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Green system reliability assessment method based on life cycle: Resources and economical view

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A B S T R A C T

The traditional assessment method of system reliability is based on unit reliability and probability theory, but the rationale behind this method of assessment does not consider resources and economy. Unit reliability tests tend to consume resources and economy, and consequently, reliability assessment of large systems tends to consume a large amount of resources and economy. Taking the series system and parallel system as examples, this study proves that the traditional assessment method of system reliability is unreasonable, especially from the perspective of resources and economy, as it does not meet green economy and sustainable development goals. The system life cycle diagram model is established on the unit life cycle. A green assessment method of system reliability is proposed from the resources and economy perspectives. This proposed method does not depend on the number of units and does not require the consumption of a large amount of resources and economy. This study promotes sustainable and cleaner production. The green assessment method of system reliability is applied to the series system and parallel system to assess system reliability.

1. Introduction

Green system reliability refers to the probability that a system completes its specified duty under specified conditions and for a specified time. For system reliability assessment: the unit reliability R_i is the basis, the reliability block diagram (RBD) is the logical architecture, the binomial distribution in probability theory is the calculation method, the calculated result R_s is taken as the assessment result of system reliability. The series system and parallel system are basic system configuration types, and their reliability assessments are the basis for complex systems. The traditional assessment methods of system reliability include Monte Carlo method, network theory, fuzzy theory and so on.

In the literatures, using sequential Monte Carlo simulation, Xiao et al. (2018) incorporated network topology optimization into system reliability assessment. Based on the semi-Markov process, Li et al. (2018) proposed a method based on the Markov renewal equation for assessing the reliability of phased mission systems, and its accuracy was verified using the Monte Carlo method. Lee and Pan (2018) proposed a nonparametric Bayesian network method for assessing system reliability at early design stages. Based on the Bayesian network and evidence theory, Mi et al. (2018) analyzed the reliability of a complex multi-state system with common cause failure. For reliability assessment of the Bayesian system, Jackson and Mosleh (2016) proposed a methodology that allows the incorporation of exact or certain data sets within complex multi-state on-demand continuous life metric systems. The wolf pack algorithm was proposed as a modified strategy for optimizing system reliability during the restoration process; thus, sensitivity, effectiveness, and expandability are analyzed (Ren et al., 2019). Wu et al. (2019) presented the sharing mechanism in system design and applied the universal generating function to assess system reliability.

In addition, based on the active learning Kriging (ALK) model and a truncated candidate region (TCR), Yang et al. (2018) proposed an ALK-TCR model for analyzing system reliability with multiple

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failure modes. Zhou et al. (2018) proposed a converter-level reliability analysis method for assisting design decision on the fuel cell during the power conditioning stage. Because of the age-related failure of power transformers, Awadallah et al. (2015) modified the end-of-life failure model to assess system reliability. At the subsystem and system levels, Guo et al. (2018) analyzed system reliability using the Bayesian melding method, which integrates expert knowledge and data. Based on fuzzy probability, Li et al. (2017) proposed a system reliability analysis method that considers system risk under different conditions.

Higher reliability is accompanied by higher economic input. Thus, system economy should be considered, as well as system reliability. For instance, Awad et al. (2014) proposed a two-stage model for the allocation of distributed storage units in distribution a system that considers the reliability benefit of improving system reliability. Zhou et al. (2016) provided a review simultaneously assessing the reliability and economics of a power system with renewables, and found that the types and scales of renewable energy generation have significant impact on system reliability and economics. Connell et al. (2019) considered market prices and normal water availability to assess power system operation from the perspective of system reliability and economics.

A system is composed of many product units, and different product units have different characteristic life cycles. Thus, a system has different life cycles that directly impact system reliability. The life cycle of resources makes system reliability assessment more complicated. Life cycle assessment (LCA) is an effective method for assessing system impact on resources. In view of graph theory, Wang et al. (2015) proposed an LCA optimization methodology for a combined cooling heating and power system incorporating solar energy and natural gas. Wong et al. (2016) summarized the latest developments in single-crystalline and multi-crystalline silicon photovoltaic systems from the perspective of LCA. Zanghelini et al. (2018) assessed the LCA context using multi-criteria decision analysis techniques and mapped the application of multi-criteria decision analysis. Pomponi and Lenzen (2018) demonstrated that hybrid LCA is accurate than process-based LCA. He et al. (2019) proposed a product sustainability assessment method that avoids the closed loops of assessment indicators.

A management system is essential for sustainable development. In China, Zhou et al. (2019) established a sustainability assessment model based on LCA that assesses environmental performance and resource consumption. Therefore, it is reasonable to assess system reliability based on life cycle as forecasting the remaining useful life can help assess the system reliability. Based on particle swarm optimization and support vector machines, Nieto et al. (2015) proposed a hybrid prediction model for the remaining useful life of aircraft engines and assessed its reliability. Barone and Frangopol (2014) investigated a probabilistic method for life cycle maintenance of structural systems and applied the method on series, parallel, and series-parallel systems.

The reliability assessment of power system is evident that reliability assessment is more complex because of several unpredictable influencing factors and the complex structure of a power system. For power system reliability assessment, Zhang et al. (2016) established a model of optimal resource allocation with modified semi-Markov processes to calculate the probability of cyber-attacks against supervisory control and data acquisition systems. Xu and Chung (2016) extended distribution system reliability assessment to incorporate the contribution of electric vehicles in different operational modes. Lei and Singh (2017) thoroughly studied generating appropriate state space as dependent failures using conventional non-sequential sampling methods.

For distribution system reliability assessment, Adefarati and Bansal (2017) proposed a comprehensive system reliability assessment method that satisfies the consumer requirements of different distribution system such as wind turbine generators, electric storage systems, and photovoltaic systems. Zhang et al. (2017) established a mean time-to-compromise model for considering different attack levels and various vulnerabilities in wind farm supervisory control and data acquisition systems and assessed the power system reliability. Nguyen and Mitra (2018) presented the impact of the intermittence and low inertia of wind power and proposed a method for assessing its system reliability at high wind penetration under frequency stability constraints. However, based on time-dependent failure rate models and long-term mission profiles, Lopes and Borges (2015) assessed power system reliability under the integration of wind generation and small hydropower plants and analyzed for correlations between these energy sources that can benefit future supply. Reliability assessment is complex for integrated storage power systems with hydropower, wind power, thermal power, and other power structures. Xu et al. (2019) established a hybrid power system model for solar-wind-hydro power that is integrated using the pumped storage station model, with its feasibility considered under steady and fault scenarios.

The traditional assessment method of system reliability is based on probability theory and the RBD. Its disadvantages are that the unit reliability test requires a lot of resources and economy, is difficult to complete, and sometimes does not conform to the green development concept. Based on LCA and resource management, we propose a green assessment method of system reliability. This method can improve the rationality of system reliability assessment results and manage resources synthetically, which can yield large reductions in resources needed. The remainder of this study is organized as follows: In Section 2, the problems of system reliability assessment are discussed. Based on life cycle assessment, in Section 3, assumptions, the SLCD model, and mathematical operations are proposed. In Section 4, the green assessment method of system reliability is proposed and applied. Conclusions are presented in Section 5.

2. Problems of traditional assessment method for system reliability

In engineering design and application, this study is found there are certain limitations to the assessment equations of traditional system reliability. Primarily, the reliability assessment results of large complex systems are quite different from the actual working states. This study illustrates the limitations of the assessment equations of reliability in series systems and parallel systems.

2.1. Reliability assessment of a series system

Series system: if all units in the system are working properly, the system can work properly, that is called a series system. The series system RBD is shown in Fig. 1.

The assessment equation of series system reliability is presented in Equation (1).

$$R_{s1} = \prod_{i=1}^{n} R_i \left(\mathrm{i} = 0, 1, \ \&, \mathrm{n} \right) \tag{1}$$

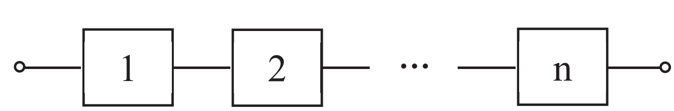

Fig. 1. Series system RBD.

2.1.1. *The series system reliability cannot be ensured in engineering*

Example 1. Assumed that a series system is composed of n units with reliability $R_i = 0.9999$. If there are more and more units, the system is larger and larger. The system reliability R_s is calculated using Equation (1), and the results are presented in Table 1.

- Table 1 found the system reliability R_s decreasing with n increasing. Next, we make three assumptions to be discussed from the perspective of resources and economy.
- Assumption 1: The system reliability $R_s = 0.00005$ is too low to be accepted in engineering design because the unit reliability $R_i = 0.9999$ and unit number $n = 10^5$. $R_i = 99.99\%$ is the best unit reliability, and if that cannot compose a series system with high reliability, how can this study design this series system?
- Assumption 2: The system reliability $R_s = 0.9$ and unit number $n = 10^5$. The unit reliability can be calculated using Equation (1) and its result is $R_i = 0.9999989$. If $R_i = 0.9999989$, for the selection of units for a full probability reliability test, the testing unit total number is 10^7 and the failure unit number is no more than 11. From the perspective of resources and economy, how much manpower and material resource will be consumed?
- Assumption 3: If the system of assumption 2 is composed of 10^5 different units, we select 10^{12} units for a reliability test. From the perspective of resources and economy, how much manpower and material resource will be consumed?

2.1.2. *The assessment method for series system reliability is unreasonable*

Example 2. A series system A is composed of units A1 and A2 while a series system B is composed of units B1 and B2, as shown in Fig. 2a and 2b. Assuming that unit reliability is $R_{A1} = 0.4$, $R_{A2} = 0.9$, $R_{B1} = 0.6$, $R_{B2} = 0.6$ at time t, then we compare their system reliability.

The system reliability is calculated using Equation (1) and the assessment results of system reliability are as follows:

$$R_{sA} = 0.4 \times 0.9 = 0.36$$

$$R_{sB} = 0.6 \times 0.6 = 0.36$$

This study finds that $R_{sA} = R_{sB}$. Thus system A and B have equal reliability.

Based on Equation (1), two different series systems have the same reliability in Example 2. If one unit is the weakest, the system may happen to fail subsequently. Because $R_{A1} < R_{B1} = R_{B2} < R_{A2}$, the reliability of system A is worse than that of system B. If $R_{sA} = R_{sB}$ is used as the basis for judging system reliability, then there are inconsistent conclusions between theory and practice. The result shows that the assessment method for series system reliability is unreasonable.

The unit that composed the system has two working states: *normal* and *failure*, which are expressed as *1* and *0*. Taking the series system as an example, there is a logical *AND* relationship among units that composed the system. When anyone of the units fails, the system fails accordingly. The operating state of the system changes from the normal state, $R_s = 1$, to the failure state, $R_s = 0$, and a step change occurs, as shown in Fig. 3 (selected $n = 6$).

Table 1
Calculation results for system reliability.

n	10^2	10^3	10^4	10^5
R_s	0.99	0.905	0.368	0.00005

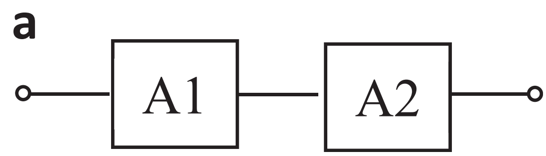

Fig. 2a. Series system A.

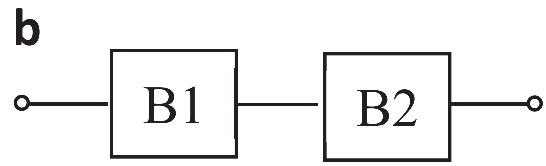

Fig. 2b. Series system B.

The vertical box of the horizontal axis in Fig. 3 represents the number of units that work properly. If the system works properly and the number of unit failures is not considered, the horizontal axis t represents the number of units, decreasing from 6 to 1 with time. From $n = 5$ to $n = 1$ is impossible because the system would have stopped working at $n = 5$. Next, based on unit reliability, it is unreasonable to assess the system reliability using Equation (1).

2.2. *Reliability assessment of a parallel system*

Parallel system: if at least one unit in the system can work properly, the system can work properly, that is called a parallel system. The parallel system RBD is shown in Fig. 4.

The assessment equation of parallel system reliability is presented in Equation (2).

$$R_{s2} = 1 - \prod_{i=1}^{n}(1 - R_i)\left(\mathrm{i} = 0, 1, \ldots, \mathrm{n}\right) \tag{2}$$

Example 3. Assuming that a parallel system composed of n identical units with reliability $R_i = 0.01\%$. The RBD is shown in Fig. 4. For n with different values, the system reliability R_s is calculated using Equation (2), and the results are presented in Table 2.

Table 2 established if the unit reliability is low. System reliability

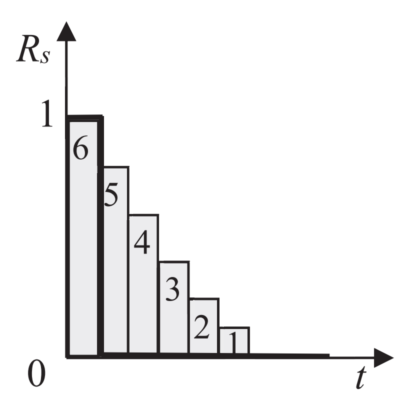

Fig. 3. Series system failure process diagram (selected $n = 6$).

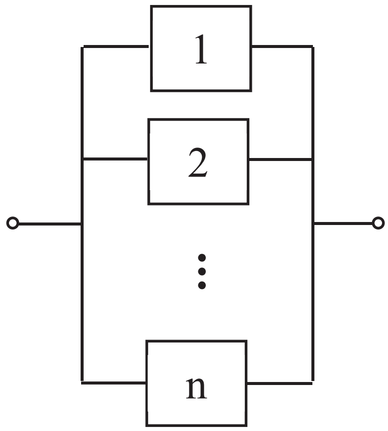

Fig. 4. Parallel system RBD.

Table 2
Calculation results for parallel system reliability.

n	10^2	10^3	10^4	10^5
R_s	0.01	0.095	0.632	0.99995

can be increased simply by increasing the unit number. Comparing the values in Table 2 is understandable. The design of system reliability will not be carried out in engineering because of the immense resources required. When designing parallel systems, designers will not adopt a scheme that improves the reliability of parallel systems by simply increasing the number of low-reliability units.

When calculating the reliability of parallel systems, one problem is that the actual working state of unit is ignored. The unit carries on with the reliability test at the rated working state, and the unit reliability is obtained. When the unit works under overload conditions, the actual reliability is lower than that obtained from the reliability test. When the unit works under light load, the actual reliability is higher than that obtained through the reliability test.

From the definition of a parallel system, it can be inferred that the unit works under light load. Consequently, the reliability of the parallel system calculated using Equation (2), which is different from the actual situation, the limitation of the reliability assessment is proved as an objective fact for parallel systems.

- Assumption 1: The unit works at the rated state in a parallel system, and then the parallel system is degraded to a series system. Thus, the RBD is degraded from Figs. 1–4, which is contrary to the reliability definition of a parallel system. The working states of unit are divided into three states: *light load*, *rated*, and *overload.* Based on the definition of a parallel system, the parallel system works properly, even when only one unit is working properly. During system design, the rated working state of a unit meets the normal working needs of the system. To improve system reliability, more components are selected in parallel. Thus the unit is under light load. If one unit fails while the unit is working at its rated state, the others become *overloaded.* The unit now has low reliability, and thus the system quickly fails. This does not meet the basic reliability definition of a parallel system.
- Assumption 2: If the reliability equation of parallel systems is right, the following assumptions need to be met:
  - o Assumption 2.1: The unit reliability of the system is independent of the unit working state, such as *overload*, *rated load*, and *light load.*
  - o Assumption 2.2: The units of the parallel system may fail in turn, and the actual working state of system during the failure process is shown in Fig. 5a (selected n = 6).

Fig. 5a showed $R_s = 1$ denotes that the system can work properly, while $R_s = 0$ denotes that the system cannot work properly. The vertical block diagram denotes the number of units that can work normally. Fig. 5a shows that the number of units working normally decreases with an increase in unit failure, but the system can still work properly, i.e., $R_s = 1$. Based on Equation (2), the theoretical reliability of a parallel system is expressed approximately as shown in Fig. 5b.

Example 4. It is assumed in the parallel system RBD shown in Fig. 4. The n units have the same reliability. Here, i represents the failure number in a parallel system, which happens from 1 to n in turn. The reliability results of the parallel system are listed in Table 3 as i increases in turn.

The parallel system reliability is calculated only in simple cases in Table 3. If the unit reliability is different and the mathematical combinations of unit failure are different, the reliability calculation will be very complex and the system reliability is uncertain.

3. Life cycle

3.1. Assumptions of unit life cycle

The system is composed of units, and the system reliability is calculated based on unit reliability. At present, the reliability of unit and system is calculated based on the theory of statistical probability. Considering examples 1, 2, 3, and 4, this study assumes that if the system reliability is assessed based only on probability theory, there are some limitations in the mathematical method. The life cycle of a unit has inherent characteristics. The system is composed of units with different logical configurations. Thus, system reliability assessment needs to consider the life cycle, and not only probability theory. Hence, this study seeks to redefine the assessment method of system reliability. Below are some assumptions:

- Assumption 1: n units with the same characteristics are selected for the reliability test. The test results are arranged in ascending order as per the failure time, and a life set T is formed, such that $T = \{t_1, \ t_2, \ \cdots, \ t_{n-1}, \ t_n\}$.

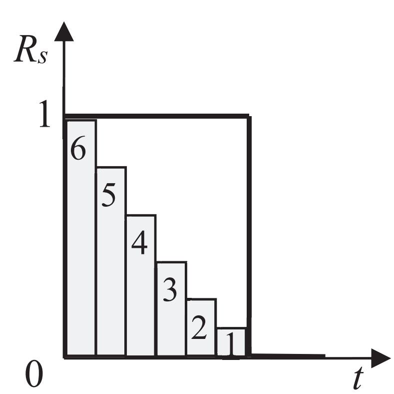

Fig. 5a. Practical reliability of a parallel system.

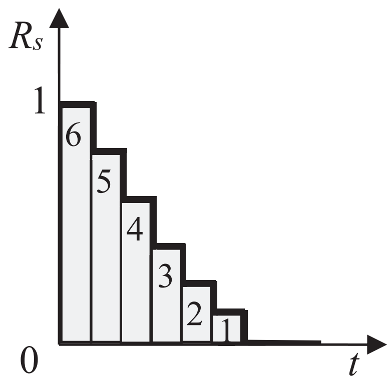

Fig. 5b. Theoretical reliability of a parallel system.

Table 3
Reliability results of a parallel system.

i	1	…	k	…	n-1	n
R_{s2}	1-F	…	1-F^k	…	1- F^{n-1}	1- F^n

- Assumption 2: A series system is composed of n units, based on assumption 1. In the unit reliability test, the unit reliability decreases after t_1. For example, at t_2, the unit reliability $R_2 < 1$; when the system works till time t_2, the first unit t_1 has failed such that the system does not work properly. The system reliability should be 0, i.e., $R_s(t_2) = 0$. As the system works to t_2, the series system reliability result R_s can be calculated using Equation (1), i.e., $R_s\,(t_2) < 1$. Equation (1) is in probability theory, but cannot accurately describe the actual state based on assumption 1. In the series system, as the first unit fails, the system stops working, and the remaining (n-1) units also stop working with normal state; thus, their reliability is not considered. The assessment problem of series system reliability is transformed into a time problem of initial failure t_1, which is consistent with the failure process described in Fig. 3.
- Assumption 3: A parallel system is composed of n units, based on assumption 1. Before t_n, the unit reliability has been decreasing, but the system can still work properly. For example, at t_{n-1}, the unit reliability is $R_{n-1} < 1$; when the system works to t_{n-1}, the parallel system reliability result R_s can be calculated using Equation (2), $R_s(t_{n-1}) < 1$. The system works properly, and thus system reliability $R_s(t_{n-1}) = 1$. Based on assumption 1, Equation (2) is right only in probability theory, and cannot accurately describe the actual state. Consequently, the assessment problem of parallel system reliability is transformed into a time problem of final failure t_n, which is consistent with the description in Fig. 5a.
- Assumption 4: Each unit does not fail within the specified time t_0 and has passed the reliability test. In theory, for a system, it can be guaranteed that there will be no failure in the specified time t_0, and the reliable operation of the system is independent of the number of units. Under certain assumptions, the problems of the series system in Example 1 and the parallel system in Example 4 can be solved.

In summary, the limitations and directions of system reliability assessment are discussed from the perspective of unit life cycle. If the system reliability assessment is redefined based on the unit life cycle, the problem of the system reliability being affected by the number of units can be solved, and the problem of the assessment result being inconsistent with the actual situation can also be solved.

3.2. Established system life cycle diagram (SLCD) model

If the life cycle characteristic of a unit is expressed by Equation (3), the real part t_0 represents the inherent reliability of units, and there is no failure unit in the reliability test before t_0. The imaginary part $R(\mathrm{t})$ denotes that although the individual unit is still working normally at time t, there is a failure probability, but the *failure* does not actually occur, so it is represented by $R(\mathrm{t})\mathrm{i}$.

$$T = t_0 + R(\mathrm{t})\mathrm{i} \tag{3}$$

The reliability test is carried out for some units that compose the system and the statistical test data are analyzed. The unit reliability is expressed by Equation (3). Through the transformation and unification of dimensional units, units with different physical quantities are converted for the assessment of system reliability; transformed into the same unit, such as time or frequency, which have important application in engineering.

Example 5. It is assumed that there are three units A_1, A_2, and A_3, with different characteristics, on which the reliability test is carried out. The test data is transformed into the same unit and expressed as Equation (4). In Equation (4), $R(t)$ is not a generic function because different units may have different $R(\mathrm{t})$. A_1 is expressed as $t_{01} + R(t_1)$, A_2 as $t_{02} + R(t_2)$ and A_3 as $t_{03} + R(t_3)$.

$$T = \begin{Bmatrix} t_{01} \\ t_{02} \\ t_{03} \end{Bmatrix} + \begin{Bmatrix} R(t_1) \\ R(t_2) \\ R(t_3) \end{Bmatrix} i \tag{4}$$

Working assumption 1: The system life cycle is expressed by the unit life cycle and considers the configuration of the system's composition.

Working assumption 2: The unit life cycle is unified to the same unit, and the reliability curve is expressed in the same coordinate system. The life cycle curve of the system is calculated using a mathematical method called the system life cycle diagram (SLCD).

Example 6. The reliability curves of three different units are selected for display to explain the SLCD composition. There may be three basic cases, such as three curves non-intersect, two curves intersect, and three curves intersect, as shown in Fig. 6a, 6b, and 6c.

3.3. SLCD mathematical operations

Fig. 6 showed SLCD applications in different situations. The corresponding SLCD logical relationships and logical operations are defined subsequently. The logical relationships include *AND* and *OR* expressed as the symbols "∩" and "∪". Their logical operation symbols are "∧" and "∨," which denote minimum value and maximum value. For large and complex systems, the operations of minimum and maximum are convenient and fast with computer-aided calculation, and the results are accurate.

Definition 1. Logical *AND* relationship

$$\mathrm{A} = \mathrm{A}_1 \wedge \ldots \wedge \mathrm{A}_n = \min \begin{Bmatrix} t_{01} \\ \vdots \\ t_{0n} \end{Bmatrix} + \min \begin{Bmatrix} R(t_1) \\ \vdots \\ R(t_n) \end{Bmatrix} i \tag{5}$$

With the curve increasing in the SLCD, the intersections of the curve also increase. The corresponding calculation is increasingly more complex. In engineering, $R(\mathrm{t})$ cannot be infinitely small. Based on the design needs, the system reliability level $R(t_R)$ can be

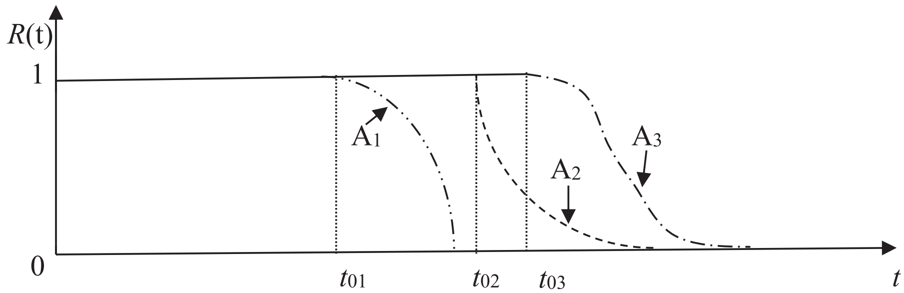

Fig. 6a. Three curves non-intersect SLCD.

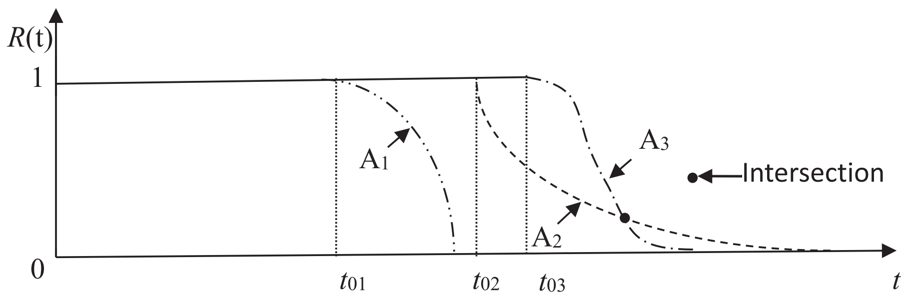

Fig. 6b. Two curves intersect SLCD.

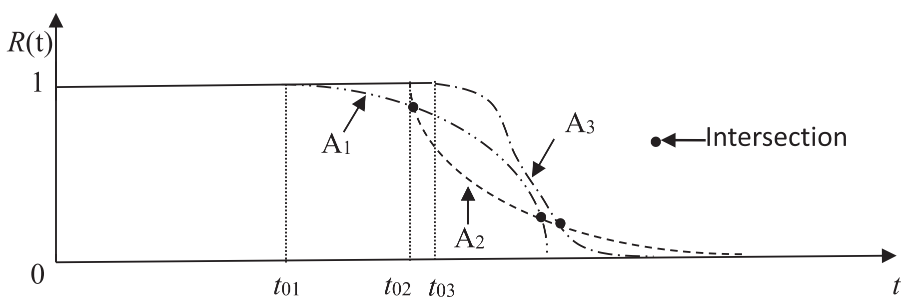

Fig. 6c. Three curves intersect SLCD.

specified, in which t_R denotes the reliable life.

$$A = A_1 \wedge \ldots \wedge A_n = \min\left\{\begin{matrix} t_{01} \\ \vdots \\ t_{0n} \end{matrix}\right\} + \min R(t_R) i \quad (6)$$

where min $R(t_R)$ is the nearest coordinate point to the origin (0, 0) on the vertical axis curve R.

Definition 2. Logical *OR* relationship

$$A = A_1 \vee \ldots \vee A_n = \max\left\{\begin{matrix} t_{01} \\ \vdots \\ t_{03} \end{matrix}\right\} + \max\left\{\begin{matrix} R(t_1) \\ \vdots \\ R(t_3) \end{matrix}\right\} i \quad (7)$$

$$A = A_1 \vee \ldots \vee A_n = \max\left\{\begin{matrix} t_{01} \\ \vdots \\ t_{0n} \end{matrix}\right\} + \max R(t_R) i \quad (8)$$

When the logic *OR* operation is carried out, the intersections problem will also occur. Thus, it is necessary to specify the reliability level $R(t_R)$.

where max $R(t_R)$ is the farthest coordinate point to the origin (0, 0) on the vertical axis curve R.

Because $R_i(t) \neq 1$, the time t_0 is different for different units, such that the reliability curve is different in $R_i(t) < 1$. If there are three or more units in Fig. 6 that are applied to the same system, their relationship needs to be considered and the expression redefined.

Example 7. Logical *AND* calculation in Fig. 6.

In Fig. 6a, $A = A_1 \wedge A_2 \wedge A_3 = t_{01} + R(t_1) i$

In Fig. 6b, $A = A_1 \wedge A_2 \wedge A_3 = t_{01} + R(t_1) i$

The relation diagrams of logic *AND* for Fig. 6a and 6b are shown in Fig. 7.

Fig. 6c is calculated using Equation (5), and the intersections are complicated. If $R(t_R)$ is specified in Fig. 6c, the corresponding t_R is obtained in Fig. 8a. The curves intersections are expressed as a black point. The specified system reliability R intersects with the first life curve and is expressed as a gray point. The corresponding reliable life is expressed as t_R. If there are many curves, their intersections are more and more. Thus, the system reliability calculation method

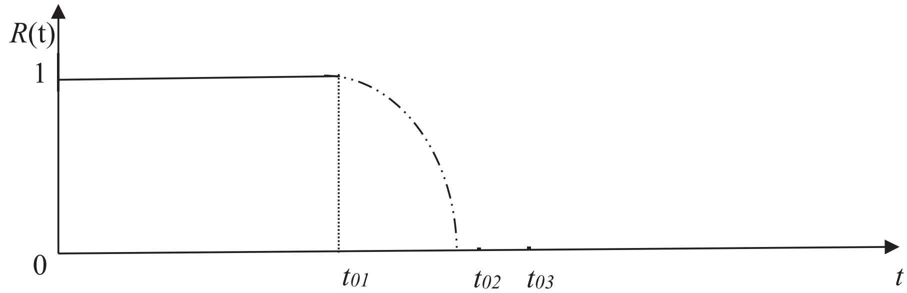

Fig. 7. Relation diagram of logic *AND* in Fig. 6a and 6b.

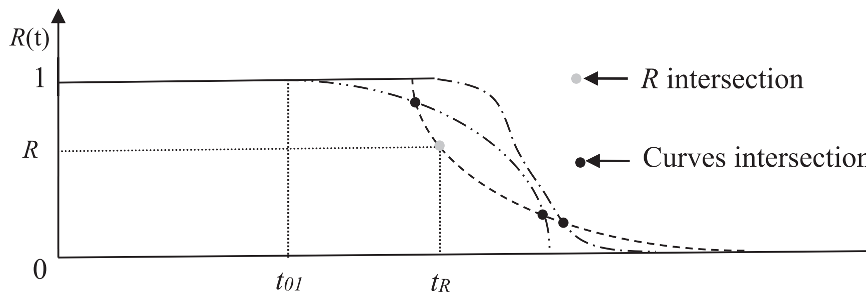

Fig. 8a. Relation diagram of logic *AND* in Fig. 6c.

is specified in Equation (6).

If the reliability $R(t_R) = 0.5$, then t_R is the median life $t_{0.5}$.

$$A = A_1 \wedge A_2 \wedge A_3 = t_{01} + \min R(t_{0.5})i$$

Consequently, the relation diagrams of logic *AND* in Fig. 6c can be simplified as shown in Fig. 8b.

Example 8. Logical *OR* calculation in Fig. 6.

$$A = A_1 \vee A_2 \vee A_3 = T = \max\begin{Bmatrix} t_{01} \\ t_{02} \\ t_{03} \end{Bmatrix} + \max\begin{Bmatrix} R(t_1) \\ R(t_2) \\ R(t_3) \end{Bmatrix} i$$

In Fig. 6a, $A = A_1 \vee A_2 \vee A_3 = t_{03} + R(t_3)i$, the relation diagram of logic *OR* is shown in Fig. 9.

If R is specified in Fig. 6b and 6c, the corresponding t_R can be obtained and shown in Fig. 10a.

If the reliability R $R(t_R) = 0.5$ in Fig. 6b and 6c, then t_R is the median life $t_{0.5}$.

$$A = A_1 \vee A_2 \vee A_3 = t_{03} + R(t_{0.5})i$$

Consequently, the relation diagram of logic “OR” in Fig. 6b and 6c can be simplified and shown in Fig. 10b.

4. Green assessment method of system reliability

In the preceding section, the problems of system reliability assessment are discussed based on statistical probability theory. The series system and parallel system are taken as examples. Based on the characteristics of unit life cycle, the definitions and operations of SLCD are proposed. Here, the SLCD is applied to system reliability assessment and it is called green assessment method of system reliability. The series system and parallel system are taken as examples, and their assessment equations are defined.

4.1. SLCD assessment of series system reliability

Definition 3. In a series system, the logical relation of the units is *AND*. The design needs and the reliability level $R(t_R)$ can be specified. Based on Equations (5) and (6), the assessment of series system reliability is presented in Equation (9) using SLCD.

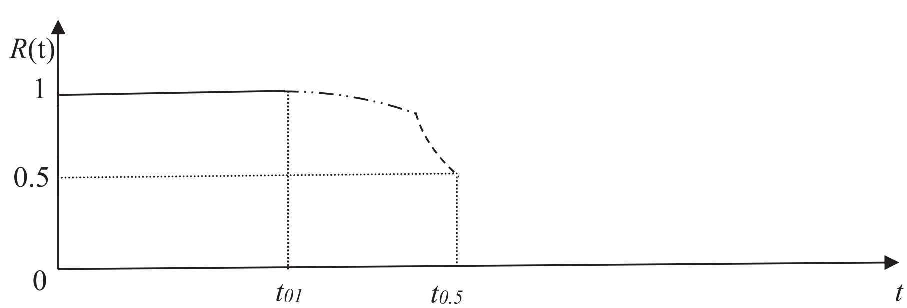

Fig. 8b. Relation diagram of logic *AND* in Fig. 6c ($R(t_R) = 0.5$).

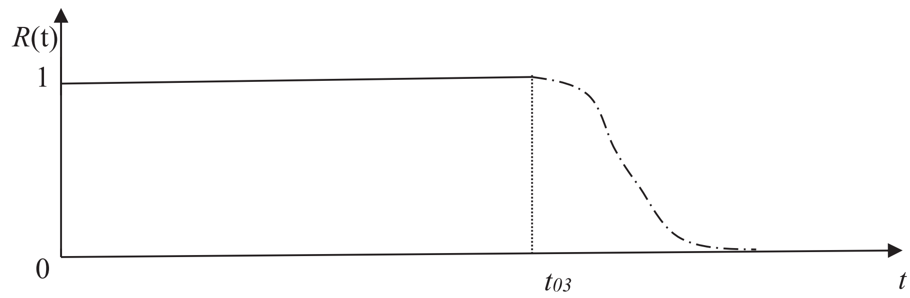

Fig. 9. Relation diagram of logic *OR* in Fig. 6a.

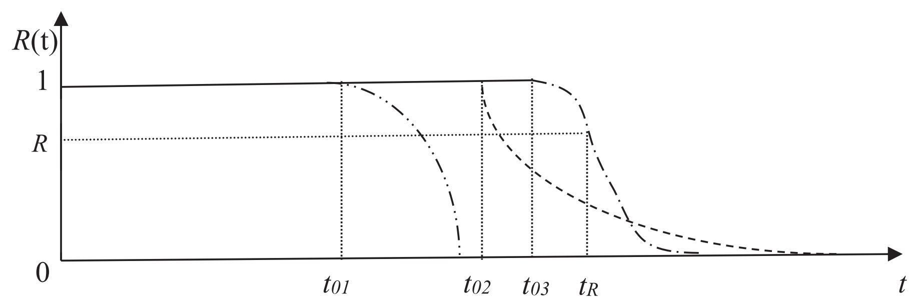

Fig. 10a. Relation diagram of logic *OR* in Fig. 6b and 6c.

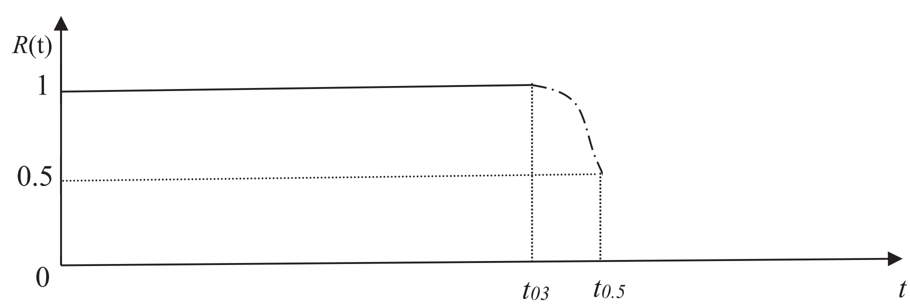

Fig. 10b. Relation diagram of logic OR for Fig. 6b and 6c.

$$R_s = R_1 \cap \ldots \cap R_n = R_1 \wedge \ldots \wedge R_n = \min\begin{Bmatrix} t_{01} \\ \vdots \\ t_{0n} \end{Bmatrix} + \min\begin{Bmatrix} R(t_1) \\ \vdots \\ R(t_n) \end{Bmatrix} i = \min\begin{Bmatrix} t_{01} \\ \vdots \\ t_{0n} \end{Bmatrix} + \min R(t_R) i \tag{9}$$

If the series system is composed of the same units, then

$$R_s = R_1 \cap \ldots \cap R_n = R_1 \wedge \ldots \wedge R_n = R \tag{10}$$

The Equation (10) result shows that the system reliability is the same as the unit reliability. The series system reliability is not directly related to the number of units and is related to the unit life cycle. The Equation (10) is applied in Example 1, some questions are solved. Such as, 1. The assessment result of system reliability will not be reduced with unit numbers increasing. 2. The unit numbers of reliability test will be reduced to save resources and economy.

Applied in assumption 1: If the system is composed of 10^5 different units, system reliability $R_s = R_i$. So the system reliability will not be reduced with the unit numbers increasing. Compared traditional method and green method in Example 1, results are as shown in Table 4.

Applied in assumption 2: If the system is composed of 10^5 same units, system reliability $R_s = 0.9$. Based on assumption 1, unit reliability is $R_i = 0.9$, so we will select 100 units to do reliability test. Compared traditional method and green method, their unit numbers of reliability test are shown in Table 5. The number of reliability test will be reduced to save resources and economy.

Applied in assumption 3: If the system is composed of 10^5 different units in assumption 2. We will select 10^7 units to do

Table 4
Compared results of system reliability.

n	10^2	10^3	10^4	10^5
Traditional method R_s	0.99	0.905	0.368	0.00005
Green method R_s	0.9999	0.9999	0.9999	0.9999

Table 5
Compared n of reliability test.

Number	Traditional method	Green method
n	10^7	10^2

Table 6
Compared n of reliability test.

Number	Traditional method	Green method
n	10^{12}	10^{7}

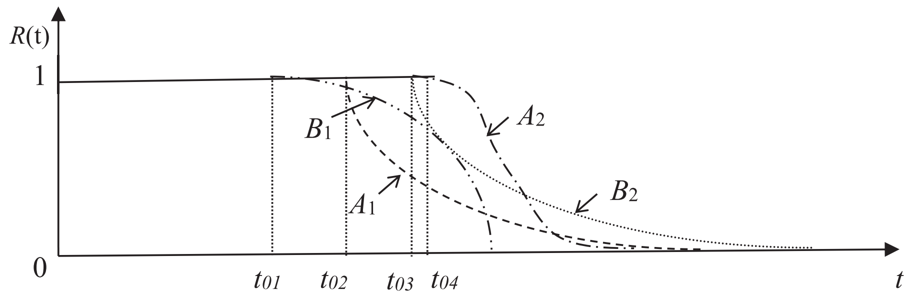

Fig. 11a. Unit life cycle.

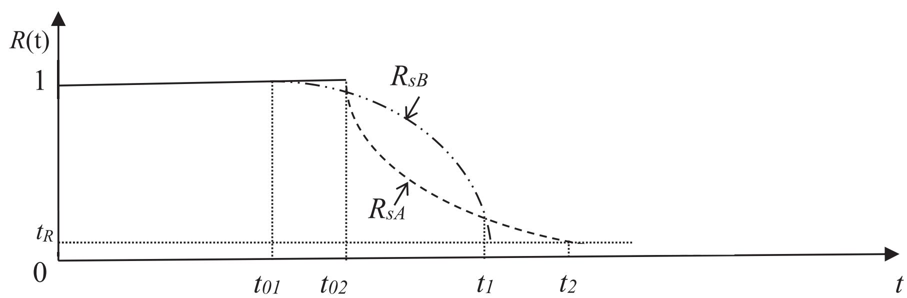

Fig. 11b. SLCD assessment of series system reliability.

reliability test. Compared traditional method and green method, their unit numbers of reliability test are shown in Table 6. The number of reliability test will be reduced to save resources and economy.

Example 9. The assessment comparison of series system reliability is a problem in Example 2. If an SLCD is used to assess the series system reliability, that problem will be solved. The unit life cycle is shown in Fig. 11a.

The assessment of series system reliability using Equation (9).

$$R_{sA} = \min\begin{Bmatrix} t_{02} \\ t_{04} \end{Bmatrix} + \min R(t_R)i = t_{02} + \min R(t_{02})i$$

$$R_{sB} = \min\begin{Bmatrix} t_{01} \\ t_{03} \end{Bmatrix} + \min R(t_R)i = t_{01} + \min R(t_{01})i$$

Calculated using equation (9), the SLCD of results is shown in Fig. 11b.

Fig. 11b indicated the reliability of system A and system B can be compared intuitively at different times. The series systems A and B work till time t_{02} and t_{01} and does not fail. The reliability of system A is higher than that of system B during the period t_{01} to t_{02}. During the period t_{02} to t_1, the reliability of system B is higher than that of system A. The reliability of system A is higher than that of system B during the period t_1 to t_2.

In Example 2, this study compares the assessment result of the SLCD in Fig. 11b and the traditional method using Equation (1). The result reasonably demonstrates the entire system life cycle and is then compared to the different system reliability in Fig. 11b. In Example 2, the assessment method of series system reliability is calculated using only probability, and its result is quite different from the actual system reliability. The SLCD can solve the problem of there being a direct relationship between the system reliability assessment and the number of units in a series system. The assessment result of a series system reliability test can also be compared reasonably, and the comparison result is consistent with the actual sate.

4.2. SLCD assessment of parallel system reliability

Definition 4. In a parallel system, the logical relation of units is *OR*, the reliability level $R(t_R)$ can be specified on the design needs. Equations (7) and (8) presented the assessment of parallel system reliability is presented in Equation (11) using SLCD.

$$\begin{aligned} R_s &= R_1 \cup \ldots \cup R_n = R_1 \vee \ldots \vee R_n \\ &= \max\begin{Bmatrix} t_{01} \\ \vdots \\ t_{0n} \end{Bmatrix} + \max\begin{Bmatrix} R(t_1) \\ \vdots \\ R(t_n) \end{Bmatrix} i = \max\begin{Bmatrix} t_{01} \\ \vdots \\ t_{0n} \end{Bmatrix} + \max R(t_R)i \end{aligned} \tag{11}$$

Example 10. It is assumed that the series system A and B in Example 2 are transformed to parallel system A and B. Their RBDs are presented in Fig. 12a and 12b. The unit reliability is shown in Fig. 12c.

The system reliability is calculated using Equation (11):

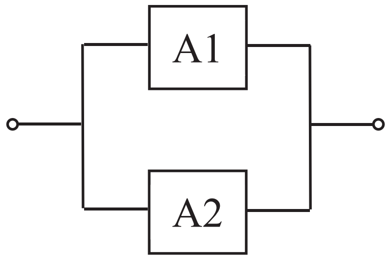

Fig. 12a. Parallel system A.

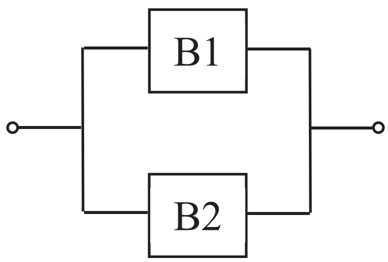

Fig. 12b. Parallel system B.

$$R_{sA} = R_{A1} \cup R_{A2} = R_{A1} \vee R_{A2} = \max\left\{ \begin{array}{c} t_{02} \\ t_{04} \end{array} \right\} + \max R(t_R) i$$
$$= t_{04} + \max R(t_{04}) i$$

$$R_{sB} = R_{B1} \cup R_{B2} = R_{B1} \vee R_{B2} = \max\left\{ \begin{array}{c} t_{01} \\ t_{03} \end{array} \right\} + \max R(t_R) i$$
$$= t_{03} + \max R(t_{03}) i$$

The SLCD assessment of parallel system reliability A and B is shown in Fig. 12d.

Fig. 12d presented the reliability of system A and B can be compared intuitively at different times. The parallel system A and B can work till time t_{04} and t_{03} and does not fail. During the period t_{03} to t_{04}, the reliability of system A is higher than that of system B. The reliability of system A is still higher than that of system B during the period t_{04} to t_3. The reliability of system B is higher than that of system A during the period t_3 to t_4.

5. Conclusions

This study discusses and proves the limitations of the traditional system reliability assessment method From the perspective of resources and economy. This method is based on unit reliability and probability theory. Unit reliability requires a reliability test that consumes resources and economy. A system is composed of units, and this method depends on the number of units and the reliability test. If the number of units increases, the system reliability assessment will consume more and more resources and economy. Based on probability theory, the result of the system reliability assessment cannot reasonably represent the real working state of the system. Thus, we propose a green assessment method of system reliability to solve this problem.

This study considered the characteristics of the unit life cycle and thus established an SLCD model. The system working state is described using an SLCD model that can show the characteristics of a system life cycle. *AND* and *OR* mathematical operations are defined to express the logical relationship among units. Based on the SLCD model, we propose a green assessment method of system reliability and apply it to the series system and parallel system. This method can make the result of the system reliability assessment more reasonable. Compared with the traditional assessment method, the green assessment method of system reliability does not depend on the number of units and reliability test. Thus, it will save resources and economy in the design and assessment of system reliability. Because it considers the system working status, it is more reasonable in its assessment of system reliability.

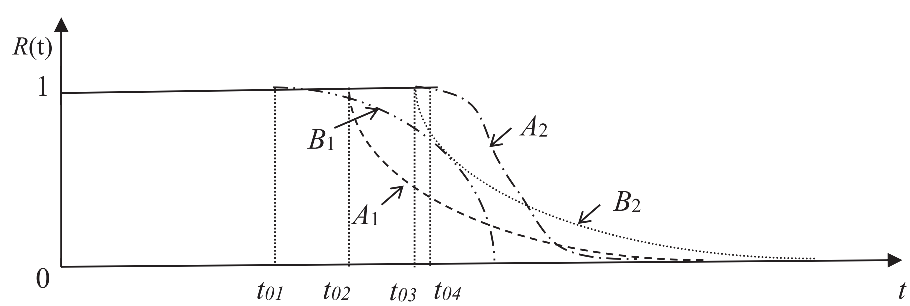

Fig. 12c. Unit life cycle.

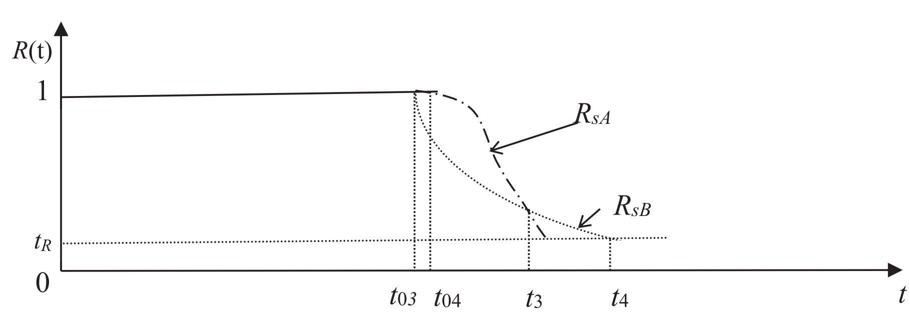

Fig. 12d. SLCD assessment of parallel system reliability.

This green assessment method of system reliability needs to be further modified and improved and applied in complex systems. For large and complex systems with a large number of units, the method requires computer assistance to complete the calculation. Different types of units have different life cycle characteristics, which need to be equivalent (converted to the same service conditions based on the service conditions of the system). To further reduce the need for resources and economy, the unit reliability test method will be studied. These are the problems that need further study and solution so that in the future, more resources and economy would be conserved, thus promoting sustainable and cleaner production.

Authorship

Jun-Gang Zhou: First Draft.
Ling-Ling Li: Data analysis.
Ming-Lang Tseng*: Final checking and re-edit the last version.
Guo-Qian Lin: Resources.
Acknowledgments

Declaration of competing interest

This study is free of Conflict of interests.

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