

# A reliability evaluation method for embryonic cellular array based on Markov status graph model

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**Abstract:** Due to the limitations of the existing fault detection methods in the embryonic cellular array (ECA), the fault detection coverage cannot reach 100%. In order to evaluate the reliability of the ECA more accurately, embryonic cell and its input and output (I/O) resources are considered as a whole, named functional unit (FU). The FU fault detection coverage parameter is introduced to ECA reliability analysis, and a new ECA reliability evaluation method based on the Markov status graph model is proposed. Simulation experiment results indicate that the proposed ECA reliability evaluation method can evaluate the ECA reliability more effectively and accurately. Based on the proposed reliability evaluation method, the influence of parameters change on the ECA reliability is studied, and simulation experiment results show that ECA reliability can be improved by increasing the FU fault detection coverage and reducing the FU failure rate. In addition, by increasing the scale of the ECA, the reliability increases to the maximum first, and then it will decrease continuously. ECA reliability variation rules can not only provide theoretical guidance for the ECA optimization design, but also point out the direction for further research.

**Keywords:** embryonic, Markov status graph model, reliability, fault detection, evaluation.

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## 1. Introduction

Reliability refers to the ability that an item will perform its specified function under the specified conditions within the specified time [1], which can be used to evaluate the quality of a product. The embryonic cellular array (ECA) is a newly designed bio-inspired hardware by simulating the growth and development of multi-cellular organisms, which is with fault self-testing and self-repairing property [2]. The ECA can improve the reliability and environmental adaptability of electronic circuits effectively, which provides a new method for the design of electronic

circuits in the fields of aerospace, deep-sea exploration and complex electromagnetic environment.

With the development of the ECA technology, the research on the ECA reliability evaluation method has been enriched. Ortega and Tyrrell [3,4] analyzed the basic structure and self-repairing process of the two dimensional ECA, and ECA reliability evaluation models with different self-repairing strategies were proposed respectively based on the  $k$ -out-of- $n$  system theory. Prodan et al. [5] proposed an original approach to ECA reliability analysis, by introducing the accuracy threshold measure borrowed from the fault-tolerant quantum computing theory, as one of the main parameters for our qualitative assessment. Zhang et al. [6] proposed a practical ECA reliability evaluation model based on the ideal reliability evaluation model, considering the implementation details in the embryonic cell, while the assistant hardware of extra register and routing channels in the switch box is extracted into the practical model. At the same time, cell granularity parameter and layout parameter were introduced to ECA reliability analysis [7,8], which makes the reliability evaluation model closer to the ECA actual working process. Zhu et al. [9] analyzed the ECA working process, a novel ECA reliability evaluation model based on the Markov non-repairable system theory was proposed. Wang et al. [10,11] proposed an ECA reliability model based on the multi-state system reliability theory, by dividing the ECA working process into multiple working states with different self-repairing strategies.

Based on the proposed ECA reliability evaluation methods, Ortega et al. [12] researched the effect on the ECA reliability with the changing of the electronic cell failure rate and the number of spare cells, which laid a foundation for the subsequent research. Prodan et al. [5] brought new perspectives on designing reliable embryonic memory structures at both the molecular and the cellular levels, and appropriate design principles were provided on both infor-

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mation encoding and storage. Lin et al. [13] researched the effect on the ECA reliability with different design methods in an  $n \times n$  scale ECA, and ECA layout optimal design rules were given. Zhang et al. [6–8] researched the method of self-repairing strategy selection, cell granularity optimization selection and ECA layout optimization design of the ECA on reliability analysis. Zhu et al. [14,15] proposed a gene backup number selection method based on the ECA reliability and hardware consumption analysis. Wang et al. [11] studied the structure optimization design, performance analysis and preventive maintenance decision of the bus-based ECA. At the same time, based on the ECA reliability and hardware resource consumption analysis, the mathematical description method for the ECA, the method of electronic cells number selection in the ECA and the ECA layout optimization method are studied [16–19], which can be used to guide the optimization design of the ECA.

Summarizing the current studies, in the process of analyzing and evaluating the ECA reliability, it is assumed that the fault detection coverage of the electronic cell is 100%. However, in the actual working process, fault detection coverage cannot reach 100%. In addition, in the existing ECA reliability models, only the failure of the electronic cells is considered, and the failure of the input and output (I/O) resources among the electronic cells is not considered. At present, ECA reliability evaluation methods are mostly based on the  $k$ -out-of- $n$  system reliability model [20–22], which can provide a time metric to evaluate the ECA reliability, and they are helpful to instructing the optimization design of the ECA. However, they cannot reflect the process of self-repairing and the ECA working states transition, which is helpful to researching the nature of the ECA reliability.

Analyzing the structural characteristics and working

process of the ECA, in the paper, the electronic cell and its corresponding I/O resources are equivalent to a functional unit (FU), and the FU fault detection coverage is introduced to the ECA reliability evaluation method. With two kinds of self-repairing strategies, ECA reliability evaluation methods were proposed based on the Markov status graph model [23]. With the ECA reliability evaluation method based on the  $k$ -out-of- $n$  system theory model as a comparison object, the validity and rationality of the ECA reliability evaluation method based on the Markov state graph model have been verified. Based on the proposed ECA reliability evaluation method, the influence of the parameters change on the ECA reliability was studied, and the research results can not only provide theoretical guidance for the optimization design of the ECA, but also point out the direction for further research.

Section 2 briefly addresses the basic structure and self-repairing strategies of the ECA. In Section 3, with two kinds of self-repairing strategies, ECA reliability evaluation methods are proposed based on the Markov status graph model respectively. Section 4 verifies the validity and rationality of the proposed ECA reliability evaluation method, and the influence of the parameters change on the ECA reliability is studied in detail. Finally, conclusions and suggestions for future work are presented in Section 5.

## 2. ECA and its self-repairing strategies

### 2.1 ECA

The ECA is a two-dimensional array of embryonic cells, which is shown in Fig. 1, and each cell in the ECA represents a processing element. Embryonic cells in the ECA can be divided into active cells and spare cells, and the structures of embryonic cells are the same. Active cells realize the function of the circuit, and spare cells are redundant units of active cells.

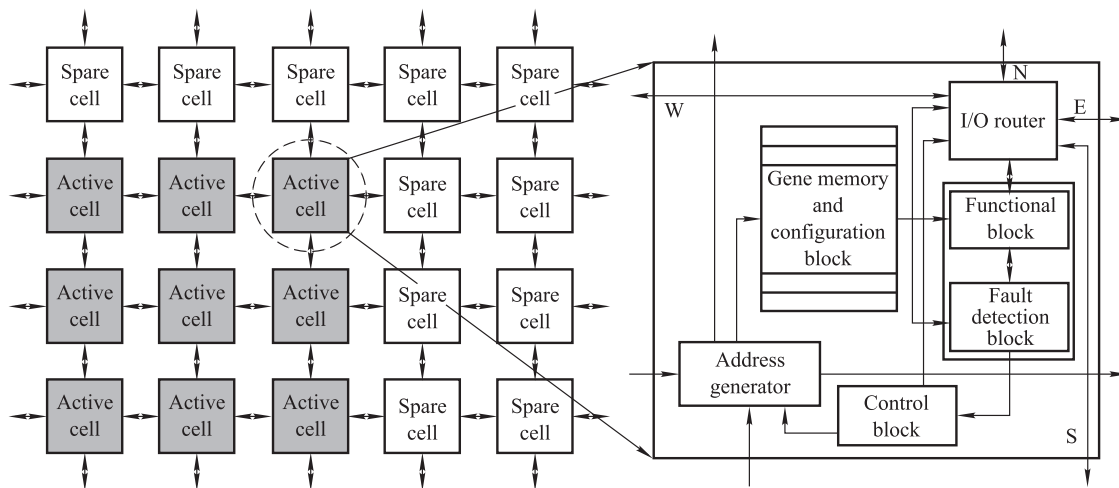
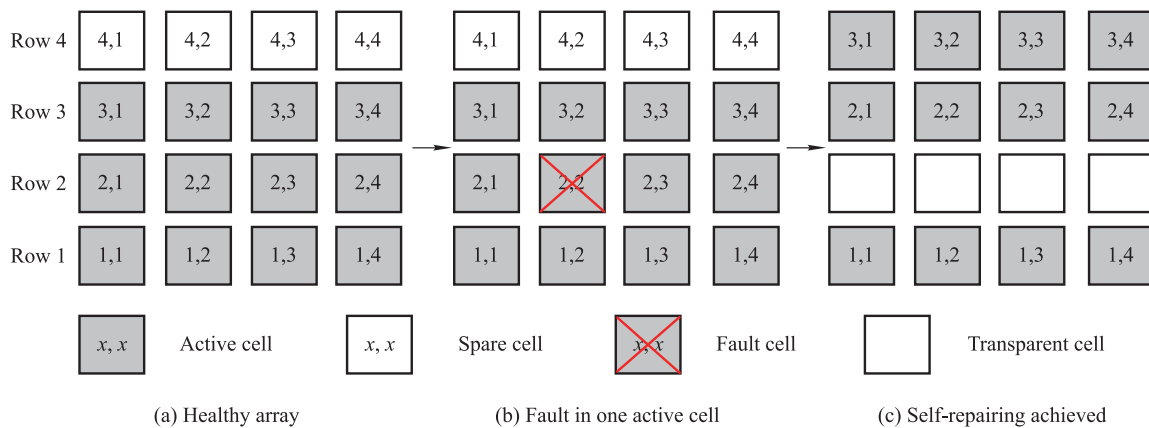


Fig. 1 Structure of ECA and embryonic cell

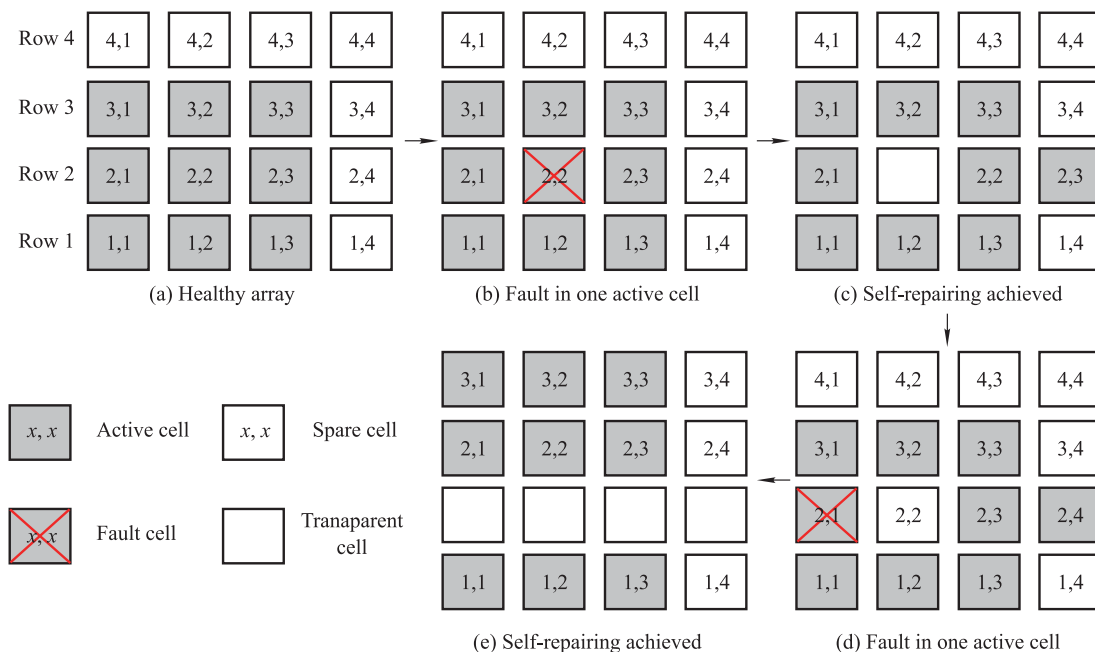
The embryonic cell is mainly composed of an address generator, a gene memory and configuration block, a functional block, a control block, a fault detection block and an input output (I/O) router [24]. The address generator will generate the co-ordinate of the cell, which will determine the function of the embryonic cell. The gene memory and configuration block stores the genes of the embryonic cell, which will be configured to all blocks in the embryonic cell. The functional block performs the function of the embryonic cell, which is determined by configuration genes. The control block will control all the blocks so as to ensure the normal and orderly working of the embryonic cell. The fault detection block realizes the fault self-testing of embryonic cells, which is the premise of fault self-repairing. The I/O router realizes the connection of embryonic cells.

**2.2 ECA fault self-repairing strategies**

The fault self-repairing strategy can effectively improve the reliability of the circuit, and the nature of fault self-repairing is the shift and re-expression of address information. According to the structural characteristics of the ECA, there are a row (column) elimination self-repairing strategy and a cell elimination self-repairing strategy for the ECA [24]. Row and column elimination self-repairing are equivalent cell replacement strategies. In the following discussion, only the row elimination self-repairing strategy will be analyzed; however, the same results apply for the column elimination self-repairing strategy. The self-repairing process of the row elimination self-repairing strategy is shown in Fig. 2, and the self-repairing process of the cell elimination self-repairing strategy is shown in Fig. 3.



**Fig. 2 Process of row elimination self-repairing**



**Fig. 3 Process of cell elimination self-repairing**

In the working process of the row elimination self-repairing strategy, the failing of one active cell provokes the elimination of the corresponding row, and cells are logically shifted upwards making use of a spare row. Active cells in the faulty cell row become transparent cells, which act as a conductor. Each embryonic cell is defined by two co-ordinates with enough memory to contain the configuration genes of the corresponding column.

The row elimination self-repairing strategy is far from optimal with respect to the use of spare resources, but the short time needed to recover from a failure makes it attractive to implement real-time fault-tolerant systems. In addition, as the array grows larger, the percentage of cells lost during reconfiguration decreases dramatically.

In order to improve the utilization of spare cells, the cell elimination self-repairing strategy is proposed. Each embryonic cell in the ECA is defined by two co-ordinates and contains the configuration genes of the entire array with enough memory.

Fig. 3 shows the self-repairing process of the cell elimination self-repairing strategy. In the cell elimination self-repairing strategy, spare cells replace faulty cells in two stages. First, when the number of the faulty cells in a row is less than the number of spare cells, and spares located in the same row replace the faulty cells; second, when the number of the faulty cells in a row surpasses the number of spare cells, row elimination self-repairing is performed.

### 3. ECA reliability evaluation based on Markov status graph model

In the process of the ECA reliability evaluation, the electronic cell and its corresponding I/O resources are equivalent to FU, and it is the basic unit for evaluating the reliability of embryonic cellular row (ECR). In the process of ECR reliability evaluation, assume the FU fault detection coverage is  $p$ , and the FU failure process follows the exponential distribution. With two kinds of self-repairing strategies, the ECR reliability based on the Markov status graph model is analyzed. Based on the analysis of the ECR reliability, the reliability of the ECA will be evaluated by analyzing the dynamic characteristics of row elimination self-repairing.

#### 3.1 Markov status graph model

The Markov status graph model is a typical Markov chain model [25,26], which is widely used in the modeling of stochastic decay processes in multi-state systems or multi-state components.

Assume the discrete states space  $E = \{e_1, e_2, \dots, e_n\}$ , and the discrete time parameter stochastic process

$\{X(t)|X(t) \in E, t \geq 0\}$ . For any moment  $0 \leq t_1 \leq t_2 \leq t_3 \leq \dots \leq t_n$ , the probability of  $t_n$  can be defined by conditional probability, which is shown in (1).

$$F_{X(t_n)|X(t_1)\dots X(t_{n-1})} = P[X(t_n) = e_n | X(t_1) = e_1 \dots X(t_{n-1}) = e_{n-1}] \quad (1)$$

If the stochastic process satisfies the requirements of (2), the stochastic process is called a Markov chain. As in the case of a general Markov process, (2) implies that the chain behavior in the future depends only on its present state and does not depend on its behavior in the past.

$$F_{X(t_n)|X(t_{n-1})} = F_{X(t_n)|X(t_1)\dots X(t_{n-1})} \quad (2)$$

The Markov status graph model is suitable for both repairable and un-repairable systems [23,27]. In the Markov status graph model, a system must meet the following conditions.

Firstly, the system must satisfy the Markov process. Note that only the Markov process where the state probabilities at a future instant does not depend on the states occupied in the past.

Secondly, the system and elements must be in the discrete state, that is, working or failure. In the working process, the system and elements only have two states. If the system and elements can operate normally, they are in the working state. When a fault occurs in the system and elements, they are in the failure state.

Thirdly, the system failure rate and the repair rate should be constant. The degradation process and repair process of the system obey the exponential distribution, so the failure rate and the repair rate are constant.

Finally, the state transition can take place at any instant of time. However, in a fairly small time interval  $\Delta t$ , there are no simultaneous state transitions of any different elements. In other words, there may be only one failure or one repair in a system at any instant  $t$ .

The general steps of the Markov status graph model are as follows [23,27,28].

(i) By analyzing the system working process, working states of the system are given. According to the states transition law of components in the system, the Markov state space graph of the system is given. The states transition rate usually refers to the failure rate or the maintenance rate.

(ii) According to system states transition space graph, the system states transition probability matrix  $T$  is given. The system states equation coefficient matrix  $A$  can be given by  $|T - U|$ , which can be used to establish system states equation.

(iii) Based on the established system states equation, the system states probability  $p_i(t)$  can be calculated. In accordance with the definition of  $p_i(t)$ , the reliability of the system can be calculated, and the calculation process is realized by Laplace transformation.

### 3.2 ECA reliability evaluation method

According to the ECA working process, the ECA is an unrepairable system. In the ECA, the working state at any moment is only related to that at the previous moment. Therefore, the ECA working process satisfies the Markov process. Embryonic cells in the ECA only have two kinds of states, that is, working or failure. The failure process of embryonic cells obeys the exponential distribution. In the ECA, there are no simultaneous state transitions of any different embryonic cells in a fairly small time interval  $\Delta t$ .

Above all, the ECA working process conforms to the requirements of the Markov status graph model. Therefore, the Markov status graph model can be used in the analysis and evaluation of the ECA reliability.

#### 3.2.1 FU

The ECA is mainly composed of embryonic cells and I/O resources. In the existing ECA reliability evaluation model, only the failure of embryonic cells is considered, and the effect of I/O resources failure on the ECA reliability is not considered. In the ECA, The connection method among embryonic cells is shown in Fig. 4.

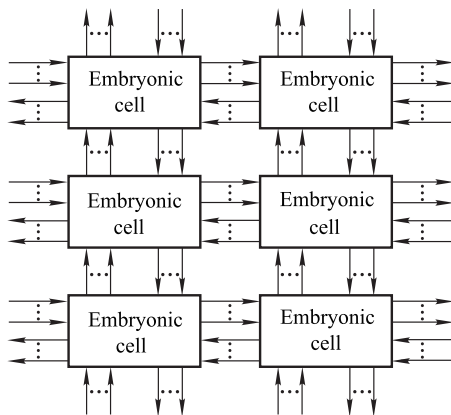


Fig. 4 Connection among embryonic cells

In the ECA, the failure of the embryonic cell will directly cause the failure of the circuit function. Similarly, the failure of I/O resources will also cause the failure of the circuit function. Therefore, the embryonic cell and its corresponding I/O resources can be equivalent to a series system, which is shown in Fig. 5.

In a series system with  $N$  units, assume the failure rate of units is  $\lambda_i$  ( $1 \leq i \leq N$ ), and all units are independent of

each other. Therefore, the series system failure rate is the sum of units failure rates, that is,  $\lambda = \sum_{i=1}^N \lambda_i$ .

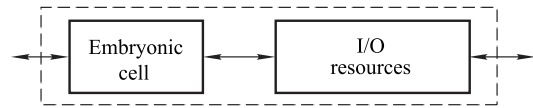


Fig. 5 A series system

In order to facilitate the analysis of the ECA reliability, the embryonic cell and its corresponding I/O resources are equivalent to an FU. In an FU, assume the embryonic cell failure rate is  $\lambda_e$ , and its corresponding I/O resources failure rate is  $\gamma_e$ . Therefore, the FU failure rate  $\lambda_f$  is  $\lambda_e + \gamma_e$ .

Assume the scale of the ECA is  $R \times C$ ; the scale of the working ECA is  $r \times c$ .  $R$  is the row number of the ECA,  $C$  is the column number of the ECA,  $r$  is the row number of the working ECA,  $c$  is the column number of working ECA, and  $R \geq r$ ,  $C \geq c$ . With different self-repairing strategies, the ECA is divided into the row elimination ECA and the cell elimination ECA, and the ECA reliability evaluation method is proposed based on the Markov status graph model.

#### 3.2.2 Reliability evaluation method of cell elimination ECA

In the cell elimination ECA, the ECR is a basic unit for analyzing ECA reliability. In the ECR, if an FU fails, only the faulty FU will be eliminated. The ECR working process can be divided into multiple working states with different numbers of faulty FUs, which are shown in Table 1.

Table 1 Working states of cell elimination ECR

Faulty FU number	Working status number	State
0	$C_C^0$	$C_0$
1	$C_C^1$	$C_1 - C_{C_1}^1$
2	$C_C^2$	$C_{C_1+1}^2 - C_{C_1+C_2}^2$
$\vdots$	$\vdots$	$\vdots$
$C - c$	$C_C^{C-c}$	$C_{\sum_{i=0}^{C-c-1} C_C^i} - C_{\sum_{i=1}^{C-c} C_C^i}$
$C - c + 1$	$C_C^{C-c+1}$	$F_1 - F_{C_C^{C-c+1}}$
	1	$F_n$

In Table 1, the state  $C_0$  to the state  $C_{\sum_{i=1}^{C-c} C_C^i}$  are normal working states of the ECR, the state  $C_0$  means all FUs work normally in the ECR, the state  $C_1$  to the state  $C_{C_1}^1$  mean one faulty FU fails in the ECR, the state  $C_{C_1+1}^2$  to the state  $C_{C_1+C_2}^2$  mean two faulty FUs fail in the ECR, the state  $C_{\sum_{i=0}^{C-c-1} C_C^i}$  to the state  $C_{\sum_{i=1}^{C-c} C_C^i}$  mean  $C - c$  faulty

FUs fail in the ECR. The state  $F_1$  to the state  $F_{C_0^{c-c+1}}$  are failure states of the ECR, which mean  $C - c + 1$  faulty FUs fail in the ECR. For the FU fault detection coverage  $p$  less than 1, there is a state  $F_n$ , which means faults in the FU are not detected. Therefore, the working states set of the ECR  $S_c$  is  $\{C_0 - C_{\sum_{i=1}^{c-c} C_C^i}, F_1 - F_{C_0^{c-c+1}}, F_n\}$ .

The reliability of the ECR is the probability that the ECR works in normal working states, that is, the probability that the ECR works in the state  $C_0$  to the state  $C_{\sum_{i=1}^{c-c} C_C^i}$ . In the

ECR, assume the failure rate of the FU is  $\lambda_f$ , and the FU fault detection coverage is  $p$ . Therefore, the state transition rate means the failure rate of the FU. According to the ECR working principle, the ECR states transition rate matrix  $T$  can be given. In order to calculate the reliability of the ECR, only the ECR normal working states transition rate matrix  $T_w$  is needed, and the ECR normal working states equation coefficient matrix  $S_w$  equals  $T_w - U_w$ ,  $U_w$  is an identity matrix with  $\sum_{i=0}^{c-c} C_C^i$  dimensions. The Markov states differential equation is obtained by the Markov chain as follows.

$$[p_{C_0}(t)', p_{C_1}(t)', \dots, p_{C_{\sum_{i=1}^{c-c} C_C^i}}(t)'] = [p_{C_0}(t), p_{C_1}(t), \dots, p_{C_{\sum_{i=1}^{c-c} C_C^i}}(t)] S_w \quad (3)$$

According to the Markov states differential equation, the probability that the ECR works in normal working states can be calculated, and the ECR reliability  $R(t)$  is

$$R(t) = \sum_{i=0}^{\sum_{j=1}^{c-c} C_C^j} p_{C_i}(t). \quad (4)$$

In order to describe the solution process of the ECR reliability more clearly, assume the scale of ECA  $R \times$

$C$  is  $4 \times 4$ , and the scale of the working ECA  $r \times c$  is  $2 \times 2$ . Therefore, the ECR working states set  $S_c$  is  $\{C_0, C_1, \dots, C_{10}, F_1, F_2, F_3, F_4, F_n\}$ . Array is used to describe the working states of the ECR, and  $S_c$  is  $\{0\ 000, 1\ 000, 0\ 100, 0\ 010, 0\ 001, 1\ 100, 1\ 010, 1\ 001, 0\ 110, 0\ 101, 0\ 011, 1\ 110, 1\ 011, 1\ 101, 0\ 111, F_n\}$ , in which 1 means the FU fails, 0 means the FU works normally. Because the ECR working states transition process is complicated, only the transition process of the state  $C_0$  is given, which is shown in Fig. 6.

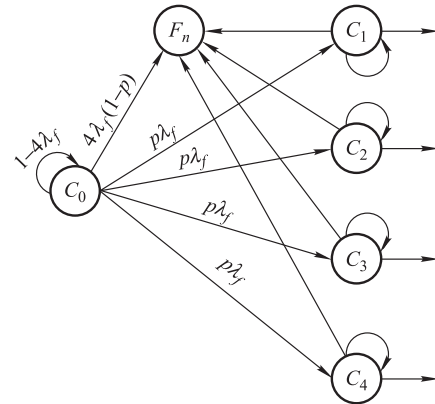


Fig. 6 Transition process of state  $C_0$

In Fig. 6, the state  $C_0$  means no FU fails in ECR, the states  $C_1, C_2, C_3$  and  $C_4$  mean one FU fails in the ECR. The transition rates from the state  $C_0$  to states  $C_1, C_2, C_3$  and  $C_4$  are the same, which is  $p\lambda_f$ . Therefore, the probability that the ECR stays in the state  $C_0$  is  $1 - 4\lambda_f$ , and the transition rate from the state  $C_0$  to the state  $F_n$  is  $4\lambda_f(1 - p)$ . The transition process of other states can be obtained by this method, and the Markov status transition graph of all working states can be given. According to the obtained Markov status transition graph, the ECR normal working states transition rate matrix  $T_w$  is

$$T_w = \begin{bmatrix} 1-4\lambda_f & p\lambda_f & p\lambda_f & p\lambda_f & p\lambda_f & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-3\lambda_f & 0 & 0 & 0 & p\lambda_f & p\lambda_f & p\lambda_f & 0 & 0 & 0 \\ 0 & 0 & 1-3\lambda_f & 0 & 0 & p\lambda_f & 0 & 0 & p\lambda_f & p\lambda_f & 0 \\ 0 & 0 & 0 & 1-3\lambda_f & 0 & 0 & p\lambda_f & 0 & p\lambda_f & 0 & p\lambda_f \\ 0 & 0 & 0 & 0 & 1-3\lambda_f & 0 & 0 & p\lambda_f & 0 & p\lambda_f & p\lambda_f \\ 0 & 0 & 0 & 0 & 0 & 1-2\lambda_f & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1-2\lambda_f & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1-2\lambda_f & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1-2\lambda_f & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1-2\lambda_f & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1-2\lambda_f \end{bmatrix}. \quad (5)$$

Therefore, the ECR normal working states equation coefficient matrix  $S_w$  is  $T_w - U_w$ , and the Markov states differential equation is obtained by the Markov chain as follows.

$$[p_{C_0}(t)', p_{C_1}(t)', \dots, p_{C_{10}}(t)'] = [p_{C_0}(t), p_{C_1}(t), \dots, p_{C_{10}}(t)] S_w \quad (6)$$

According to the Markov states differential equation, the probability that the ECR works in normal working states can be calculated. In order to ensure the ECR works normally, the ECR must work in one state among the state  $C_0$  to the state  $C_{10}$ . Therefore, the probability that the ECR works in the state  $C_0$  is

$$p_{C_0}(t) = \exp(-4\lambda_f t). \quad (7)$$

The probabilities that the ECR works in the states  $C_1$ ,  $C_2$ ,  $C_3$  and  $C_4$  are the same, which is

$$p_{C_1}(t) = p_{C_2}(t) = p_{C_3}(t) = p_{C_4}(t) = p \exp(-3\lambda_f t)(1 - \exp(-\lambda_f t)). \quad (8)$$

The probabilities that the ECR works in the state  $C_5$  to the state  $C_{10}$  are the same, which is

$$p_{C_5}(t) = p_{C_6}(t) = p_{C_7}(t) = p_{C_8}(t) = p_{C_9}(t) = p_{C_{10}}(t) = p^2 \exp(-2\lambda_f t)(1 - \exp(-\lambda_f t))^2. \quad (9)$$

Therefore, in the above ECA, the reliability of one ECR is

$$R(t) = \sum_{i=0}^{10} p_{C_i}(t) = p_{C_0}(t) + 4p_{C_1}(t) + 6p_{C_5}(t). \quad (10)$$

In order to ensure the ECR works properly, the ECR must work in the the state  $C_0$  to the state  $C_{\sum_{i=1}^{C-c} C_C^i}$ , the probability that the ECR works in the state  $C_0$  is

$$p_0(t) = \exp(-C\lambda_f t). \quad (11)$$

The probability that the ECR works in the state  $C_1$  to the state  $C_{C^1}$  is

$$p_1(t) = p C_C^1 \exp(-(C-1)\lambda_f t) \cdot (1 - \exp(-\lambda_f t)). \quad (12)$$

The probability that the ECR works in the state  $C_{C^1+1}$  to the state  $C_{C^1+C_C^2}$  is

$$p_2(t) = p^2 C_C^2 \exp(-(C-2)\lambda_f t) \cdot (1 - \exp(-\lambda_f t))^2. \quad (13)$$

The probability that the ECR works in the state  $C_{\sum_{j=0}^{i-1} C_C^j}$  to the state  $C_{\sum_{j=0}^{i-1} C_C^j}$  ( $1 \leq i \leq C-c$ ) is

$$p_i(t) = p^i C_C^i \exp(-(C-i)\lambda_f t) \cdot (1 - \exp(-\lambda_f t))^i. \quad (14)$$

The probability that the ECR works in the state  $C_{\sum_{i=1}^{C-c-1} C_C^{i+1}}$  to the state  $C_{\sum_{i=1}^{C-c} C_C^i}$  is

$$p_{C-c}(t) = p^{C-c} C_C^{C-c} \exp(-c\lambda_f t) \cdot (1 - \exp(-\lambda_f t))^{C-c}. \quad (15)$$

Therefore, in cell elimination ECA, the reliability of one ECR is

$$R_c(t) = p_0(t) + p_1(t) + \dots + p_{C-c}(t) =$$

$$\sum_{i=0}^{C-c} p^i C_C^i \exp(-(C-i)\lambda_f t) (1 - \exp(-\lambda_f t))^i. \quad (16)$$

In the cell elimination ECA, when redundant FUs are used up in an ECR, row elimination self-repairing of the ECA will work. In the working process of row elimination self-repairing, the ECR is regarded as a whole, and the working principle of row elimination self-repairing in the ECA is the same as that of cell elimination self-repairing in the ECR. Based on the reliability evaluation method of the cell elimination ECR, the reliability of the cell elimination ECA is

$$R_{E_c}(t) = \sum_{k=0}^{R-r} p^k C_R^k R_c^{R-k}(t) (1 - R_c(t))^k. \quad (17)$$

And the mean time to failure (MTTF) of the cell elimination ECA is

$$T_{E_c} = \int_0^{\infty} R_{E_c}(t) dt. \quad (18)$$

### 3.2.3 Reliability evaluation of row elimination ECA

According to the reliability evaluation method in the cell elimination ECA, the reliability of the row elimination ECA can be evaluated similarly, so the concrete analysis process will not be repeated here. In the row elimination ECA, any working FU's failing will result in the failure of the ECR, and the faulty ECR will be eliminated. In the ECR, the working process can be divided into multiple working states with different numbers of faulty working FUs and faulty redundant FUs, and working states are shown in Table 2.

**Table 2 Working states of row elimination ECR**

Faulty working unit number	Faulty redundant unit number	Working status number	State
0	0	$C_{C-c}^0$	$R_0$
	1	$C_{C-c}^1$	$R_1 - R_{C-c}$
	2	$C_{C-c}^2$	$R_{C-c+1} - R_{C-c+C_{C-c}^2}$
	$\vdots$	$\vdots$	$\vdots$
	$C-c$	$C_{C-c}^{C-c}$	$R_{C-c} - \sum_{i=1}^{C-c} C_{C-c}^i$
1	0	$C_c^1 \cdot C_{C-c}^0$	$F_1 - F_{C_c^1 \cdot C_{C-c}^0}$
	1	$C_c^1 \cdot C_{C-c}^1$	$F_{C_c^1 \cdot C_{C-c}^1} - F_{C_c^1 \cdot (\sum_{i=0}^1 C_{C-c}^i)}$
	2	$C_c^1 \cdot C_{C-c}^2$	$F_{C_c^1 \cdot (\sum_{i=0}^2 C_{C-c}^i)} - F_{C_c^1 \cdot (\sum_{i=0}^2 C_{C-c}^i)}$
	$\vdots$	$\vdots$	$\vdots$
	$C-c$	$C_c^1 \cdot C_{C-c}^{C-c}$	$F_{C_c^1 \cdot (\sum_{i=0}^{C-c-1} C_{C-c}^i)} - F_{C_c^1 \cdot (\sum_{i=0}^{C-c} C_{C-c}^i)}$

In Table 2, the state  $R_0$  to the state  $R_{C-c} - \sum_{i=1}^{C-c} C_{C-c}^i$  are normal working states of the ECR, the state  $R_0$  means no FU fails in the ECR, the state  $R_1$  to the state  $R_{C-c}$  mean one redundant FU fails in the ECR, the state  $R_{C-c+1}$  to the state  $R_{C-c+C_{C-c}^2}$  mean two redundant FUs fail in the ECR, the state  $R_{C-c} - \sum_{i=1}^{C-c} C_{C-c}^i$  means all redundant FUs fail in the ECR. The state  $F_1$  to the state  $F_{C_c^1 \cdot (\sum_{i=0}^{C-c} C_{C-c}^i)}$  are failure states of the ECR, the state  $F_1$  to state  $F_{C_c^1 \cdot C_{C-c}^0}$  mean one working FU fails in the ECR, the state  $F_{C_c^1 \cdot C_{C-c}^0+1}$  to the state  $F_{C_c^1 \cdot (\sum_{i=0}^1 C_{C-c}^i)}$  mean one working FU and one redundant FU fail in the ECR, the state  $F_{C_c^1 \cdot (\sum_{i=0}^2 C_{C-c}^i)}$  to the state  $F_{C_c^1 \cdot (\sum_{i=0}^2 C_{C-c}^i)}$  mean one working FU and two redundant FUs fail in the ECR, the state  $F_{C_c^1 \cdot (\sum_{i=0}^{C-c-1} C_{C-c}^i)}$  to the state  $F_{C_c^1 \cdot (\sum_{i=0}^{C-c} C_{C-c}^i)}$  mean one working FU and  $C-c$  redundant FUs fail in the ECR. For the FU fault detection coverage  $p$  less than 1, there is a state  $F_n$ . The state  $F_n$  means the faulty FU is not detected. Therefore, the working states set of the row elimination ECR  $S_r$  is  $\{R_0 - R_{C-c} - \sum_{i=0}^{C-c} C_{C-c}^i, F_1 - F_{C_c^1 \cdot (\sum_{i=0}^{C-c} C_{C-c}^i)}, F_n\}$ .

The probability that the ECR works in the state  $R_0$  is

$$p'_0(t) = \exp(-C\lambda_f t). \quad (19)$$

The probability that the ECR works in the state  $R_0$  to state  $R_{C-c}$  is

$$p'_1(t) = p C_{C-c}^1 \exp(-(C-1)\lambda_f t) \cdot (1 - \exp(-\lambda_f t)). \quad (20)$$

The probability that the ECR works in the state  $R_{C-c+1}$  to the state  $R_{C-c+C_{C-c}^2}$  is

$$p'_2(t) = p^2 C_{C-c}^2 \exp(-(C-2)\lambda_f t) \cdot (1 - \exp(-\lambda_f t))^2. \quad (21)$$

The probability that the ECR works in the state  $R_{C-c} - \sum_{i=1}^{C-c} C_{C-c}^i$  to the state  $R_{C-c} - \sum_{i=1}^{C-c} C_{C-c}^i$  ( $0 \leq i \leq C-c$ ) is

$$p'_i(t) = p^i C_{C-c}^i \exp(-(C-i)\lambda_f t) \cdot (1 - \exp(-\lambda_f t))^i. \quad (22)$$

The probability that the ECR works in the state  $R_{C-c} - \sum_{i=1}^{C-c} C_{C-c}^i$  is

$$p'_{C-c}(t) = p^{C-c} C_{C-c}^{C-c} \exp(-c\lambda_f t) \cdot (1 - \exp(-\lambda_f t))^{C-c}. \quad (23)$$

Therefore, the reliability of the row elimination ECR is

$$R_r(t) = p'_0(t) + p'_1(t) + \dots + p'_{C-c}(t) = \sum_{i=0}^{C-c} p^i C_{C-c}^i \exp(-(C-i)\lambda_f t) (1 - \exp(-\lambda_f t))^i. \quad (24)$$

Above all, the reliability of the row elimination ECA is

$$R_{E_r}(t) = \sum_{k=0}^{R-r} p^k C_R^k R_r^{R-k}(t) (1 - R_r(t))^k. \quad (25)$$

The MTTF of the row elimination ECA is

$$T_{E_r} = \int_0^\infty R_{E_r}(t) dt. \quad (26)$$

#### 4. Experimental verification and parameters analysis

At present, the research on the ECA technology is still in the theoretical stage, and there is lack of mature specialized



hardware. Therefore, it is difficult to obtain the experimental data of the ECA through the accelerated degradation experiment so as to verify the validity and rationality of the proposed ECA reliability evaluation method. At present, the  $k$ -out-of- $n$  reliability theory is widely applied to analyzing the ECA reliability, and the ECA reliability evaluation method based on the  $k$ -out-of- $n$  reliability theory is chosen as a comparison object. By comparing ECA reliability data from two kinds of reliability evaluation methods, the validity of the proposed ECA reliability evaluation method based on the Markov status graph model is verified. Analyzing the influence of the parameters change on the ECA reliability, the rationality of the proposed ECA reliability evaluation method is verified.

**4.1 Comparative analysis**

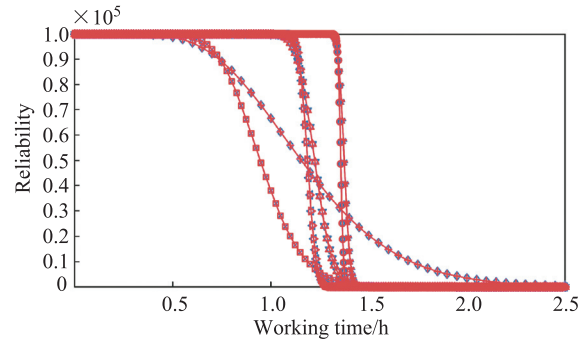
Six kinds of ECAs are chosen as experimental objects, and the scales of ECAs are shown in Table 3. The reliability of ECAs is analyzed based on two kinds of ECA reliability evaluation methods respectively.

**Table 3 ECAs with six kinds of scales**

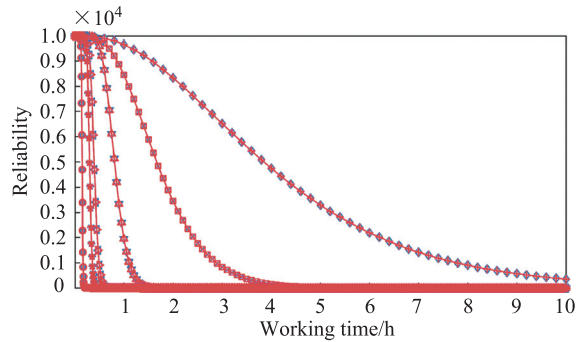
ECA	1	2	3	4	5	6
$R \times C$	5×5	10×10	30×30	60×60	100×100	200×200
$r \times c$	3×3	6×6	15×15	30×30	45×45	90×90

In the ECA with a determined scale, the evaluation of the ECA reliability based on the  $k$ -out-of- $n$  system theory is only related to the FU failure rate  $\lambda_f$ , and the evaluation of the ECA reliability based on the Markov status graph model is related to both the FU failure rate  $\lambda_f$  and the FU fault detection coverage  $p$ . In order to verify the validity of the proposed ECA reliability evaluation method based on

the Markov status graph model, assume the FU fault detection coverage  $p = 1$ ,  $\lambda_f = 6E-6$  h. With two kinds of ECA reliability evaluation methods, the reliability curves of six kinds of ECAs are shown in Fig. 7, and the MTTF values of six kinds of ECAs are shown in Table 4.



(a) Reliability of cell elimination ECA



(b) Reliability of row elimination ECA

- ◆ : ECA1,  $n/k$ ;    + : ECA1, MSG;    × : ECA2,  $n/k$ ;
- : ECA2, MSG;    ▽ : ECA3,  $n/k$ ;    △ : ECA3, MSG;
- ◀ : ECA4,  $n/k$ ;    ▶ : ECA4, MSG;    ● : ECA5,  $n/k$ ;
- : ECA5, MSG;    \* : ECA6,  $n/k$ ;    ✱ : ECA6, MSG.

**Fig. 7 Reliability curves of six kinds of ECAs**

**Table 4 MTTF values of six kinds of ECAs**

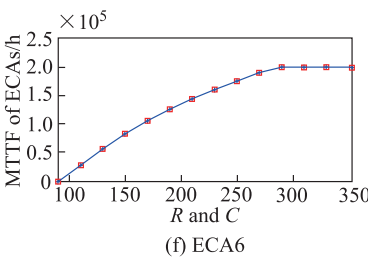
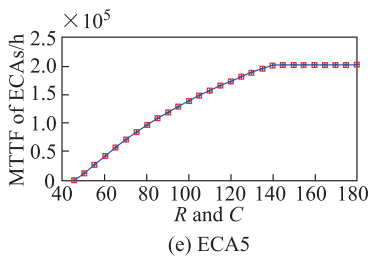
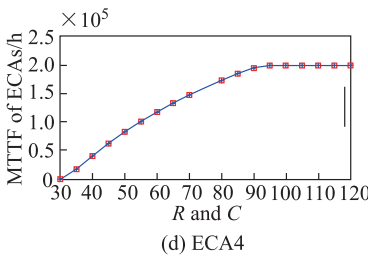
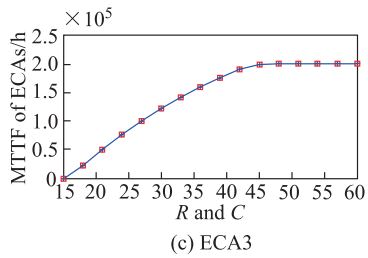
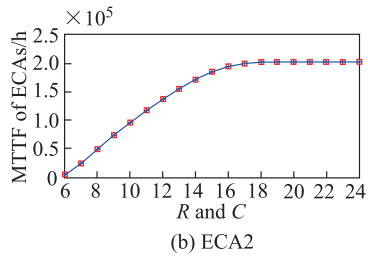
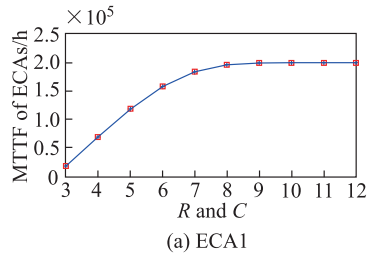
Reliability model and self-repairing strategy	ECA scale ( $R \times C(r \times c)$ )					
	5×5 (3×3)	10×10 (6×6)	30×30 (15×15)	60×60 (30×30)	100×100 (45×45)	200×200 (90×90)
$k$ -out-of- $n$ model and cell elimination	1.198 5E5	9.565 0E4	1.225 5E5	1.188 0E5	1.374 7E5	1.357 2E5
MSG and cell elimination	1.198 5E5	9.565 0E4	1.225 5E5	1.188 0E5	1.374 7E5	1.357 2E5
$k$ -out-of- $n$ model and row elimination	4.351 9E4	1.793 4E4	8.260 3E3	3.990 1E3	3.017 2E3	1.493 7E3
MSG and row elimination	4.351 9E4	1.793 4E4	8.260 3E3	3.990 1E3	3.017 2E3	1.493 7E3

In Fig. 7, “ $n/k$ ” means the ECA reliability evaluation method based on the  $k$ -out-of- $n$  system reliability model, “MSG” means ECA reliability evaluation method based on the Markov status graph model, “ECA1” means  $R = C = 5$  and  $r = c = 3$ , “ECA2” to “ECA6” are shown in Table 3. Fig. 7(a) shows the reliability curves of six kinds of cell elimination ECAs, which are calculated by two kinds of ECA reliability evaluation methods above. ECA reliability curves of six kinds of ECAs are completely coincident, and the MTTF values of six kinds of scales are the same respectively.

In a similar way, Fig. 7(b) shows the reliability curves of six kinds of row elimination ECAs, which are calculated by two kinds of ECA reliability evaluation methods above. ECA reliability curves of six kinds of ECAs are completely coincident, and MTTF values of six kinds of ECAs are the same respectively.

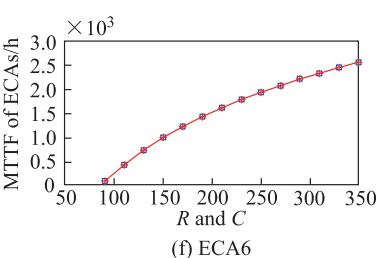
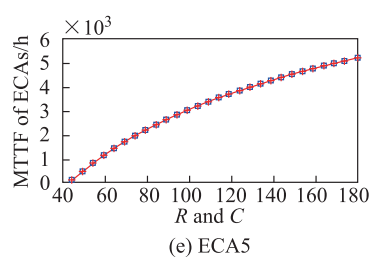
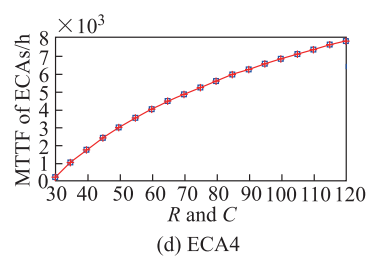
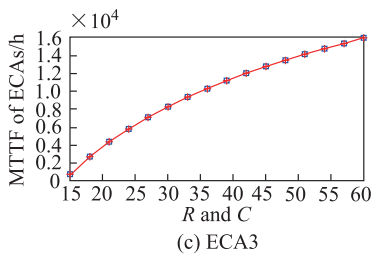
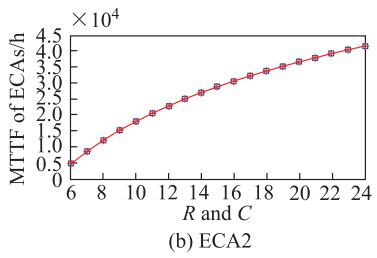
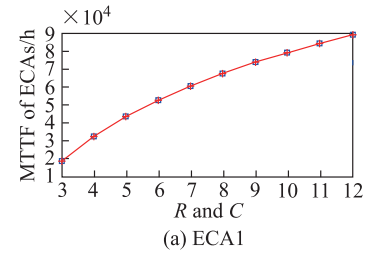
In order to further demonstrate the validity and accuracy of the proposed method, assume the working ECA scales of six kinds of ECAs are shown in Table 3,  $R$  and  $C$  increase from  $r$  and  $c$  to  $4r$  and  $4c$  respectively, and the growth rates are the same. With two kinds of evaluation

methods above, the MTTF values of six kinds of row elimination ECAs are shown in Fig. 8, and MTTF values of six kinds of row elimination ECAs are shown in Fig. 9.



—○— : MSG; —■— :  $n/k$ .

Fig. 8 MTTF curves of six kinds of cell elimination ECAs



—○— : MSG; —■— :  $n/k$ .

Fig. 9 MTTF curves of six kinds of row elimination ECAs

In Fig. 8 and Fig. 9, “ $n/k$ ” means the ECA reliability evaluation method based on the  $k$ -out-of- $n$  system reliability model, “MSG” means the ECA reliability evaluation method based on the Markov status graph model, and the MTTF of ECA is evaluated by the above two kinds of methods respectively. In ECAs, the scale of working ECAs is determined. When  $R$  and  $C$  increase from  $r$  and  $c$  to  $4r$  and  $4c$  respectively, the MTTF curves of six kinds of cell elimination ECAs are completely coincident. Similarly, the MTTF curves of six kinds of row elimination ECAs are completely coincident. Therefore, the proposed ECA re-

liability evaluation method can effectively and accurately evaluate the reliability of the ECA.

In order to verify the rationality of the proposed ECA reliability method, assume  $p = 1, 0.95, 0.9, 0.85, 0.8$ ,  $\lambda_f = 6E-6$  h, and ECA scales are shown in Table 3. When the cell elimination self-repairing strategy is adopted, the MTTF values of six kinds of ECAs are shown in Table 5. Similarly, when the row elimination self-repairing strategy is adopted, the MTTF values of six kinds of ECAs are shown in Table 6.

**Table 5** MTTF values of six kinds of cell elimination ECAs with different  $p$

$p$	ECA1	ECA2	ECA3	ECA4	ECA5	ECA6
1	1.198 5E5	9.565 0E4	1.225 5E5	1.188 0E5	1.374 7E5	1.357 2E5
0.95	1.078 4E5	7.859 7E4	5.896 1E4	2.062 7E4	8.066 9E3	1.877 7E3
0.9	9.581 2E4	6.130 3E4	2.096 1E4	5.393 2E3	1.866 8E3	4.386 1E2
0.85	8.415 1E4	4.618 0E4	9.645 2E3	2.308 3E3	7.924 3E2	1.910 0E2
0.8	7.317 6E4	3.426 3E4	5.358 9E3	1.255 4E3	4.360 4E2	1.064 1E2

**Table 6** MTTF values of six kinds of row elimination ECAs with different  $p$

$p$	ECA1	ECA2	ECA3	ECA4	ECA5	ECA6
1	4.351 9E4	1.793 4E4	8.260 3E3	3.990 1E3	3.017 2E3	1.493 7E3
0.95	3.987 7E4	1.552 8E4	5.242 9E3	1.782 2E3	8.061 8E2	1.942 9E2
0.9	3.649 4E4	1.344 6E4	3.466 8E3	9.518 4E2	3.656 1E2	86.639 8
0.85	3.335 6E4	1.164 9E4	2.399 8E3	5.946 7E2	2.222 9E2	53.746 0
0.8	3.045 0E4	1.010 1E4	1.740 4E3	4.158 9E2	1.554 1E2	37.983 8

As shown in Table 5 and Table 6, when the ECA scale and the self-repairing strategy are determined, the higher  $p$  is, the larger the MTTF of ECA is. In the process that  $p$  increases, the higher  $p$  is, the larger growth rate of MTTF is. In addition, in the process that  $p$  increases, the larger the ECA scale is, the larger the growth rate of ECA is. In the ECA, fault detection is the premise of fault self-repairing, if the fault cannot be detected, the ECA will fail immediately. Therefore, the higher  $p$  is, the lower the failure rate of the ECA is, that is, the larger MTTF is. The larger ECA scale means more embryonic cells; therefore, the probability that faults occur is higher; therefore, the higher  $p$  is, the larger the growth rate of MTTF is.

Above all, the proposed ECA reliability evaluation method based on the Markov status graph model can evaluate ECA reliability effectively and more accurately.

#### 4.2 Analysis of parameters in ECA

Based on the analysis in Section 3.2.2, the ECA reliability is related to the number of ECA rows  $R$  and  $r$ , the number of ECA columns  $C$  and  $c$ , the FU fault detection coverage  $p$  and the FU failure rate  $\lambda_f$ . When the functional circuit is mapped to the ECA, the working scale of the ECA is determined, that is,  $c$  and  $r$  are determined. In order to

optimize the structural design of the ECA, the effects on reliability with the changing of parameters in the ECA are studied. Selecting different values of  $p$ ,  $\lambda_f$ ,  $C$  and  $R$  in the ECA, the ECA reliability is evaluated by the proposed method respectively. In order to increase the credibility of the experiment, six kinds of ECAs with different scales are selected, which are shown in Table 7.

**Table 7** Six kinds of ECAs

ECA	1	2	3	4	5	6
$R \times C$	$12 \times 10$	$28 \times 20$	$52 \times 30$	$86 \times 60$	$100 \times 80$	$120 \times 100$
$r \times c$	$5 \times 6$	$16 \times 12$	$23 \times 18$	$34 \times 28$	$43 \times 36$	$52 \times 48$

##### 4.2.1 Effect on ECA reliability with the changing of $p$

The changing of the FU fault detection coverage  $p$  will directly affect the transition rates among ECA working states so as to affect the probability that the ECA works in working states, and it will finally affect the ECA reliability. In order to analyze the effect on the ECA reliability with the changing of  $p$ , assume  $\lambda_f = 6E-6$  h, and the scales of the ECA are shown in Table 7. During the process that  $p$  increases from 0.5 to 1, the MTTF curves of six kinds of ECAs are shown in Fig. 10.

In Fig. 10, “ECA1 – ECA6” mean six kinds of ECAs in Table 7 respectively. Fig. 10(a) shows the MTTF curves of

six kinds of cell elimination ECAs with different  $p$ , and Fig. 10(b) shows the MTTF curves of six kinds of row elimination ECAs with different  $p$ . As shown in Fig. 10, in the process of increasing  $p$  from 0.5 to 1, MTTF values of six kinds of ECAs are increasing continuously, and the growth rates of MTTF are also increasing.

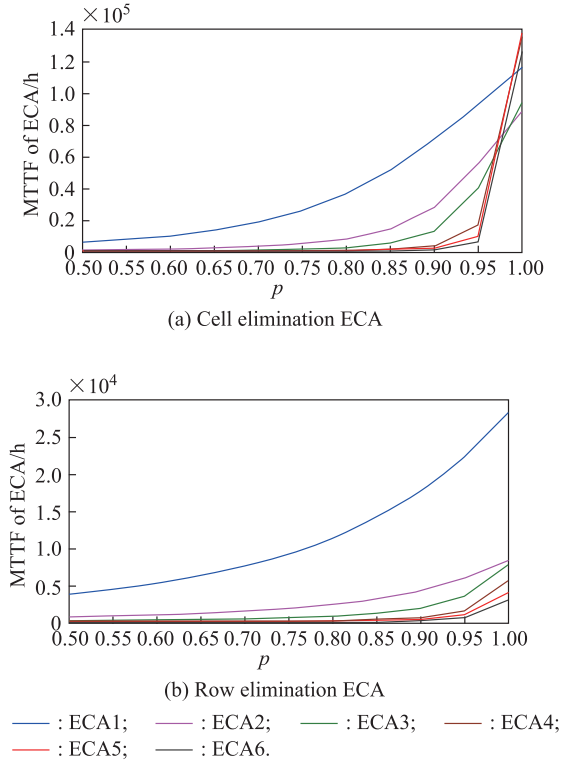


Fig. 10 MTTF curves of six kinds of ECAs with different  $p$

In the ECA, fault detection is the premise of fault self-repairing. If the fault in the ECA cannot be detected in time, the ECA will fail immediately. Therefore, the larger  $p$  is, the lower the ECA failure rate is, that is, the MTTF values of ECA will increase with the increase of  $p$ . As shown in (17) and (25), the reliability of ECA is positively corrected with  $p$ , and the larger  $p$  is, the larger the growth rate of MTTF is.

#### 4.2.2 Effect on ECA reliability with the changing of $\lambda_f$

The changing of the FU failure rate  $\lambda_f$  will directly affect the transition rates among ECA working states so as to affect the probability that the ECA works in working states, and it will finally affect the reliability of ECA. In order to analyze the effect on the ECA reliability with the changing of  $\lambda_f$ , assume  $p = 0.96$ , and  $C, R, c$  and  $r$  are shown in Table 7. In the process that  $\lambda_f$  decreases from  $1E-5$  h to  $1E-6$  h, the MTTF curves of six kinds of ECAs are shown in Fig. 11.

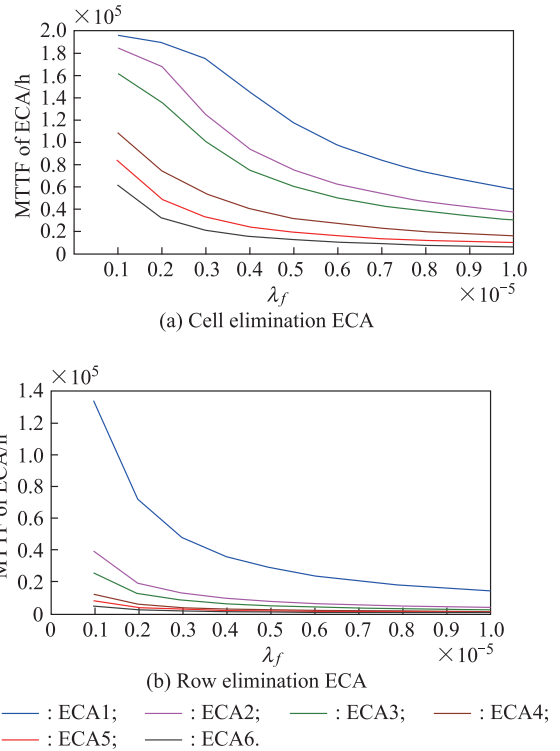


Fig. 11 MTTF curves of six kinds of ECAs with different  $\lambda_f$

In Fig. 11, “ECA1 – ECA6” mean six kinds of ECAs in Table 7 respectively. Fig. 11(a) shows the MTTF curves of six kinds of cell elimination ECAs with different  $\lambda_f$ , and Fig. 11(b) shows the MTTF curves of six kinds of row elimination ECAs with different  $\lambda_f$ . As shown in Fig. 11, in the process of reducing  $\lambda_f$  from  $1E-5$  h to  $1E-6$  h, MTTF values of six kinds of ECAs are increasing continuously.

In the ECA, when the scale is determined, the smaller  $\lambda_f$  is, the lower the failure rate of the ECA is. Therefore, the MTTF values of the ECA will increase with the decreasing of  $\lambda_f$ . In the process of reducing  $\lambda_f$  from  $1E-5$  h to  $1E-6$  h, the growth rates of MTTF values are increasing in six kinds of row elimination ECAs. In six kinds of cell elimination ECAs, the growth rates of MTTF values are increasing first, then they will decrease in “ECA1 – ECA3”.

#### 4.2.3 Effect on ECA reliability with the changing of $R$

As shown in (17) and (25), the changing of  $R$  will directly affect the reliability of ECA. In order to analyze the effect on the ECA reliability with different  $R$ , assuming  $\lambda_f = 6E-6$  h,  $p = 0.96$ ,  $C, r$  and  $c$  are shown in Table 7. When  $R$  increases from  $r$  to 120, the MTTF curves of six kinds of ECAs are shown in Fig. 12.

Fig. 12(a) shows the MTTF curves of six kinds of cell elimination ECAs with different  $R$ . In six kinds of cell elimination ECAs, when  $R$  increases from  $r$  to 120, the

MTTF values of ECAs increase to the maximum first, and then the MTTF values of ECAs are decreasing continuously. From ECA1 to ECA6, when  $R$  equals 20, 36, 45, 72, 83 and 94 respectively, the MTTF values of six kinds of cell elimination ECAs reach the maximum.

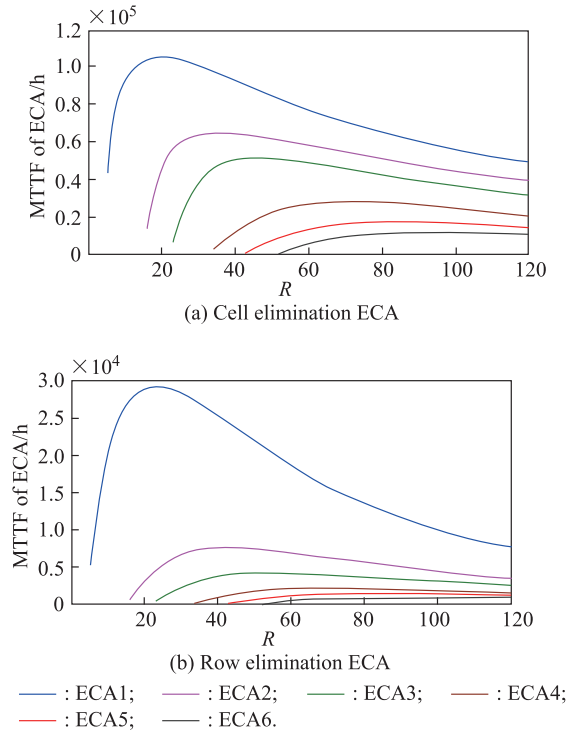


Fig. 12 MTTF curves of six kinds of ECAs with different  $R$

In the cell elimination ECA, the theoretical maximum number of self-repairing is  $R(C - c)$ . Therefore, with the increasing of  $R$ , the theoretical maximum number of self-repairing is increasing, and the MTTF of the ECA is increasing. With the further increasing of ECA scales, the number of electronic cells is increasing, and the failure rate of the ECA is also increasing. Therefore, in six kinds of cell elimination ECAs, when the MTTF values reach the maximum, the MTTF values will decrease with the increasing of  $R$ .

As shown in Fig. 12(a), in the increasing process of MTTF, the smaller the scale is, the larger the growth rate of MTTF is. In the ECA, the smaller the scale is, the lower the failure rate of ECA is. When  $R = r$ , the numbers of electronic cells in ECA1 to ECA6 are 50, 320, 690, 2 040, 3 440 and 5 200 respectively. At the same time,  $R$  increases by 1, the number of self-repairing increases by  $C - c$ , that is, the numbers of self-repairing increase by 4, 8, 12, 22, 44 and 52 respectively.

Fig. 12(b) shows the MTTF curves of six kinds of row elimination ECAs with different  $R$ . In six kinds of row elimination ECAs, when  $R$  increases from  $r$  to 120, the

MTTF values of ECAs increase to the maximum first, and then the MTTF values of ECAs are decreasing continuously. From ECA1 to ECA6, when  $R$  equals 23, 43, 54, 69, 81 and 93 respectively, the MTTF values of six kinds of row elimination ECAs reach the maximum.

In the row elimination ECA, the theoretical maximum number of self-repairing is  $R - r$ . Therefore, with the increase of  $R$ , the theoretical maximum number of self-repairing is increasing, and the MTTF of ECA is increasing. In the increasing process of  $R$ , the number of electronic cells is increasing, and the failure rate of the ECA is also increasing. In six kinds of row elimination ECAs, when the MTTF values reach the maximum, the MTTF values will decrease with the increasing of  $R$ .

As shown in Fig. 12(b), in the increasing process of MTTF, the smaller the scale is, the larger the growth rate of MTTF is. In the ECA, the smaller the scale is, the lower the failure rate of ECA is. When  $R = r$ , the numbers of electronic cells in ECA1 to ECA6 are 50, 320, 690, 2 040, 3 440, 5 200 respectively. At the same time,  $R$  increases by 1, the number of self-repairing increases by 1 too.

#### 4.2.4 Effect on ECA reliability with the changing of $C$

In order to analyze the effect on the ECA reliability with different  $C$ , assume  $\lambda_f = 6E-6$  h,  $p = 0.96$ , and  $R, r$  and  $c$  are shown in Table 7. In the process that  $C$  increases from  $c$  to 100, the MTTF curves of six kinds of ECAs are shown in Fig. 13.

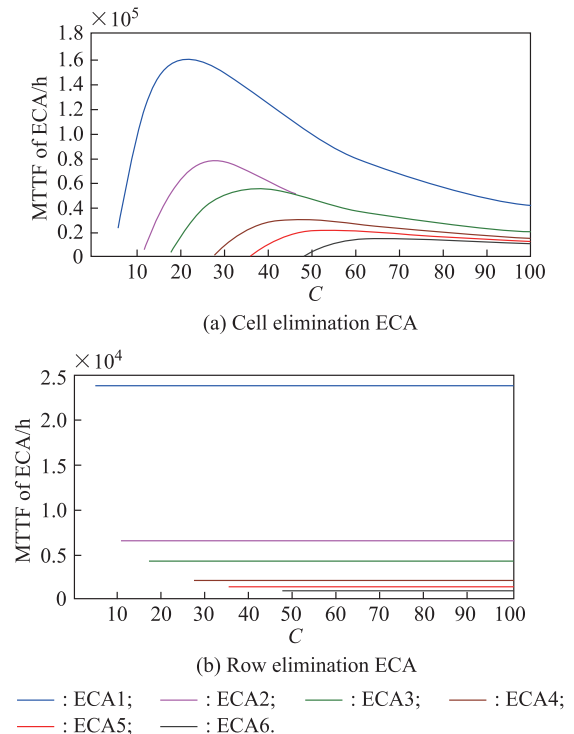


Fig. 13 MTTF curves of six kinds of ECAs with different  $C$

Fig. 13(a) shows the MTTF curves of six kinds of cell elimination ECAs with different  $C$ . In six kinds of ECAs, when  $C$  increases from  $c$  to 100, the MTTF values of ECAs increase to the maximum first, and then the MTTF values of ECAs are decreasing continuously. From ECA1 to ECA6, when  $C$  equals 22, 28, 38, 48, 55 and 67 respectively, the MTTF values of six kinds of cell elimination ECAs reach the maximum.

In the cell elimination ECA, the theoretical maximum number of self-repairing is  $R(C - c)$ . Therefore, with the increase of  $C$ , the theoretical maximum number of self-repairing is increasing, and the MTTF of the ECA is also increasing. In addition, with the increase of  $C$ , the number of electronic cells is increasing, and the failure rate of the ECA is also increasing. Therefore, in six kinds of cell elimination ECAs, when the MTTF values reach the maximum, the MTTF values will decrease with the increasing of  $C$ .

In the increasing process of MTTF, the smaller the ECA scale is, the larger the growth rate of MTTF is. In the ECA, the smaller the ECA scale is, the lower the failure rate of the ECA is. When  $C = c$ , the numbers of electronic cells in ECA1 to ECA6 are 72, 336, 936, 2 428, 3 600 and 5 760 respectively. At the same time,  $C$  increases by 1, the number of self-repairing increases by  $R$ , that is, the numbers of self-repairing increase by 12, 28, 52, 86, 100 and 120 respectively.

Fig. 13(b) shows the MTTF curves of six kinds of row elimination ECAs with different  $C$ . In six kinds of ECAs, the MTTF values do not change with the increase of  $C$ . In the row elimination ECA, the failing of one active cell provokes the elimination of the corresponding ECR. Therefore, the number of  $C$  does not affect the MTTF of the ECA.

Above all, the MTTF of the ECA can be improved by increasing  $p$  and reducing  $\lambda_f$ . In the ECA, the higher  $p$  is, the higher the MTTF is. At the same time, the lower  $\lambda_f$  is, the higher the MTTF of the ECA is. In the increasing process of  $R$ , the MTTF of the ECA increases to the maximum first, and then it will decline continuously. Similarly, in the increasing process of  $C$ , the MTTF of the ECA increases to the maximum first, and then it will decline continuously in the cell elimination ECA.

## 5. Conclusions

This paper analyzes the structural characteristics of the ECA, and the embryonic cell and its corresponding I/O resources can be equivalent to an FU. Introducing the FU fault detection coverage  $p$  to ECA reliability evaluation, a new ECA reliability evaluation method is proposed based

on the Markov status graph model.

Selecting the most widely used ECA reliability evaluation method based on the  $k$ -out-of- $n$  system reliability model as the comparison object, and experimental results indicate that the proposed ECA reliability evaluation model based on the Markov status graph model can evaluate the reliability of ECA effectively and more accurately. Based on the verification of the proposed method, parameters in the ECA are analyzed, and the ECA reliability variation law is got. In the ECA, the reliability of the ECA can be improved effectively by increasing the FU fault detection coverage rate and reducing the FU failure rate. In the process of increasing the scale of the ECA, the reliability will increase first, then it will reach the maximum, and after that it will decrease continuously. The ECA reliability variation law is able to guide the optimization design of the ECA from the theoretical point of view.

Based on the analysis of parameters in the ECA, in the future, more effective fault detection methods will be researched so as to improve the ECA reliability. At the same time, the optimization selection method of  $R$  and  $C$  in the ECA will be studied so as to guide the optimization design of the ECA layout.

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