contain part of the reusable battery modules. When the inspection error is greater, there are more reusable battery modules, which will cause the loss of collector and waste of resources. After the initial inspection, the collector shall hand over the "non-reusable battery modules" to the material collector for material recycling, and the "reusable battery modules" shall be sent to the manufacturer. The manufacturer disassembles and tests the "reusable battery modules" and divides it into: non-reusable battery cells,"battery cells of grade I" and "battery cells of grade II " according to the battery performance. As the current inspection technology is backward and various performances are not easy to detect, some inspection errors will also occur in mass inspection: such as the "battery cells of grade I " contains part of the battery cells of grade II, and the " battery cells of grade II" contains part of the battery cells of grade I. Manufacturer will shall hand over the "non-reusable battery cells" to the material collector for material recycling. "Battery cells of grade I" is reorganized into "battery modules of grade I", "battery cells of grade II " is reorganized into "battery modules of grade II". The manufacturer will sale the two reorganized battery modules at two different prices.

3.2.1 Key parameters in model

The key parameters involved in the Figure 1 are listed as follows.

a:the error rate that non-reusable battery modules is inspected as reusable battery modules.

b:the error rate that reusable battery modules is inspected as non-reusable battery modules.

c:the error rate that battery cells of grade I is inspected as battery cells of grade II

d:the error rate that battery cells of grade II is inspected as battery cells of grade I.

q:proportion of battery modules that can be reusable in recovered batteries

p:the proportion of grade II batteries in the reusable battery cells

3.2.2 Key formulas in the model

Formula (1)-(7) is the formula associated with the key parameters in the dynamics model of the recycling and remanufacturing system of used lithium batteries.

$$\text{Non-usable battery modules rate=inspection rate*} [q*b+(1-q)*(1-a)] \quad (1)$$

$$\text{Manufacturer`s purchase rate=inspection time*} [q*(1\text{-}b)+(1-q)*a] \text{/purchasing time} \quad (2)$$

$$\text{Non-usable battery cells rate=disassembly rate*N cells*} (1-q)*a/[q*(1-b)+(1-q)*a] \quad (3)$$

$$\text{Battery cells of gradeIsort rate= disassembly rate*N cells*} (1-p-c+c*p+d*p)*q*(1-b)/[q*(1-b)+a*(1-q)] \quad (4)$$

$$\text{Battery cells of grade II sort rate= disassembly rate*N cells*} (p+c-c*p-d*p)*q*(1-b)/[q*(1-b)+a*(1-q)] \quad (5)$$

Collector`s profit= (purchase price of unit module - transportation cost) *purchasing time *purchasing rate + treating rate*C treating time*unit module treating revenue-(unit collecting price*collecting time*expected collecting rate +(collector's inventory of used lithium battery modules (CI)+ "non-reusable battery module" inventory) *unit module inventory cost+ inspection rate*inspection time*inspection cost) (6)

Manufacturer`s profit= (sale price of unit group I battery modules*sale rate (grade I)+sale price of unit battery module of group II*sale rate (grade II))*sale time + unit cell treat revenue*M treat time*manufacturer treat rate-(purchase price of unit module*purchase time*purchase rate +("manufacturer's inventory of "reusable battery modules"(MI)" +"battery modules of grade I" inventory +"battery modules of grade II" inventory)*unit module inventory cost +disassembly rate * disassembly time*unit disassembly cost +reorganize time*unit reorganize price*("battery cells of grade II reorganized rate (second stage)"+"battery cells of grade I reorganize rate (second stage)")) (7)

3.2.3 Model parameter set

The parameter settings involved in the stock-flow diagram of the used lithium battery collecting and remanufacturing system are shown in Table 1.

Table 1 collector and manufacturer parameters

Collector	Value	Manufacturer	Value
sale price of unit" re-usable battery module	250	sale price of unit" battery module of grade II "	300
unit collect price of battery module	150	sale price of unit" battery module of grade I "	320
unit inspect price	3	unit purchase price	250
unit transport cost	5	unit disassembly price	5
unit module treat revenue	50	unit reorganize price	0.1
M cells	40	unit module inventory cost	2
N cells	100	unit cell treat revenue	1

4. Simulation analysis

Simulation mainly includes analyzing the impact of inspection errors c and d on manufacturers. In which INTIAL TIME is 0, FINAL TIME is 52 weeks, TIME STEP is 1 week, and all the other time variables are 2 weeks.

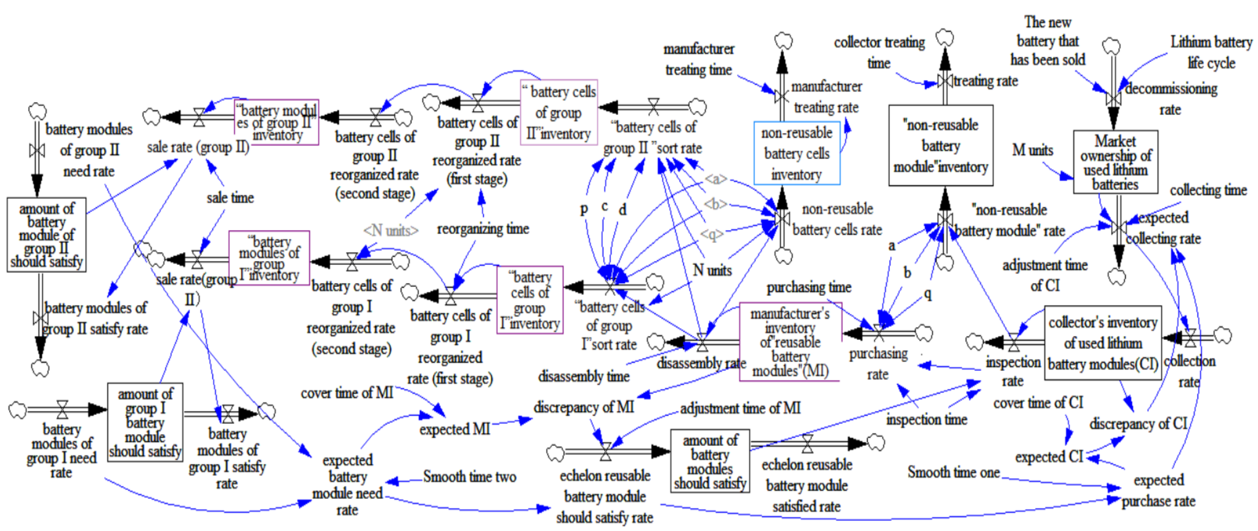

Figure 1 The stock-flow diagram of the used lithium battery collecting and remanufacturing system

4.1 Impact of inspection error rates c and d on manufacturer

Inspection error rates c and d directly affect consistency of battery modules. The consistency is the key factor in determining battery modules availability and battery life.

The discharge capacity of the power battery is determined by the "short plate battery". If the battery cells of grade II is inspected as battery cells of grade I, and then reorganized as one " battery modules of grade I", it will directly affect the safety and performance of the "battery modules of grade I". The manufacturers not only ensure profit, but also ensure the consistency of the reorganized battery modules.

4.2 Impact of inspection error rates c and d on manufacturer when p<0.5

First of all, we assume that the proportion of battery modules that can be reusable in recovered batteries q=0.5, p=0.4; inspection error rates a=b=0; c and d are equal to 0,10%,20%,30%, respectively. Changes of manufacturer`s profit margin at different inspection error rates are shown in Figure 2. The changes in the "battery cells of grade I" inventory and the "battery cells of grade II " inventory are shown in Figures 3 and 4.

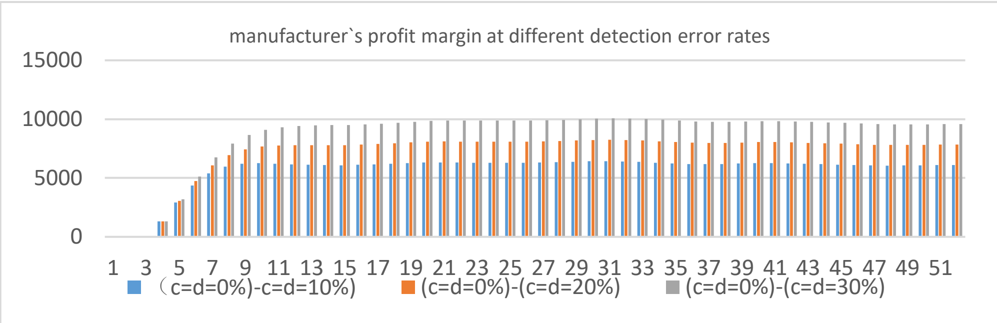

Figure 2 Changes of manufacturer`s profit margin at different detection error rates

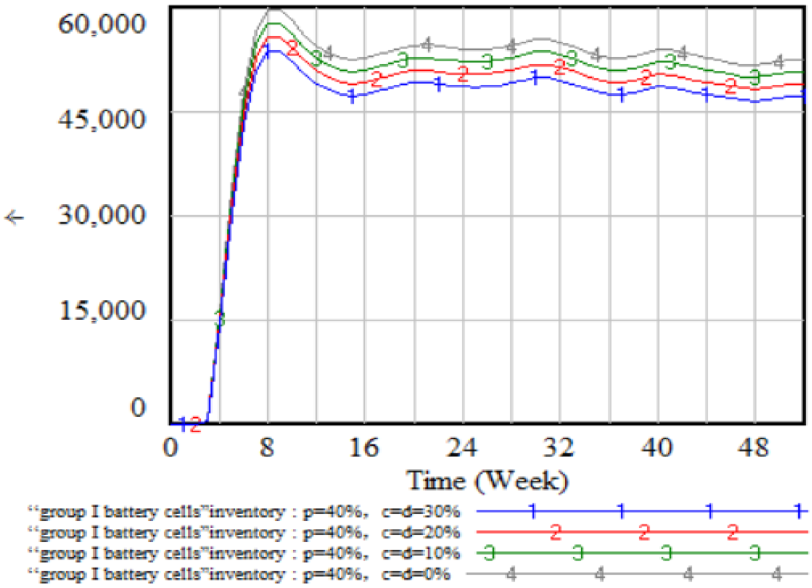

Figure 3 Impact of inspection error rates c and d on the "battery cells of grade I" inventory

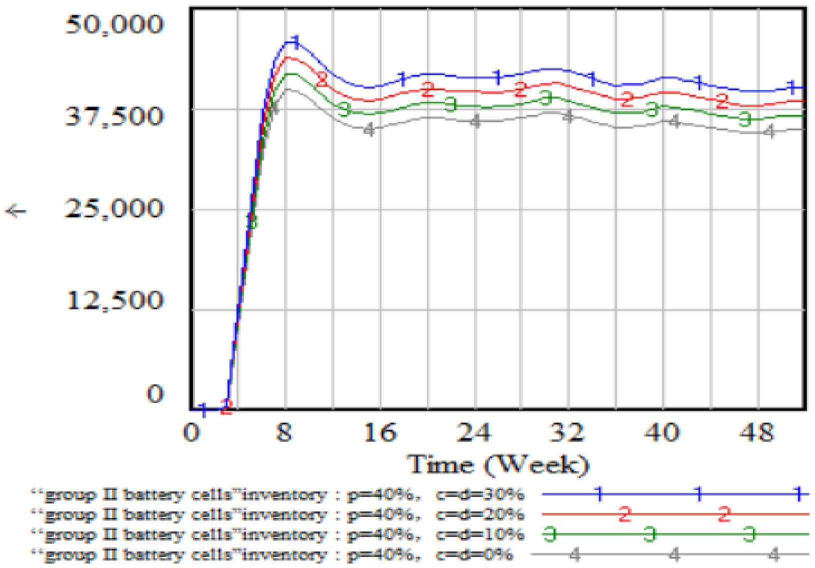

Figure 4 Impact of inspection error rates c and d on the "battery cells of grade I" inventory

From Figure 2, we can see that the manufacturer's profit margin at the inspection error rates c=d=0 and c=d=30% is greater than the difference between c=d=0 and c=d=20%. Similarly, the manufacturer's profit margin at the inspection error rates c=d=0 and c=d=20% is greater than the difference between c=d=0 and c=d=10%. The results show that the manufacturer's profit increases gradually with the decrease of inspection error rates.

From Figure 3 and Figure 4, we find that with the increase of inspection error rates, "battery cells of grade I" inventory gradually reduces, "battery cells of grade II " inventory gradually increases.

We assume that the inspection error rates a=b=0; c and d are equal to 0, 10%, 20%, 30%, respectively. Among the other variables: p=0.3, q=0.5. We continue to analyze the manufacturer's profit changes under different inspection errors.

We extract the manufacturer's weekly profit data when the detection error rate is set to different values, and analyze the difference between manufacturer's profit when the detection error rate c and d are equal to 0 and the detection error rate is not equal to 0, as shown in Figure 5.

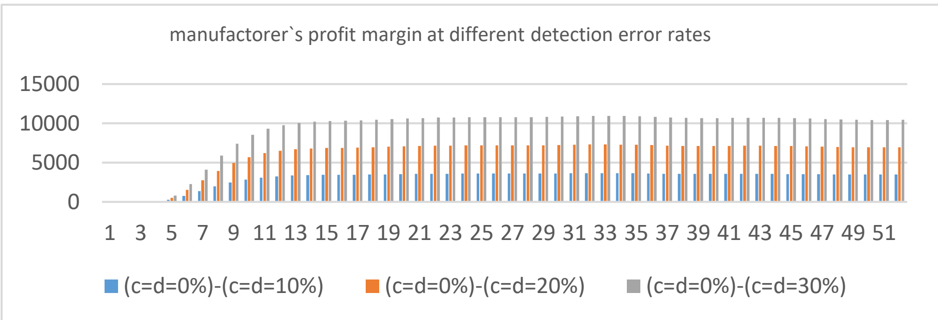

Figure 5 Changes of manufacturer`s profit margin at different detection error rates

From Figure 2, we can see that the manufacturer's profit margin at the inspection error rates c=d=0 and c=d=30% is greater than the difference between c=d=0 and c=d=20%.It is indicated that the manufacturer's profit increases gradually with the decrease of the inspection error rates, the conclusion is consistent with Figure 2.

Only p is given here for 0.4 and 0.3, respectively, when p is taken for 0.2,0.1and 0, the changes of manufacturer`s profit are consistent with the trend in Figures 2 and 5.

The results show that in the reusable cells, when 1-p is in (0.5, 1), the manufacturer's profit increases gradually as the inspection error rates decreases. The manufacturer's profit is the largest when the inspection error rate is 0. Therefore, when p is in the (0, 0.5) range, the inspection error rates c and d decrease is beneficial to the manufacturer.

4.3 Impact of inspection error rates c and d on manufacturer when p>0.5

We assume that the inspection error rates a=b=0, c and d are equal to 0,10%,20%, 30%, respectively. Among the other variables: p=0.6, q=0.5.

In Figure 6, we can see that the manufacturer's profit margin at the inspection error rate of c=d=30% and c=d=0 is greater than the difference between c=d=20% and c=d=0. Similarly, the manufacturer's profit margin at the inspection error rate of c=d=20% and c=d=0 is greater than the difference between c=d=10% and c=d=0. The simulation results show that the manufacturer's profit increases with the increase of the inspection error rates when p is 0.6. Under the same assumption, when the ratio p = 0.7,0.8,0.9 and 1, the simulation result is consistent with the trend of changes in Figures 6 and 8.

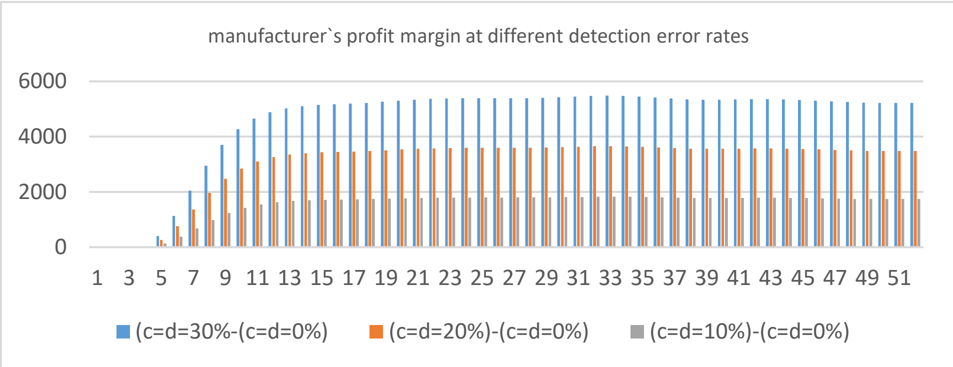

Figure 6 Changes of manufacturer`s profit margin at different detection error rates

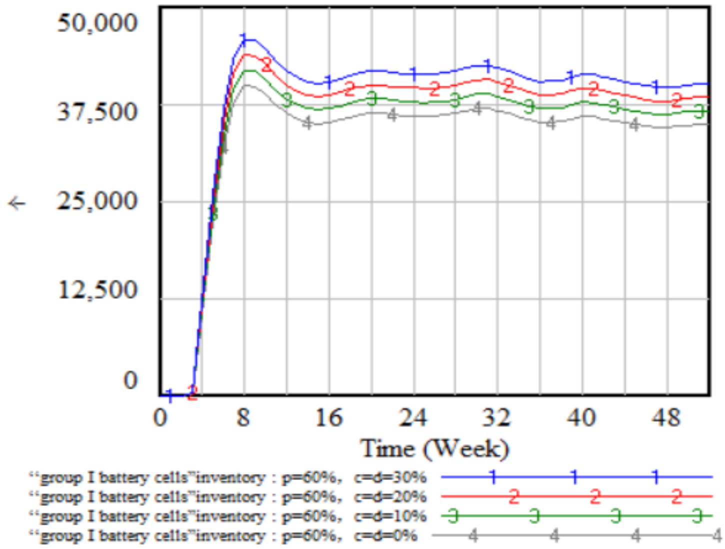

Figure 7 Impact of inspection error rates c and d on the "battery cells of grade I" inventory

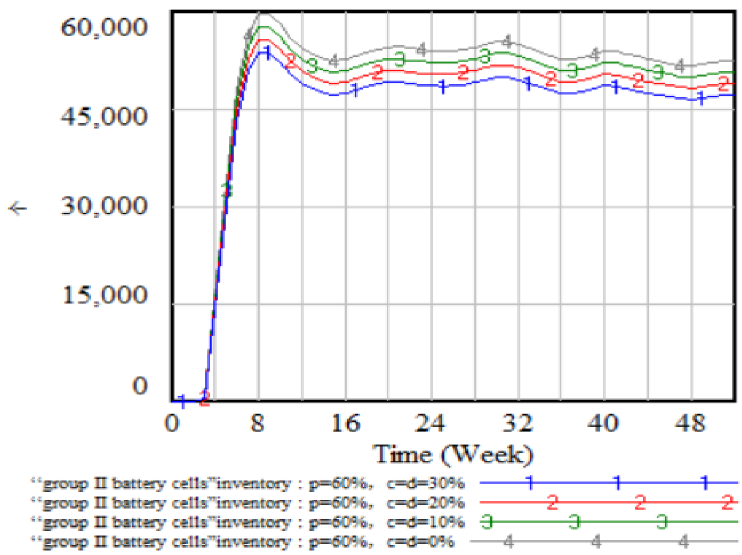

Figure 8 Impact of inspection error rates c and d on the "battery cells of grade I" inventory

Through the changes in Figure 7 and Figure 8, we can find that the inventory of "battery cells of grade I" increases with the increase of inspection error rates, and the inventory of "battery cells of grade II " decreases gradually with the increase of inspection error rates, it indicates that more battery cells of grade II are inspected as battery cells of grade I. According to the principle of battery performance consistency, the performance and safety of battery modules depend on the consistency of reassembled cells. If the battery cells performance in the recombinant battery module is not consistent, for example, some battery cells of grade I contains some battery cells of grade II, it will cause the battery module of grade I life shortened and early scraped. Therefore, in the long run, the manufacturer should reduce the inspection error rates.

5. Conclusion

From the above simulation analysis, we can see that when p is between (0, 0.5), the inspection error rates c and d is smaller, and the manufacturer's profit is higher. When p is between (0.5, 1), although the inspection error rate c and d is higher, the manufacturer's profit is higher. The inspection error rate is large, which will cause " battery module of gradeI" inconsistency, thus affect the value of again using after collecting and remanufacturing of used lithium batteries. Therefore, to ensure the range of its p remains between (0, 0.5), the manufacturer should increase the proportion on battery cells of grade I in the ladder able battery cells.

Acknowledgements

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