

Wang, Junjun; Chen, Ming

**Article**

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# Remanufacturing process for used automotive electronic control components in China

Junjun Wang and Ming Chen\*

\* Correspondence:  
mingchen@sjtu.edu.cn  
School of Mechanical Engineering,  
Shanghai Jiao Tong University,  
Shanghai 200240, People's Republic  
of China

## Abstract

China's recycling roadmap and technology scheme for used automotive electronic control components are investigated. The mathematical analysis model of the remanufacturing process is established on the basis of stochastic network technology, as well as on the graphical evaluation and review technique (GERT). In addition, the calculation method used for estimating single-product remanufacturing time is examined. The objective of this study is to determine the probability of success for the remanufacturing of used automotive electronic control components and remanufacturing time. On the basis of experimental parameters, we simulate the remanufacturing process using the Monte Carlo simulation in Crystal Ball. Compared with the result of the GERT model (8.5114 h), the simulation error rate is 0.225%. This consistency in results indicates that both the stochastic network model and Crystal Ball can accurately simulate the remanufacturing process of used automotive electronic control components, making these techniques feasible approaches for such processes. Aside from numerical experiments on and sensitivity analyses of key processes, the relationship between total remanufacturing time and five influencing factors is identified. Total remanufacturing time can be significantly reduced by optimizing the key processes. The optimization methods are also investigated.

**Keywords:** Used automotive electronic control components; Recycling; Stochastic network model; Monte Carlo simulation in Crystal Ball; Simulation; China

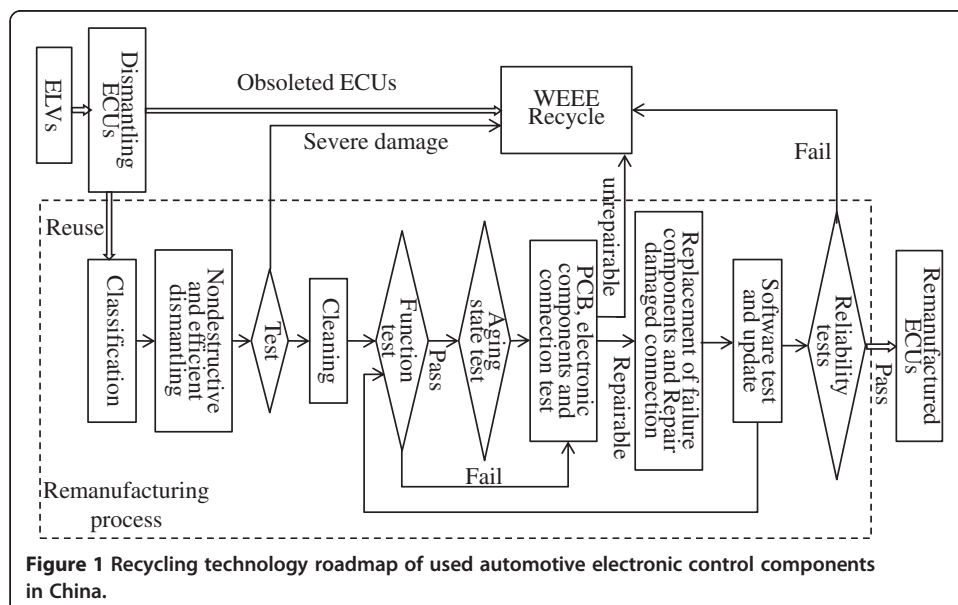
## Introduction

According to the statistics of the China Association of Automobile Manufacturers, the vehicle market of China sets a new sales record of approximately 18,264,700 in 2010, bringing the total number of vehicles in the country to 90,860,000. With the rise in vehicle sales, relevant agencies forecasted that the volume of scrap vehicles will reach 6.44 million in 2015. With the rapid development of electronic information technology, the use of electronic components in vehicles has dramatically increased. Electronic control units (ECUs) control almost all of the functions of a vehicle [1]. According to the statistics of Bayerische Motoren Werke AG, automotive electronic components have exceeded more than 30% of the cost of vehicles. There are 48 microcomputers in some luxury cars, and the electronic components have accounted for more than 50% of their cost. Thus, the volume of used automotive electronic control components in China is foreseen to soar in the next few years. Used automotive electronic control

components in the country are currently scrapped together with end-of-life vehicles (ELVs) for material recycling. These vehicles are discarded inappropriately because of lack of technology support and profitable models. This improper disposal results in serious environmental pollution and resource wastage, thereby creating an urgent need for the development of recycling processes for used electronic control components.

In developed countries, ECUs in ELVs can be reused after remanufacturing [2]; they can also be exported after strict bench tests and are marked 'recycled products' [3]. China automotive experts and scholars have realized that recycling and reusing used automotive electronic control components are important issues. Figure 1 shows the recycling technology roadmap based on the current research and development situation of ECUs, as well as on the actual conditions, in China [4]. The three characteristics of used automotive electronic control components are as follows: (1) These components contain heavy metals (such as Pd), which if not properly recycled can seriously endanger the environment as well as the health and survival of human beings and other organisms. (2) These components are high-tech, highly reliable, and high value-added products. (3) The residual life of these components is very long. Thus, the remanufacture and reuse of these components are feasible initiatives. On the basis of the three characteristics mentioned above and the current technical strength of China, we infer that the best recycling scheme for used automotive electronic control components follows the order reuse > remanufacture > material recycle > harmless treatment.

However, a number of uncertainties are associated with the recycling of used automotive electronic control components. These include the estimation of operation and cost-related parameters for the recycling process, as well as the decisions about resolution for product returns and costs of coordination along the recycling system [5]. These uncertainties are related to time, quality, quantity, and variety of



**Figure 1** Recycling technology roadmap of used automotive electronic control components in China.

returns; they are also dependent on the influence of regulations and consumer opinion.

The graphical evaluation and review technique (GERT) is an approach used for analyzing a class of networks with the following characteristics: (1) a probability that a branch of the network is part of a realization of the network and (2) an elapsed time or time interval associated with the branch if the branch is part of the realization of the network. Such networks are referred to as stochastic networks and consist of a set of branches and nodes. The GERT research was conceptualized by the RAND Corporation at the Apollo Checkout Study for Headquarters and sponsored by the National Aeronautics and Space Administration (NASA) under contract NASr-21(08); it evolved from a study of the terminal countdown of an Apollo space system in April 1966 [6]. The GERT is a procedure intended for the analysis of a stochastic network composed of EXCLUSIVE-OR, INCLUSIVE-OR, and AND nodes (vertices), as well as multi-parameter branches (transmittances or edges). In the GERT, the branches of the networks are described by two or more parameters: (1) a probability that the branch is traversed and (2) the time (or other attribute) required to traverse the branch if it is taken. A transformation is developed to combine these two parameters into a single parameter. For EXCLUSIVE-OR nodes, a method is derived for the evaluation of networks in terms of the probability of generating an output node. This method is also used to assess the moment-generating function (mgf) of the time spent in generating the output node. The overall concept that comprises the stochastic networks, transformation, and evaluation method is labeled the GERT. The memorandum presents the general concepts and fundamentals of the GERT and introduces its applications for future research.

Samli and Bellas [7] present a discussion of the special characteristics of the GERT and illustrated its capabilities as a tool in the planning and control of marketing research; the authors compare the differences between GERT and program/project evaluation and review technique (PERT). Randolph and Ringeisen [8] use the GERT to analyze the teaching-learning process and indicated its potential in learning theory. They demonstrate that this approach is very similar to the Markov processes, which have been used extensively to analyze learning models. Sharif and Chin [9] present an analytical technique for technological forecasting. The developed procedure is based on an integrated approach, which combines normative and exploratory approaches to technological forecasting using a stochastic network system. Generally, it can also be applied to technological forecasting. Singh and Shankar [10] apply the GERT to model a two-stage attribute sampling plan based on an exponential failure model. Guo and Qiao [11] establish a hierarchical GERT network to describe the product development process. The activity-time parameters in the process are calculated, and the resource conflicts among parallel activities can be resolved through the readjustment of the activities according to the weighted time-resource priority rule.

Hayashi et al. [12] evaluate the research and development (R&D) of polymer electrolyte fuel cell application technologies using a R&D process model constructed with the GERT. The authors take uncertainties in technology developments into consideration. Abdi et al. [13] model and analyze the mechanization projects of wheat

production using the GERT networks. Their results show that the network model can answer any statistical questions concerning the project. Network models, particularly the GERT networks, are increasingly becoming powerful tools for modeling, scheduling, planning, controlling, and analyzing agricultural mechanization projects. Chia-Nan et al. [14] resolve the reentry problem in wafer manufacturing using the GERT and solve the uncertainty problem using a vague set. The algorithm steps for vague GERT are proposed on the basis of the manufacturing procedure of the lithographic area in 300-mm wafer fabrication. A simple decision support system is developed to process the complex calculation procedure and provide more information to managers.

The recycling system for used automotive electronic control components can be described in terms of stochastic networks, and many problems encountered in this system can be solved using the GERT [15].

The present study aims to determine the probability of success for remanufacturing used automotive electronic control components and remanufacturing time, as well as investigate the feasibility of reusing automotive electronic control components. The proposed model is set up on the basis of the recycling technology roadmap of used automotive electronic control components (Figure 1). Calculations are then performed using an analytical method. After the simulation of the remanufacturing process in the Crystal Ball software, the feasibility of the stochastic network model is verified through the comparison and analysis of the numerical calculation and software simulation results.




## GERT model formulation and calculation using an analytical method

### Components of stochastic networks



Stochastic networks are composed of directed branches (arcs, edges, and transmittances) and logical nodes (vertices). A directed branch is associated with nodes at which it terminates. Two parameters are associated with a branch: (1) the probability that a branch is taken,  $p_a$ , given that the node from which it emanates is realized; and (2) if a branch is taken, a time  $t_a$  required to accomplish the activity that the branch represents, where  $t_a$  can be a random variable.

A node in a stochastic network consists of an input (receiving and contributive) side and an output (emitting and distributive) side. Three logical relations are found on the input side, and two types of relations are found on the output side. The former is shown in Table 1.

**Table 1 GERT input side node**

Name	Symbol	Characteristics
EXCLUSIVE-OR		The realization of any branch leading into the node causes the node to be realized. However, only one of the branches leading into this node can be realized at a given time
INCLUSIVE-OR		The realization of any branch leading into the node causes the node to be realized. The time of realization is the smallest of the completion times of the activities leading into the INCLUSIVE-OR node
AND		The node is realized only if all the branches leading into the node are realized. Thus, the realization time is the largest of the completion times of the activities leading into the AND node

**Table 2 GERT output side node**

Name	Symbol	Characteristics
DETERMINISTIC		All branches emanating from the node are taken if the node is realized (i.e., all branches emanating from this node have a $p$ parameter equal to 1)
PROBABILISTIC		Exactly one branch emanating from the node is taken if the node is realized

**GERT network calculation**

The steps involved in applying the GERT are as follows:

1. A qualitative description of a system or problem is converted into a model in network form.
2. The necessary data are collected to describe the branches of the network.
3. An equivalent one-branch function between two nodes of the network is obtained.
4. The equivalent function is converted into the following two performance measures of the network:
  - a. The probability that a specific node is realized.
  - b. The mgf of the time associated with an equivalent network.
5. Inferences concerning the system under study are made on the basis of the information obtained in step 4.

The two relations on the output side are shown in Table 2.

For notational convenience, the input and output symbols are combined to show that six types of nodes are possible (Table 3).

**Moment-generating function and  $w$ -function**







A function  $w_k$  is defined for each arc  $k$ . If  $p_k$  is the probability that arc  $k$  is chosen and if  $M_k(s)$  is the mgf of random variable  $X_k$ , which represents the length of the  $k$ th arc, then  $w_k$  is given by

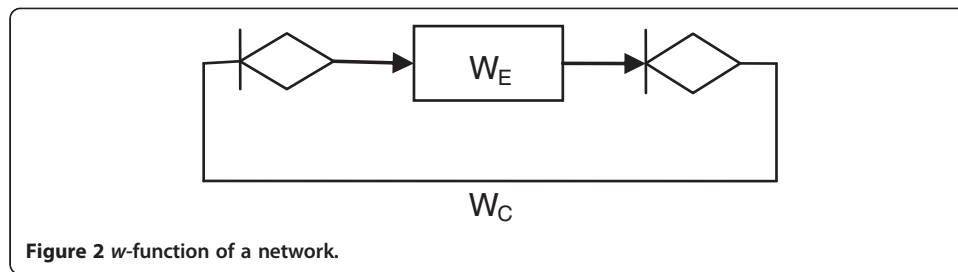
$$w_k(s) = p_k M_k(s) = p_k \int_{-\infty}^{+\infty} e^{sx_k} dF_{X_k}(x_k), \tag{1}$$

where  $F_{X_k}$  is the distribution function of  $X_k$  and the integral is the familiar Riemann-Stieltjes integral.

A closing arc is added to apply a topology equation from flow graph theory because this equation pertains only to closed networks. Any network can be depicted by a black box, in which the closing arc creates a single-loop network, where  $w_c$  represents the  $w$ -function of the closing arc, and  $w_E$  is the  $w$ -function of the entire network (see Figure 2).

**Table 3 GERT node symbols**

Output	Input		
	EXCLUSIVE-OR	INCLUSIVE-OR	AND
DETERMINISTIC			
PROBABILISTIC			



**Figure 2** *w*-function of a network.

We define  $w_E(s)$  by  $w_E(s) = p_E m_E(s)$ , where  $p_E$  is the probability that the black box is entered and  $M_E(s)$  is the mgf of the entire network. Given that  $M_E(0) = 1$ ,

$$p_E = w_E(0). \tag{2}$$

Thus, for any value of  $s$ , function  $w_E(s)$  yields the mgf from the equation [8]:

$$M_E(s) = \frac{w_E(s)}{w_E(0)}. \tag{3}$$

The mgf of common distributions are shown in Table 4.

#### Equivalent network

An equivalent network is defined as a reduction of a multi-branched network into a one-branch network, where the parameters of the latter are derived from the parameters of the multi-branched network branches.

Table 5 illustrates the equivalent one-branch network for series, parallel, and self-loop networks.

To obtain the expected value of  $X$ , the total network characteristic should identify the first moment from the mgf:

$$\mu_E = \left. \frac{dM_E(s)}{ds} \right|_{s=0}. \tag{4}$$

#### Formulation and calculation of the model for used automotive electronic control components

A number of uncertainties are associated with the recycling process of used automotive electronic control components. The recycling process is of stochastic type. The relationship between the individual remanufacturing processes and the working time of each process is random. Because of the different work environments, the damage

**Table 4** Moment-generating function of some distributions

Name	Distribution law (density function)	Mean	Variance	mgf
Uniform	$f(x) = \begin{cases} 1/(b-a), & (a < x < b) \\ 0, & \text{(else)} \end{cases}$	$(a + b)/2$	$(b - a)^2/12$	$(e^{bs} - e^{as})/s(b - a)$
Normal	$f(x) = \exp[-(x-\mu)^2/2\sigma^2] / \sqrt{2\pi}\sigma$ ( $-\infty < \mu < +\infty, \sigma > 0$ )	$\mu$	$\sigma^2$	$\exp(\mu s + \sigma^2 s^2/2)$

**Table 5 Network reduction employing the topological equation**

Network type	Graphical representation	Equivalent network
Series		
Parallel		
Self-loop(1)		
Self-loop(2)		

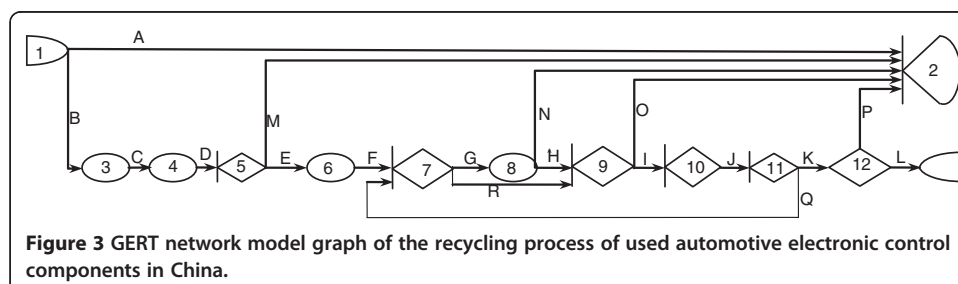
imposed on the ECU is not constant, and its disassembly, cleaning, test, and remanufacturing processes are random. According to the recycling technology roadmap of used automotive electronic control components in China (Figure 1), the remanufacturing process is a circular loop. Thus, modeling the recycling process using the GERT is a feasible approach. The GERT model is shown in Figure 3.

In accordance with the experimental data and statistical methods, we depict the manner by which probability is derived, and the time probability distribution for each activity is performed in the GERT network model graph (Figure 3) in Table 6.

The GERT network model graph (see Figure 3) can be broken down into two parts, as shown in Figures 4 and 5.

The branches connected to node 2 of the first step simplification of the GERT network model graph (I, Figure 4) represent the activity 'WEEE recycle,' which is not the focus of this study.

Figure 5 shows the remanufacturing process of used automotive electronic control components. After being remanufactured, these components can be reused and labeled 'remanufactured products.' This recycling scheme can help minimize environmental pollution and facilitate ECU technology breakthroughs in China. In addition, it is the most economical and high value-added recycling mode. This study focuses on this recycling scheme.





**Table 6 Activity code and description**

No.	Activity	Branch	Probability of success	Time distribution (h)	mgf	Equivalent function
A	WEEE recycle	1-2	0.55	Constant (0.5)	$\exp(0.5 s)$	$0.55\exp(0.5 s)$
B	Classification	1-3	0.45	Normal $\mu = 1, \sigma = 1$	$\exp(s + 0.5 s^2)$	$0.45\exp(s + 0.5 s^2)$
C	Dismantling	3-4	1	Normal $\mu = 1, \sigma = 1$	$\exp(s + 0.5 s^2)$	$\exp(s + 0.5 s^2)$
D	Test	4-5	1	Normal $\mu = 1, \sigma = 1$	$\exp(s + 0.5 s^2)$	$\exp(s + 0.5 s^2)$
E	Cleaning	5-6	0.96	Constant (0.025)	$\exp(0.025 s)$	$0.96\exp(0.025 s)$
F	Function test	6-7	1	Constant (0.3)	$\exp(0.3 s)$	$\exp(0.3 s)$
G	Aging state test	7-8	0.95	Constant (0.5)	$\exp(0.5 s)$	$0.95\exp(0.5 s)$
H	Hardware test	8-9	0.94	Constant (0.5)	$\exp(0.5 s)$	$0.94\exp(0.5 s)$
I	Hardware repair	9-10	0.96	Normal $\mu = 1, \sigma = 1$	$\exp(s + 0.5 s^2)$	$0.96\exp(s + 0.5 s^2)$
J	Software test and update	10-11	1	Constant (0.2)	$\exp(0.2 s)$	$\exp(0.2 s)$
K	Reliability tests	11-12	0.98	Constant (2)	$\exp(2 s)$	$0.98\exp(2 s)$
L	Reuse ECUs	12-13	0.99	Normal $\mu = 1, \sigma = 1$	$\exp(s + 0.5 s^2)$	$0.99\exp(s + 0.5 s^2)$
M	WEEE recycle	5-2	0.04	Constant (0.5)	$\exp(0.5 s)$	$0.04\exp(0.5 s)$
N	WEEE recycle	8-2	0.06	Constant (0.5)	$\exp(0.5 s)$	$0.06\exp(0.5 s)$
O	WEEE recycle	9-2	0.04	Constant (0.5)	$\exp(0.5 s)$	$0.04\exp(0.5 s)$
P	WEEE recycle	12-2	0.01	Constant (0.5)	$\exp(0.5 s)$	$0.01\exp(0.5 s)$
Q	Function test	11-7	0.02	Constant (0.025)	$\exp(0.025 s)$	$0.02\exp(0.025 s)$
R	Hardware test	7-9	0.05	Constant (0.5)	$\exp(0.5 s)$	$0.05\exp(0.5 s)$

According to the equivalence calculations of basic networks, the branches from nodes 7 to 9 (Figure 5) can be simplified into a single branch (Figure 6). The branches from nodes 7 to 12 (Figure 5) can also be simplified into a single branch (Figure 7).

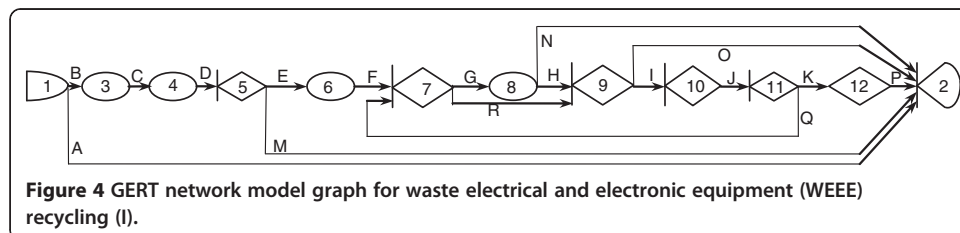
Finally, the GERT network model graph (see Figure 2) can be simplified, as shown in Figure 8.

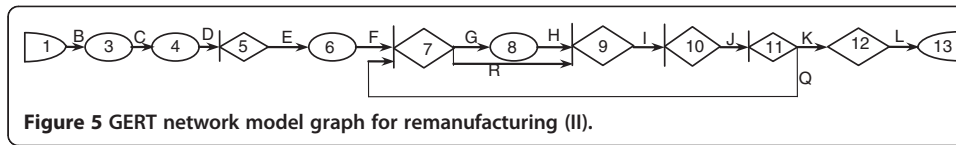
The equivalent function is as follows:

$$w_E(s) = w_B w_C w_D w_E w_F w_V w_L = \frac{w_B w_C w_D w_E w_F w_L w_U w_K}{1 - w_Q w_U} = \frac{w_B w_C w_D w_E w_F (w_G w_H + w_R) w_I w_J w_K w_L}{1 - w_Q (w_G w_H + w_R) w_I w_J} \quad (5)$$

After being remanufactured, the probability that a used automotive electronic control component can be safely reused is expressed as follows:

$$p_E = w_E(0) = 38.64\% \quad (6)$$





**Figure 5** GERT network model graph for remanufacturing (II).

Similarly, after being remanufactured, the probability that a used ECU can be safely reused is 38.64%.

$$T = \frac{dM_E(s)}{ds} |_{s=0} = 8.5114 \text{ h} \quad (7)$$

The remanufacturing process of used automotive electronic control components takes about 8.5 h to complete.

At present, an automotive ECU is designed for models of automobiles. After one type of automobile is released in the market, its ECU can no longer be used. In addition, 55% of used automotive electronic control components are recycled as WEEE (branches 1 and 2). If the ECU design is standardized (i.e., has standardized interfaces, pin assignments, function modules, etc.), the reuse probability can be improved to 95%. Then,

$$p_E = w_E(0) = 81.57\% \quad (8)$$

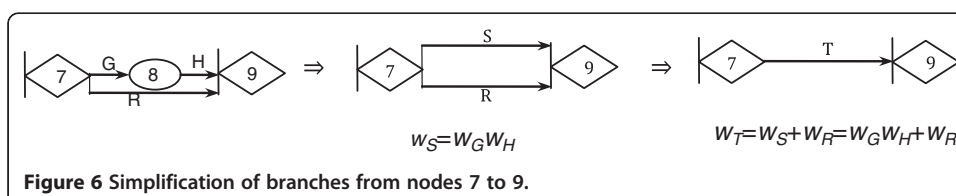
### Using Monte Carlo simulation in Crystal Ball to analyze the recycling process

#### Monte Carlo simulation in Crystal Ball

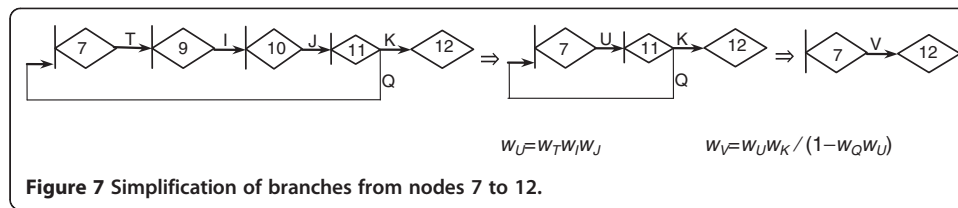
Crystal Ball [16] is a tool that helps executives, analysts, and others analyze risk by performing simulations on spreadsheet models. The forecasts that result from these simulations help quantify areas of risk so that decision-makers can have as much information as possible to enable sound decision-making.

A type of spreadsheet simulation is the Monte Carlo simulation, which repeatedly generates random values for uncertain variables to simulate a model [15]. Monte Carlo simulation is implemented in Crystal Ball [17] to generate a range of values for assumptions and to overcome the limitations encountered in traditional spreadsheet analyses.

A range of possible values can be described for each uncertain cell in the spreadsheet. With the Monte Carlo simulation, Crystal Ball displays results in a forecast chart that shows the entire range of possible outcomes and the likelihood of achieving each outcome. In addition, it keeps track of the results of each scenario.



**Figure 6** Simplification of branches from nodes 7 to 9.



### Steps in using Crystal Ball

The general steps in creating and interpreting simulations with Crystal Ball are as follows:

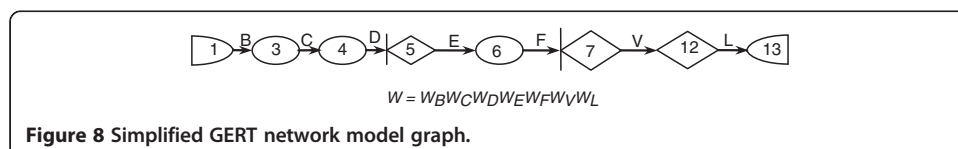
1. A spreadsheet model is created in Microsoft Excel format with data and formula cells that represent the scenario.
2. Crystal Ball is initiated.
3. The spreadsheet model is loaded.
4. The assumptions and forecasts are then defined using Crystal Ball.
5. Run preferences are set.
6. The simulation is run.
7. The results are analyzed, beginning from viewing the forecast charts. First, overlay charts, sensitivity charts, and trend charts are created and used. Then, reports may be created or data may be extracted for use in other applications.

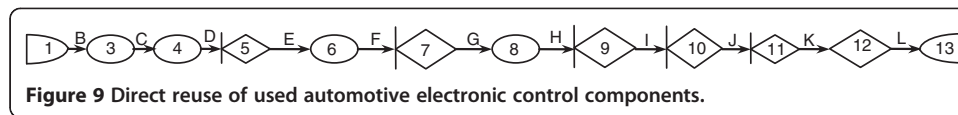
### Monte Carlo simulation in Crystal Ball for the recycling process of used automotive electronic control components

#### Simulation model and calculation

The remanufacturing process can be obtained (Figures 9 and 10) according to the Monte Carlo simulation and remanufacturing process of used automotive electronic control components.

Figure 9 shows the direct reuse of used automotive electronic control components. The Crystal Ball spreadsheet model is subsequently established (Figure 11). In this model, the used automotive electronic control components are successfully tested and recovered. No element is damaged and replaced. The assumption parameters of the Crystal Ball model (see Figure 11, define assumptions) are taken from Table 6. Figure 10 illustrates the reuse of used automotive electronic control components after these are remanufactured; this process is similar to that of the direct reuse Crystal Ball simulation. In this paper, only the direct reuse of used automotive electronic control components (Figure 9) is simulated in Crystal Ball.





The simulation is performed by calculating the total remanufacturing time (Figure 12, define forecasts). After 10,000 trials (Figure 13), the simulation results are shown in the 'result reports' (Figure 14).

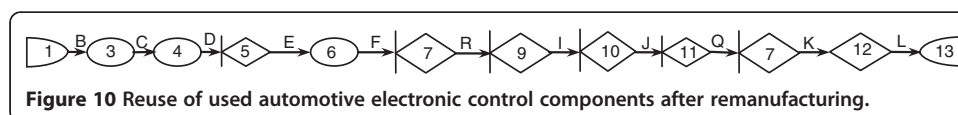
### Analysis of results

According to the result reports, the median of the total remanufacturing time is 8.50594 h (8.5114 h in the GERT model) and the minimum total time is 4.42469 h, while the maximum total time is 12.64542 h.

The sensitivity charts (Figure 15) show that the key factors that affect the total remanufacturing time are dismantling (20.6%) > reuse ECUs (20.3%) > test (20.0%) > hardware repair (19.9%) > classification (19.2%).

Reducing the total time using these factors means

- *Highly efficient dismantling without damages.* Dismantling is the most critical factor that affects the total remanufacturing time. Special dismantling technologies and equipment must be developed and investigated because these can efficiently dismantle ECUs without damaging them. The dismantling time is reduced to 0.025 h, as shown in Figure 16.
- *Reuse ECUs (assembly, packaging, and storage).* This process includes reassembly, repackaging, and re-storage. Given that the ECUs are difficult to dismantle and some damages may occur during dismantling, more time is need for reassembly, repackaging, and re-storage. Thus, special reassembly, repackaging, and re-storage technologies and equipment must also be developed and studied. The design for dismantling should be considered when designing ECUs. The process time for ECU reuse is reduced to 0.025 h.
- *High-speed test technology.* Such innovations are important means for reducing total remanufacturing time, which in turn, enables the development of special test technology and equipment. The test process time drops to 0.025 h.
- *Fast hardware repair technology.* ECU hardware repair is a precise and complex process. Thus, repair knowledge and experience should be accumulated to significantly reduce repair process time. The hardware repair process time is reduced to 0.025 h.
- *Fast classification.* ECUs should be selected and stored by category during ELV dismantling. These tasks can save classification time. The classification process time decreases to 0.025 h.



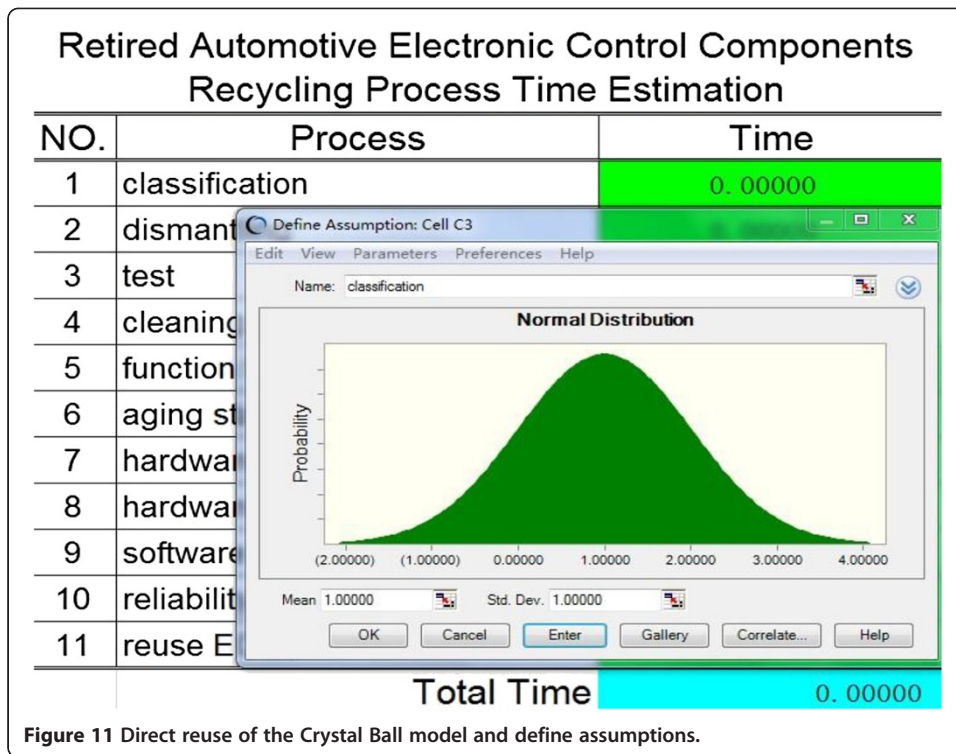


Figure 11 Direct reuse of the Crystal Ball model and define assumptions.

After 10,000 trials, the simulation results are shown in the ‘result reports after the optimization of key processes’ (Figure 17).

As shown in Figure 17, the median of the total remanufacturing time decreases by 63.85% from 8.50594 h before optimization to 3.07487 h after the optimization.

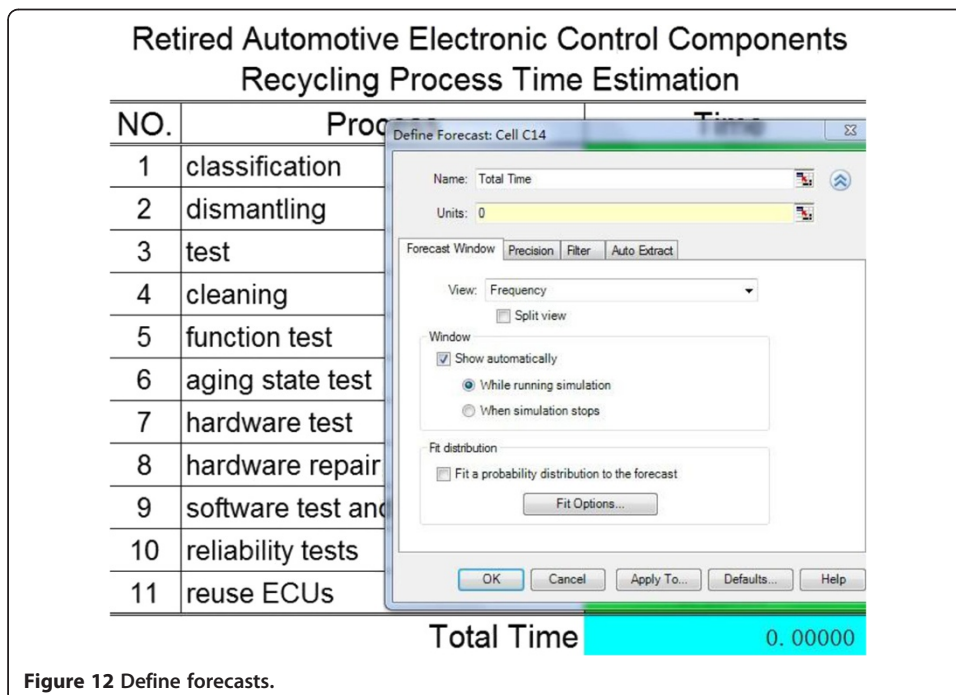
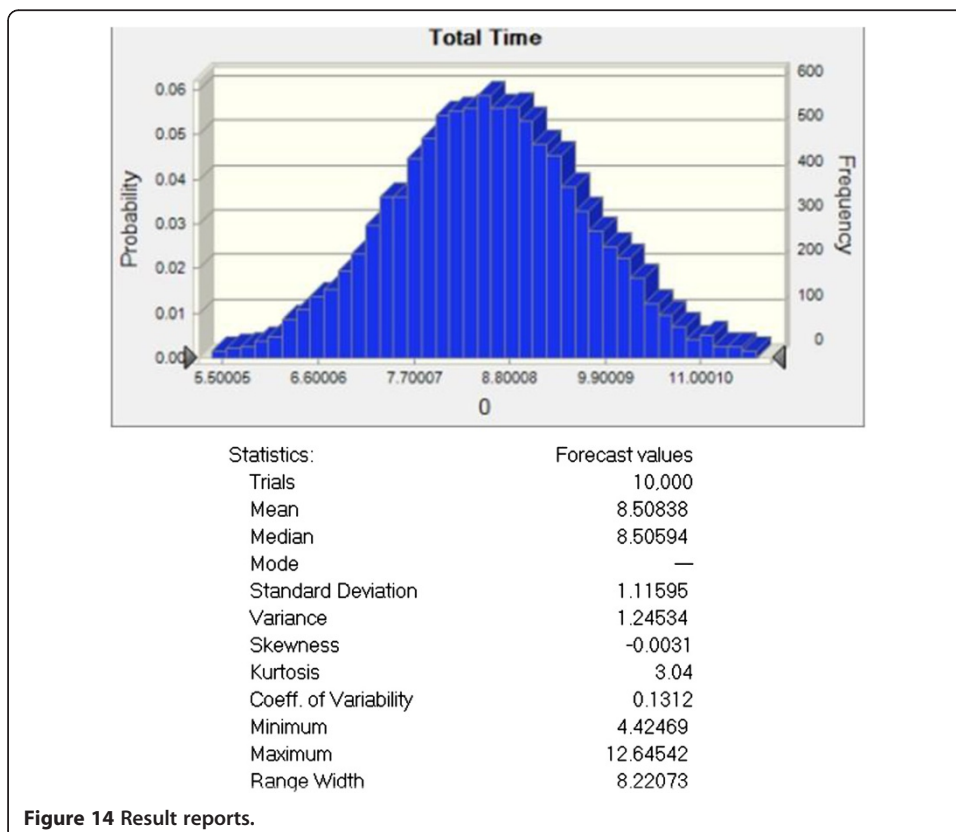
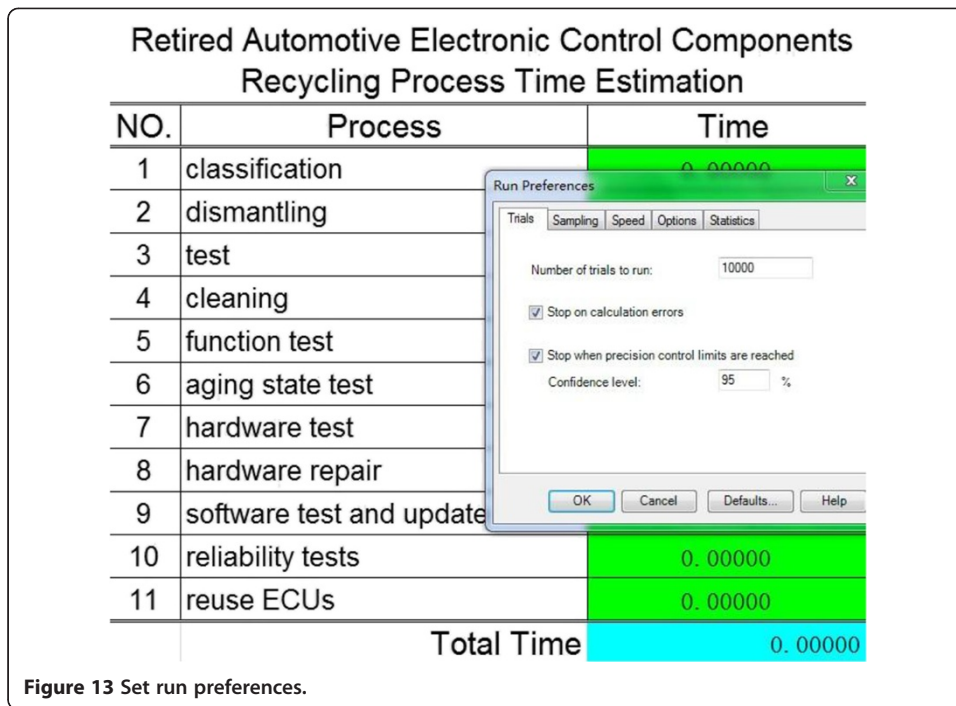
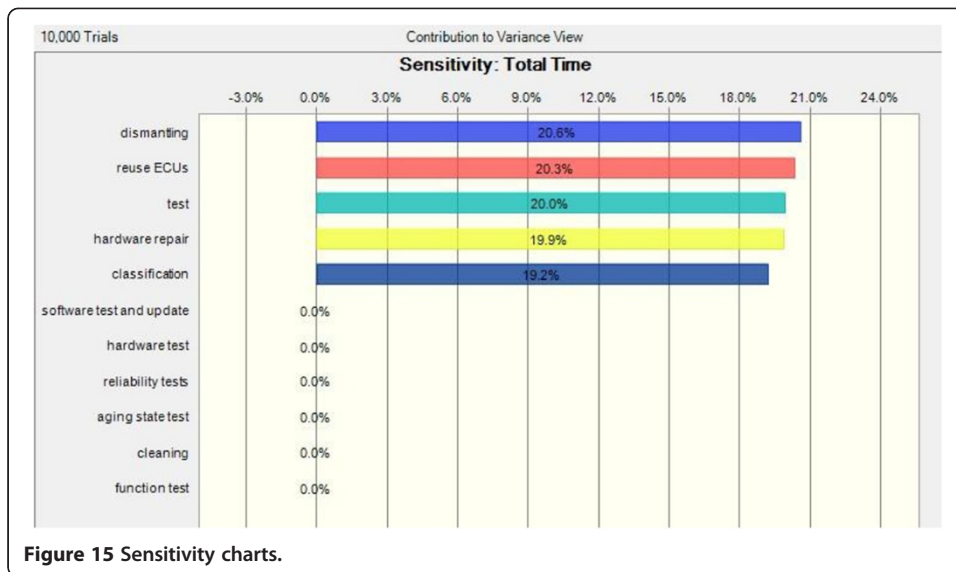


Figure 12 Define forecasts.

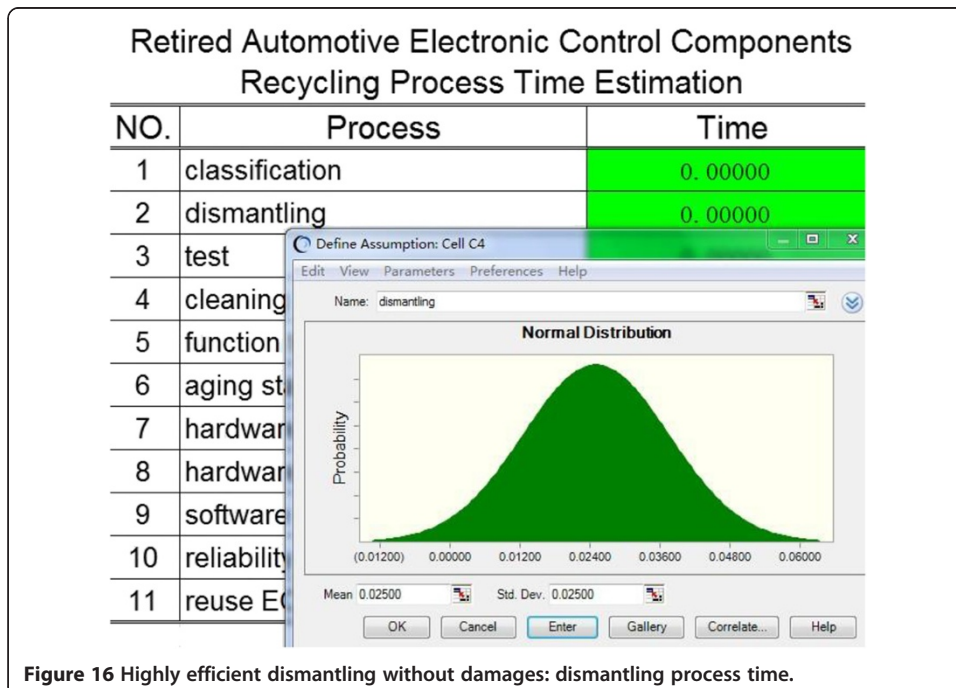


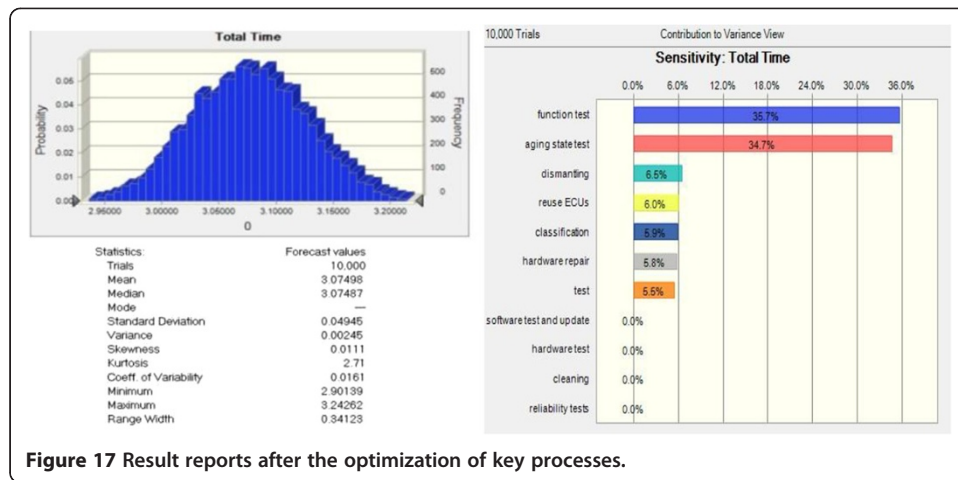


### Numerical experiments

The number of trials is set to 100, 1,000, 10,000, 100,000, and 1,000,000. The simulation results are shown in Table 7. The average total remanufacturing time for all five simulations is as follows:

$$\frac{8.53620 + 8.55494 + 8.50594 + 8.52929 + 8.52645}{5} = 8.530564 \text{ h.} \quad (9)$$





### Comparison and analysis of the results of the GERT calculation and Crystal Ball simulation

Compared with the result of the GERT model (8.5114 h), the simulation error rate is

$$\frac{8.530564 - 8.5114}{8.5114} = 0.225\% \quad (10)$$

The low error rate validates the suitability of both methods (GERT calculation and Crystal Ball simulation) for modeling and simulating the used automotive electronic control component recycling process. As shown in Figure 18, the results of the GERT and Crystal Ball are almost the same.

The consistency in results indicates that the stochastic network model is feasible for the remanufacturing process of used automotive electronic control components. In addition, Crystal Ball can accurately simulate the said process.

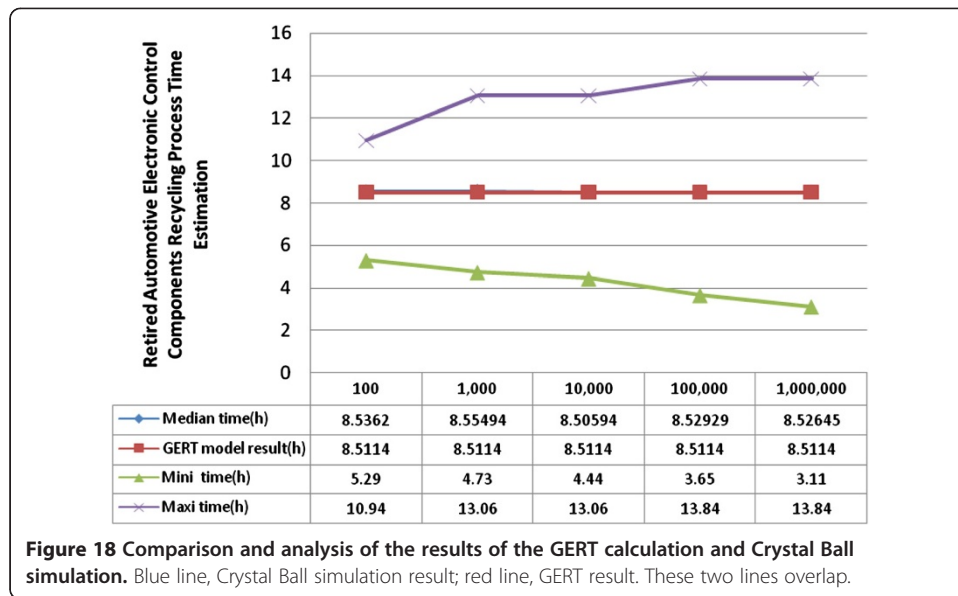
### Discussion and conclusion

In this study, China's recycling roadmap and technology scheme for used automotive electronic control components are investigated. The mathematical analysis model for the remanufacturing process of used automotive electronic control components is established on the basis of stochastic network technology and the GERT. These models can calculate the probability of success for the remanufacturing process of used automotive electronic control components and total remanufacturing time. The remanufacturing process of used automotive electronic control components is simulated by Monte Carlo simulation in Crystal Ball. The error rate of the results is

**Table 7 Comparison and analysis of the GERT calculation and Crystal Ball simulation results**

Trials	100	1,000	10,000	100,000	1,000,000
Median time (h)	8.53620	8.55494	8.50594	8.52929	8.52645
Min. and max. time (h)	5.29 10.94	4.73 13.06	4.44 13.06	3.65 13.84	3.11 13.84
GERT model result (h)	8.5114				





only 0.225%, which demonstrates that both methods (GERT calculation and Crystal Ball simulation) are suitable for modeling and simulating the recycling process of used automotive electronic control components. In addition, the numerical experiments for the Crystal Ball simulation are conducted. The total time can be significantly reduced by analyzing and optimizing the sensitivity of the key processes. The optimization methods are also investigated.

The following aspects will be the focus of future investigations: First, the GERT modeling and calculation should be investigated further. Second, remanufacturing key technologies, such as test technology, fast hardware repair technology, and high-efficiency dismantling without damages, should be continuously examined. Finally, corresponding key equipment should be developed. Last year, the Industry-University-Research Center for Auto Recycling Industrial Technology Innovation was built in Wuxi City of Jiangsu Province, where these key technologies and equipment are currently being developed and studied.

**Abbreviations**

ECU: Electronic control unit; ELV: End-of-life vehicle; GERT: Graphical evaluation and review technique; mgf: Moment-generating function; NASA: National Aeronautics and Space Administration; PERT: Program/project evaluation and review technique; R&D: Research and development; WEEE: Waste electrical and electronic equipment.

**Competing interests**

The authors declare that they have no competing interests.

**Authors' contributions**

JW carried out the used ECU remanufacturing technology studies, participated in the model simulation, and drafted the manuscript. MC carried out the parameter definition. JW participated in the design of the study and performed the statistical analysis. Both authors read and approved the final manuscript.

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