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## PHYSICS-OF-FAILURE AND COMPUTER-AIDED SIMULATION FUSION APPROACH WITH A SOFTWARE SYSTEM FOR ELECTRONICS RELIABILITY ANALYSIS

### METODA I OPROGRAMOWANIE DO ANALIZY NIEZAWODNOŚCI URZĄDZEŃ ELEKTRONICZNYCH OPARTE NA POŁĄCZENIU METODOLOGII FIZYKI USZKODZEŃ I SYMULACJI KOMPUTEROWEJ

*Electronics, such as those used in the communication, aerospace and energy domains, often have high reliability requirements. To reduce the development and testing cost of electronics, reliability analysis needs to be incorporated into the design stage. Compared with traditional approaches, the physics of failure (PoF) methodology can better address cost reduction in the design stage. However, there are many difficulties in practical engineering applications, such as processing large amounts of engineering information simultaneously. Therefore, a flexible approach and a software system for assisting designers in developing a reliability analysis based on the PoF method in electronic product design processing are proposed. This approach integrates the PoF method and computer-aided simulation methods, such as CAD, FEM and CFD. The software system integrates functional modules such as product modeling, load-stress analysis and reliability analysis, which can help designers analyze the reliability of electronic products in actual engineering design. This system includes software and hardware that validate the simulation models. Finally, a case study is proposed in which the software system is used to analyze the filter module reliability of an industrial communication system. The results of the analysis indicate that the system can effectively promote reliability and can ensure the accuracy of analysis with high computing efficiency.*

**Keywords:** *physics of failure, reliability analysis, electronics, prognostics and health management, computer-aided simulation, software system.*

*Urządzenia elektroniczne, na przykład te używane w łączności, lotnictwie i energetyce, często muszą spełniać wysokie wymagania dotyczące niezawodności. Aby zmniejszyć koszty rozwoju i testowania tego typu urządzeń, należy opracować metodę analizy niezawodności, którą można wykorzystywać już na etapie projektowania. Metodologia fizyki uszkodzeń (PoF) pozwala, lepiej niż tradycyjne podejścia, rozwiązywać problemy związane z niezawodnością już na etapie powstawania projektu. Jednak jej zastosowanie w praktyce inżynierskiej nastręcza wielu trudności, związanych, między innymi, z koniecznością jednoczesnego przetwarzania dużych ilości informacji inżynierskich. W związku z tym, w przedstawionej pracy zaproponowano elastyczne podejście oraz system oprogramowania, które mogą być wykorzystywane przez projektantów do opracowania analizy niezawodności produktu elektronicznego w oparciu o PoF na etapie projektowania. Podejście to stanowi połączenie metody PoF i metod symulacji komputerowej, takich jak CAD, FEM i CFD. System oprogramowania zawiera moduły funkcjonalne, takie jak modelowanie produktu, analiza obciążeń, analiza niezawodności i inne, które mogą wspomagać projektantów w analizie niezawodności projektowanych przez nich produktów elektronicznych. Na system ten, oprócz oprogramowania składa się także sprzęt komputerowy, który służy do walidacji modeli symulacyjnych. W artykule przedstawiono studium przypadku, w którym zaproponowany system oprogramowania wykorzystano do analizy niezawodności modułu filtra wykorzystywanego w systemie łączności przemysłowej. Wyniki analizy pokazują, że opracowane oprogramowanie skutecznie poprawia niezawodność urządzeń jak też zapewnia dokładność analizy przy jednoczesnej wysokiej wydajności obliczeniowej.*

**Słowa kluczowe:** *fizyka uszkodzeń, analiza niezawodności, urządzenia elektroniczne, prognozyka i zarządzanie zdrowiem, symulacja komputerowa, system oprogramowania.*

## 1. Introduction

The reliability discipline is regarded as a ‘black box art’ or ‘number game’ in science. Usually, electronics reliability analysis conducts a series of tasks in practice that focus on potential failure mode identification and reliability parameter calculation. Traditional electronics reliability analysis mainly depends on statistical experiments to obtain product failure information. Traditional electronics reliability analysis is mainly based on qualitative or semi-quantitative analysis, which ignores failure mechanism analysis in the product design stage. For this problem, the physics of failure (PoF) methodology is more suitable. The PoF approach focuses on failure mechanisms and root causes of failure in products and emphasizes the quantitative analysis and description of physical and chemical processes for product failure [10, 30].

The PoF was formally conceptualized in the first of a series of symposia in 1962 organized by the Rome Air Development Center (RADC) of the US Air Force [2]. After that, the PoF approach became an important research topic in the reliability field. Since 1967, the IEEE Reliability Physics Symposium (IRPS) has continued to present research related to the PoF [2]. In addition, several related research institutions have had an important influence on the development of the PoF. Computer Aided Life Cycle Engineering (CALCE) at the University of Maryland carried out many studies on the PoF approach and its application and presented the PoF-based reliability prediction method [15, 21-23]. The RADC and the Research Foundation of the Illinois Institute of Technology also promoted the development of the PoF [2, 4]. In China, the School of Reliability and Systems Engineering, Beihang University, cooperates with CALCE and has also performed many studies on PoF-based reliability prediction and fault prognostics for electronics [26-28]. In addition to traditional failure mechanism analysis, the PoF approach is extensively applied to accelerated tests [3] and lifetime assessment [12, 13, 16, 31]. For example, Bretts et al [24] introduced physical models into accelerated tests to estimate the time to failure (TTF) of resistors. As the PoF approach has developed, some researchers have attempted to introduce this approach into prognostics and health management (PHM). Pecht et al [19, 25] presented a PoF-based PHM approach for effective reliability prediction. K. Ma et al [16] researched the application of the PoF for prediction and design in power electronics systems. H. Oh et al [20] reviewed the application of the PoF in performing prognostics of insulated gate bipolar transistor modules.

Although the PoF approach has obtained abundant research results, there are many difficulties in using it in practical engineering applications. First, the PoF is a multidisciplinary application involving engineering, physics and chemistry. Abundant professional experiments or computer simulations are necessary to establish physical models, which brings more difficulties for engineers. Second, many kinds of simulation softwares are employed in the computer simulation process. The heterogeneous output files of different software make information extraction and communication more difficult. A large number of information files is inconvenient for unified engineering management. Therefore, professional PoF software is required to solve these difficulties. Due to the complexity of information processing, many research fields develop information systems to manage and process related information [5,6,17]. Professional software can build physical models, which can provide convenience for engineers. Moreover, according to experiment and engineering experience, the inserted physical models can be revised, which can reduce difficulties in obtaining information. At present, there is some professional PoF software in the commercial market, such as CALCE SARA [7], DFR Solutions Sherlock ADA [8, 18] and Reliass ASENT [9]. CALCE SARA and DFR Solutions Sherlock ADA can support a complete PoF analysis for microelectronics applications. The detailed comparability of those software programs can be found in [11]. However, there are still some

problems with the above software. First, ASENT only supports thermal analysis. Second, except for DFR Solutions Sherlock, all of this software adopts a simplified numerical method in load-stress analysis, which reduces the accuracy of the analysis results. Additionally, ASENT and SARA do not support 3D modeling. In some engineering applications, to improve the credibility of reliability analysis results, finite element analysis based on 3D models is executed prior to providing the input data for reliability analysis. Information conversion among the different commercial software programs is complicated in application. Finally, in the reliability analysis process, none of the above software integrates the simulation model validation function.

In accordance with recent product development solutions, this paper presents a physics-of-failure and computer-aided simulation fusion approach. We employed an advanced PoF approach and product digital prototype method to develop professional PoF software. This software system integrates the CAD, CFD and FEA techniques into a computation environment and avoids information conversion among different commercial software. With the integrated technique, this software reduces the application difficulty of the PoF approach in the engineering field. The integrated computation environment is also equipped with corresponding hardware to achieve simulation model validation. The accuracy of the analysis results can be effectively improved through model validation. Parallel computing is applied to the integrated system to improve computational efficiency. This paper shows the details of the environment, such as the method application, information integration process and operating process.

The remaining part of this paper is organized as follows: section II illustrates the basic theory for PoF-based electronics reliability analysis and model validation; section III discusses the system architecture, the information transfer interface design for the software and the model validation process and related hardware setup; section IV introduces a typical case used in airborne electronics and the improvement of reliability; section V summarizes the characteristics, advantages and innovations of the software system.

## 2. Basic theory for system design

### 2.1. PoF-based reliability analysis method

In this software, an advanced PoF method is employed to conduct reliability analysis. Failure mechanism models are an important basis for applying the PoF method, and their foundation is based on the understanding of product failure laws. The failure mechanism model usually describes the functional relationship between a product's life, reliability or performance parameters and geometric parameters, material characteristics and various typical environmental load parameters (such as temperature, humidity, and vibration). A typical functional relationship can be expressed as [29]:

$$TTF_i = f(\mathbf{g}, \mathbf{m}, \mathbf{e}, \mathbf{o}, \dots), \quad (1)$$

where  $TTF_i$  is the time to failure under the  $i$ th failure mechanism,  $\mathbf{g}$  is the geometric parameter vector,  $\mathbf{m}$  is the material parameter vector,  $\mathbf{e}$  is the environmental parameter vector, and  $\mathbf{o}$  is the operation load parameter vector.

Generally, product failure is caused by multiple failure mechanisms. To cover all failure mechanisms, a multipoint distribution fusion approach is used to obtain the probability density function (PDF) of the product lifetime. Due to model parameter uncertainty, the calculated TTF is different each time based on the failure mechanism model. Therefore, the failure information matrix can be obtained by Monte Carlo simulation as follows:

$$I = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_n \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1m} \\ a_{21} & a_{22} & \dots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nm} \end{bmatrix} = \begin{bmatrix} f(x_{A_1}) \\ f(x_{A_2}) \\ \vdots \\ f(x_{A_n}) \end{bmatrix} \quad (2)$$

where  $A_n$  represents the failure information vector of a failure mechanism. Based on the failure information vector, the corresponding PDF  $f(x_{A_n})$  of the failure mechanism can be calculated by the distribution fitting method.

In addition, some failure modes of components are not independent. Under the coupled influence of temperature and vibration, the correlation between failure modes often shows a positive correlation; that is, the generation of one failure mode accelerates the failure process of another failure mode. Since each failure mode of a component often causes the overall failure of the component, the component can be regarded as a series relationship among various failure mode conditions. The component failure mode correlation can be used as the series failure correlation of each failure mode. To resolve this issue, the copula approach is used to construct the correlation model. The copula function organically links the joint probability density function of a multivariate random variable with the marginal probability density function of each variable [32, 33]. The correlation among the random variables is considered, and the solving process of the joint probability density function of the multivariate random variables can be simplified.

According to Sklar's theorem [32], the following joint cumulative distribution function can be obtained:

$$F(x_{A_1}, x_{A_2}, \dots, x_{A_n}) = C(F_{A_1}(x_{A_1}), F_{A_2}(x_{A_2}), \dots, F_{A_n}(x_{A_n})) \quad (3)$$

From the above formula, the PDF of the joint probability density function can be obtained as:

$$\begin{aligned} f_C(x_{A_1}, x_{A_2}, \dots, x_{A_n}) &= \frac{\partial^n F}{\partial x_{A_1} \partial x_{A_2} \dots \partial x_{A_n}} \\ &= \frac{\partial^n C(F_{A_1}(x_{A_1}), F_{A_2}(x_{A_2}), \dots, F_{A_n}(x_{A_n}))}{\partial F_{A_1} \partial F_{A_2} \dots \partial F_{A_n}} \frac{\partial F_{A_1}}{\partial x_{A_1}} \frac{\partial F_{A_2}}{\partial x_{A_2}} \dots \frac{\partial F_{A_n}}{\partial x_{A_n}} \\ &= c(F_{A_1}(x_{A_1}), F_{A_2}(x_{A_2}), \dots, F_{A_n}(x_{A_n})) f(x_{A_1}) f(x_{A_2}) \dots f(x_{A_n}) \end{aligned} \quad (4)$$

Then, the failure correlation matrix is as follows:

$$J = \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_m \end{bmatrix} = \begin{bmatrix} FM_1 & FM_2 & & \\ FM_1 & FM_2 & FM_3 & \\ \vdots & \vdots & \ddots & \\ FM_1 & FM_2 & \dots & FM_n \end{bmatrix} = \begin{bmatrix} f_{C_1}(x_{A_1}, x_{A_2}) \\ f_{C_2}(x_{A_1}, x_{A_2}, x_{A_3}) \\ \vdots \\ f_{C_m}(x_{A_1}, x_{A_2}, \dots, x_{A_n}) \end{bmatrix} \quad (5)$$

where  $C_m$  represents the failure mode vector. The Monte Carlo method is used to sample random numbers from the PDF  $[f(x_{A_1}), f(x_{A_2}), \dots, f(x_{A_n}), f_{C_1}(x_{A_1}, x_{A_2}), f_{C_2}(x_{A_1}, x_{A_2}, x_{A_3}), \dots, f_{C_m}(x_{A_1}, x_{A_2}, \dots, x_{A_n})]$ , which yields the TTF results of the corresponding failure mechanism

$(t_{A_1}^{(1)}, t_{A_2}^{(1)}, \dots, t_{A_n}^{(1)}, t_{C_1}^{(1)}, t_{C_2}^{(1)}, \dots, t_{C_m}^{(1)})$ . Then, the TTF samples of a product can be represented as:

$$TTF^{(1)} = \min(t_{A_1}^{(1)}, t_{A_2}^{(1)}, \dots, t_{A_n}^{(1)}, t_{C_1}^{(1)}, t_{C_2}^{(1)}, \dots, t_{C_m}^{(1)}) \quad (6)$$

By repeating the above process  $n$  times, the TTF sample sets can be obtained, which are denoted as  $(TTF^{(1)}, TTF^{(2)}, \dots, TTF^{(n)})$ . Using these sample sets to perform the distribution goodness test, the lifetime PDF  $g(x)$  of the product is obtained.

The above process can be summarized as follows: First, determine the prior distribution of the input parameters in the PoF model. Then, a Monte Carlo simulation is used to obtain the sampling values of the input parameters. The sampling values are substituted into the PoF model to obtain the TTF sample values corresponding to the  $n$ th failure mechanisms. The copula method is used to obtain the PDF of correlation failure. A competition model is used to determine the minimum TTF, and the selected PoF model is sampled and fitted again. The TTF distribution function of the product is obtained. The algorithm is summarized in Table 1.

Table 1. PoF-based reliability analysis algorithm

<p><b>Generate failure information matrix</b></p> <p>For <math>i = 1:n</math></p> <p>Sample <math>(\mathbf{g}, \mathbf{m}, \mathbf{e}, \mathbf{o}) \sim U(a, b Z)</math> based on the prior distribution of model parameters</p> <p>Sample <math>(a_{i1}, a_{i2}, \dots, a_{im}) \sim f(\mathbf{g}, \mathbf{m}, \mathbf{e}, \mathbf{o})</math> based on the corresponding failure mechanism model</p> <p>Fit the distribution <math>f(x_{A_i}) \sim (a_{i1}, a_{i2}, \dots, a_{im})</math></p> <p>End</p> <p><b>Generate failure correlation matrix</b></p> <p>For <math>i = 1:m</math></p> <p>Construct the joint probability density function <math>f_{C_m}(x_{A_1}, x_{A_2}, \dots, x_{A_n})</math> based on Eq.(4)</p> <p>End</p> <p><b>Multi-point distribution fusion</b></p> <p>For <math>j = 1:n</math></p> <p>Sample <math>\begin{bmatrix} t_{A_1}^{(j)}, t_{A_2}^{(j)}, \dots, t_{A_n}^{(j)} \\ t_{C_1}^{(j)}, t_{C_2}^{(j)}, \dots, t_{C_m}^{(j)} \end{bmatrix} \sim \begin{bmatrix} f(x_{A_1}), f(x_{A_2}), \dots, f(x_{A_n}), f_{C_1}(x_{A_1}, x_{A_2}), \\ f_{C_2}(x_{A_1}, x_{A_2}, x_{A_3}), \dots, f_{C_m}(x_{A_1}, x_{A_2}, \dots, x_{A_n}) \end{bmatrix}</math></p> <p>based on the PDF of the failure mode</p> <p>Calculate the minimum from <math>TTF^{(j)} \sim (t_{A_1}^{(j)}, t_{A_2}^{(j)}, \dots, t_{A_n}^{(j)}, t_{C_1}^{(j)}, t_{C_2}^{(j)}, \dots, t_{C_m}^{(j)})</math></p> <p>based on Eq.(6)</p> <p>Generate the TTF sample vector <math>(TTF^{(1)}, TTF^{(2)}, \dots, TTF^{(n)})</math></p> <p>End</p> <p><b>Calculate PDF of product lifetime</b></p> <p>Fit the distribution <math>g(x) \sim (TTF^{(1)}, TTF^{(2)}, \dots, TTF^{(n)})</math></p>
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2.2. Model validation approach

2.2.1. Thermal model validation approach

In the thermal simulation model validation, the temperatures of the corresponding temperature test points are generally compared under the same steady state. If the error is within the allowable range, the simulation model is taken to reflect the real situation. Since thermal test values are generally discrete values and do not satisfy the completely random sampling rule, this paper selects the Theil inequality coefficient (TIC) [14] approach to verify the thermal simulation model. Suppose that  $x_i$  is the simulation model output sequence and  $z_i$  is the actual system output sequence. The data length is N. Then, the function formula is as follows:

$$\rho(x, z) = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - z_i)^2}}{\sqrt{\frac{1}{N} \sum_{i=1}^N (x_i)^2} + \sqrt{\frac{1}{N} \sum_{i=1}^N (z_i)^2}} = \frac{\sqrt{\sum_{i=1}^N (x_i - z_i)^2}}{\sqrt{\sum_{i=1}^N (x_i)^2} + \sqrt{\sum_{i=1}^N (z_i)^2}} \quad (7)$$

If  $\rho = 0$ , the simulation model output sequence is exactly the same as the actual system output sequence. If  $\rho = 1$ , the simulation model output sequence is completely uncorrelated with the actual system output sequence. Therefore, the closer the TIC value is to 0, the higher the accuracy of the simulation model. If the TIC is greater than the prediction threshold  $\delta$ , the simulation result will not satisfy the accuracy requirements. Considering the model simplification and measurement noise, the threshold  $\delta$  is set to 0.4. The product model needs to be revised until the TIC is smaller than the threshold  $\delta$ . The revised model parameters include the actual power consumption, equivalent thermal resistance of the device and equivalent thermal conductivity of the material.

2.2.2. Vibration model validation approach

In vibration analysis, the modal analysis results are generally used to regulate the simulation model. Therefore, the modal assurance criterion (MAC) [1] is chosen as the model validation approach. The formula for the MAC is as follows:

$$MAC_{ij} = \frac{[\varphi_i^T \varphi_j]^2}{(\varphi_i^T \varphi_i)(\varphi_j^T \varphi_j)} \quad (8)$$

where  $\varphi_i$  and  $\varphi_j$  are modal vectors calculated by a simulation analysis and a physical test, respectively. The MAC can be used to check the consistency or mutual independence between the simulated modal results and the experimental modal results. In theory, if MAC=1, the experimental modal vector is exactly the same as the simulated modal vector. If MAC=0, it means that the two modes are orthogonal; that is, the experimental modal vector has no linear relationship with the simulated modal vector. However, due to the model simplification, the external noise interference of measurement data and improper data processing, the calculation result of the MAC will be affected. Generally, when MAC > 0.7, the two modes can be considered to have a good linear relationship, and the simulation model reflects the real vibration. When MAC < 0.2, the simulation model does not reflect the real vibration.

3. System architecture

3.1. Program structure

The Physics of Failure-based electronics reliability analysis (PofEra) is an integrated multidisciplinary simulation analysis system that employs the advanced PoF and product digital prototype methods to assess electronics reliability. Graphical modeling, finite element analysis (FEA) and computational fluid dynamics (CFD) analysis are integrated into the system. This system can save and import product parameter information and environmental load information and enable the visualization of the model and analysis results. Moreover, the different function modules can execute either separately or in a sequential order. The PofEra comprises seven main program modules: product modeling (PM), the mission profile (MP), load-stress analysis (LSA), reliability analysis (RA), simulation validation (SV), reliability optimization (RO) and a basic database (DB). Fig. 1 shows the detailed function structure of the different function modules.

- a) PM module: Supports constructing the CAD model of circuit boards, which covers the device, circuit board and PTH modeling. In addition, this module enables the input model to be provided by other CAD software (such as CATIA/UG).
- b) MP module: Provides the environment and time information for load-stress analysis and failure prediction.
- c) LSA module: Enables the thermal and vibration analyses to be carried out under the corresponding mission profiles. The thermal and vibration analyses apply the CFD program and FEA program, respectively.

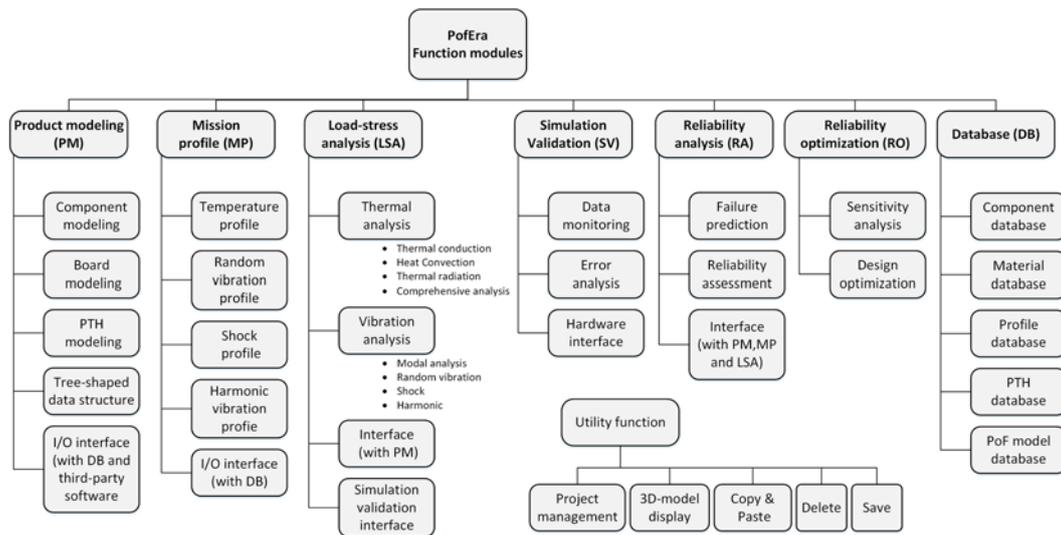


Fig. 1. Function modules of PofEra

- d) SV module: Validates the simulation credibility through a consistency test between the simulation and practical test results.
- e) RA module: Predicts the reliability or remaining useful life for the components and circuit board based on the mission profile.
- f) RO module: Proposes improved measures according to the sensitivity analysis results to avoid failure. Health management can be realized based on the remaining useful life results.
- g) DB module: Stores and provides part of the basic data, including material data, device data and PTH data.

**3.2. Software hierarchy**

The software hierarchy of the PofEra system is composed of four hierarchies—the software foundation hierarchy, information management hierarchy, function model hierarchy and user interface hierarchy—as shown in Fig. 2. First, the software foundation hierarchy mainly establishes a software system support environment, such as the operating system Microsoft .NET framework, CFD program, FEA program and database program. These platforms are the essential foundations to build the other hierarchies. For example, the CFD program is the solver of thermal analysis. Similarly, the FEA program is the solver of vibration analysis. Then, the information management hierarchy employs a database program to manage the relevant product information. In the electronics reliability analysis, there is a large amount of involved information, such as device information, package information, joint information and environment load information. Most of the information can be accumulated and reused. Therefore, the reasonable organization and management of product information can improve software efficiency. Additionally, the function module hierarchy contains individual realization and interface relationships of different function modules. Finally, the user interface hierarchy provides a user interface that is used to manage and apply various function modules. Each function module can be individually applied using the GUI, which can obtain the required output of all information in table-based and graphical forms.

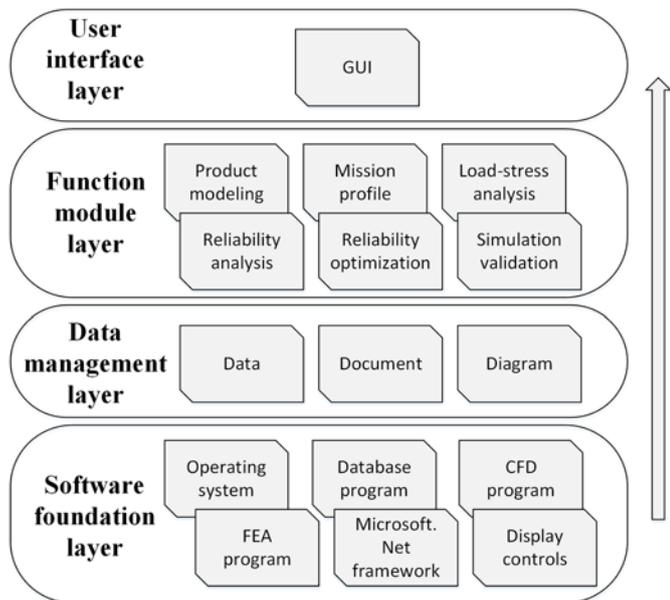


Fig. 2. Software hierarchy of PofEra

**3.3. Information transfer interface design**

The PofEra system achieves information integration for the comprehensive reliability simulation analysis of electronic products. The PofEra system avoids information interaction among the different software. Therefore, the system has complicated information transmission relationships. Fig. 3 illustrates the information transmission relationships among different modules. First, the PM module provides the product design information of the CAD model to the LSA module. According to the CAD model, the thermal and vibration analysis generate the CFD and FEA models, respectively. Then, the corresponding simulation analyses are carried out based on the local load information (temperature and vibration values) from the MP module. The SV module receives the experimental information from the hardware to verify the simulation model. Then, failure prediction in the RA module applies partial design information, simulation results and profile time information to predict the TTF of the device. Based on the device prediction results, a multipoint information fusion algorithm is employed to fit the life distribution of the circuit board and obtain the corresponding mean time to failure (MTTF) in the reliability analysis. Finally, according to the assessment results, the improved measures are fed back to the designers to optimize the electronic product. Because the PofEra system is not related to the product design, the transmission of feedback information is indicated by the dashed line.

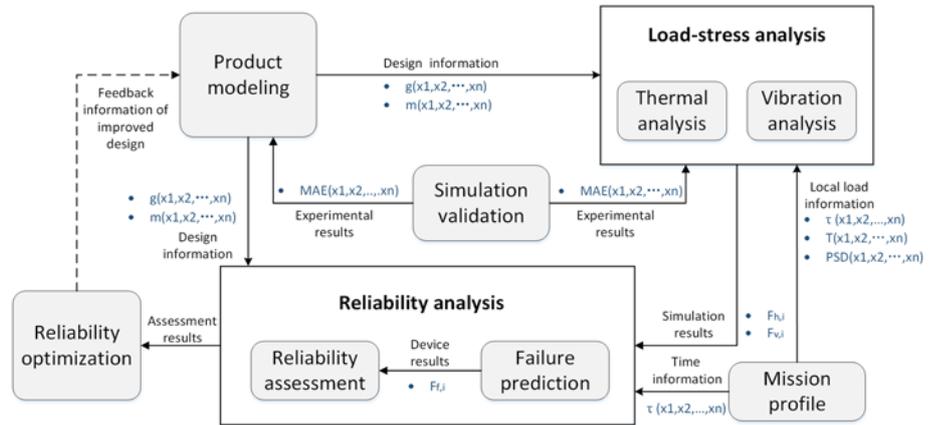


Fig. 3. Information transmission relationship of PofEra

The different function modules will generate different kinds of data types. Therefore, several data types should be considered in the application process, such as stl, XML and sheet. For the convenience of data transmission, most data should be transferred to the union data format; the XML format is selected as the union format. The transmission and transferability of data is achieved, as shown in Fig. 4.

The API program is developed in the C# language, which contains the PM program, MP program, LSA program, RA program, and RO program. The API program provides the commands and runs the analysis programs, which link the different modules. The function of the different programs is illustrated in Table 2. Then, the analysis results from the data of each module location are presented graphically using the GUI program. The display controls are used to display the 3D-model and graphical data. In the execution process, part of the data come from the database. The database can perform data selection and updating as well as deletion and insertion for the data tables.

**3.4. Parallel computing**

In addition, according to the requirement of the mission profile, multiple sets of load-stress analyses will be executed under different stress conditions, which is often very time-consuming. To improve the

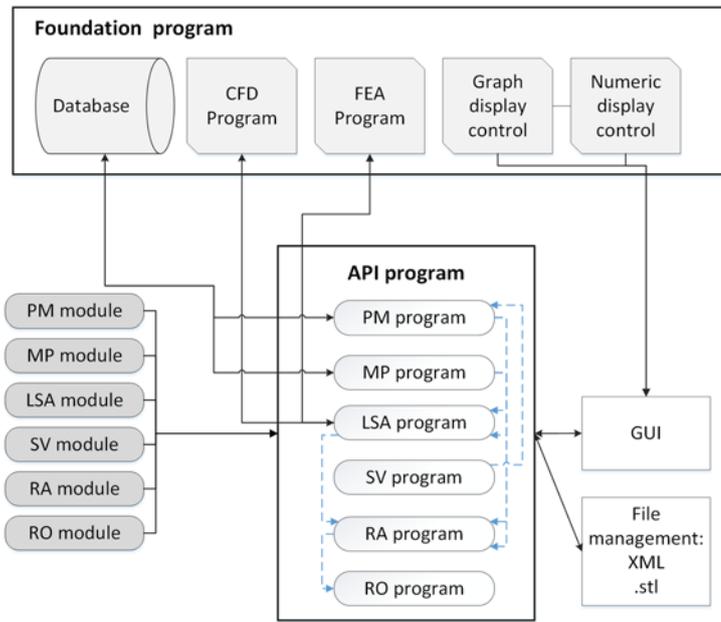


Fig. 4. Achievement of information transmission and transferability

computing efficiency, distributed resource allocation and parallel computing are applied to the PofEra system. The foundation programs are installed at a public server, including the CFD program, FEA program and SQL server. The clients access the corresponding services through a server. The thermal and vibration analysis based on the CFD program and FEA program can be simultaneously executed on the public server. Then, multiple sets of load-stress analysis results can be called by the reliability analysis module. The parallel computing schematic diagram is shown in Fig. 5.

Parallel computing can be divided into two phases: first, establishing a computing task execution sequence; second, task assignment and calculation. The task assignment process is shown in Fig. 6.

a) To complete failure prediction, the corresponding calculations are divided into three parts: thermal analysis  $N_{h,i}$ , vibration analysis  $N_{v,i}$  and failure prediction  $N_{f,i}$ , where  $i = 1, 2, \dots, n$ . According to the random task allocation method, all the calculation tasks are reordered to form a new task calculation sequence. First, a random number sequence  $\{R_{3n}\}$  is generated corresponding to the task sequence  $Q = \{N_{3n}\}$ . Then, the sequence  $\{R_{3n}\}$  is rewritten in order from small to large to form the sequence  $\{S_{3n}\}$ . A new computation task sequence

Table 2. Function of the API program

API program	Function
PM program	1. calling the basic data from the database 2. generating the '.stl' files containing the modeling information 3. generating the XML files containing the product design information
MP program	1. calling the basic data from the database 2. generating the XML files containing the profile information
LSA program	1. calling the '.stl' files and profile XML files for the CFD or FEA program 2. reading the analysis results from the CFD or FEA program 3. generating the XML files containing the analysis results
SV program	1. reading the experimental results from the hardware equipment 2. completing the error analysis between the simulation and test results 3. generating the XML files containing the error analysis results
RA program	1. calling the XML files (design information, profile and analysis results) 2. calculating the TTF of devices 3. generating the XML files containing the prediction results 4. assessing product reliability based on the prediction XML files and generating the assessment results
RO program	1. calling the XML files (prediction and assessment results) 2. carrying out the sensitivity analysis

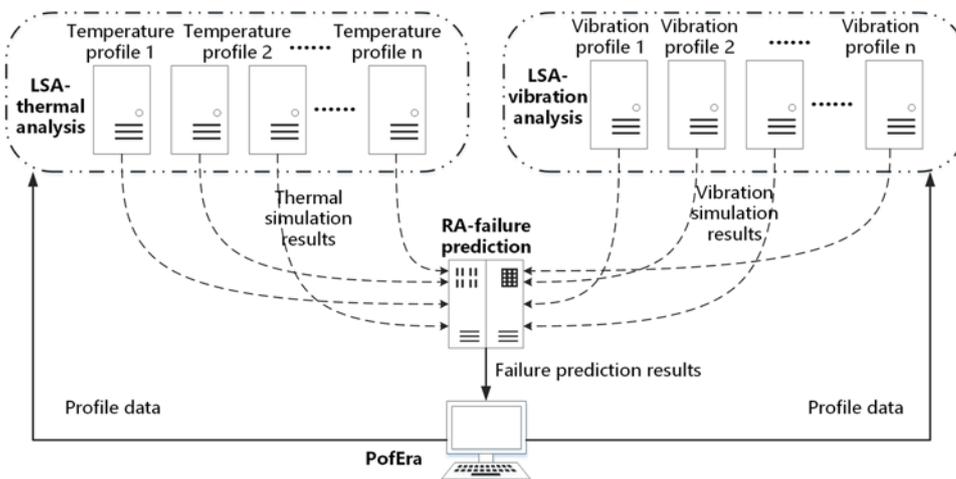


Fig. 5. Parallel computing schematic diagram

$Q' = \{L_{3n}\}$  is obtained according to the sequence  $\{S_{3n}\}$ . The new task sequence can make task assignment more uniform on each processor.

b) All computing tasks are assigned to the  $p$  computing nodes according to a new computing task sequence  $Q' = \{L_{3n}\}$ . After performing thermal analysis and vibration analysis, the corresponding data files ( $F_{h,i}, F_{v,i}, i = 1, 2, \dots, n$ ) are generated. If the assigned failure prediction task has no corresponding data file for thermal analysis and vibration analysis, the calculation node suspends the response of the task assignment and performs the thermal analysis and vibration analysis that have

not yet been performed. The performed load analysis task will be removed in the task sequence to avoid repeated analysis. Then, the assigned failure prediction task is executed, and the other task assignment in the task sequence is accepted after the failure prediction task is executed.

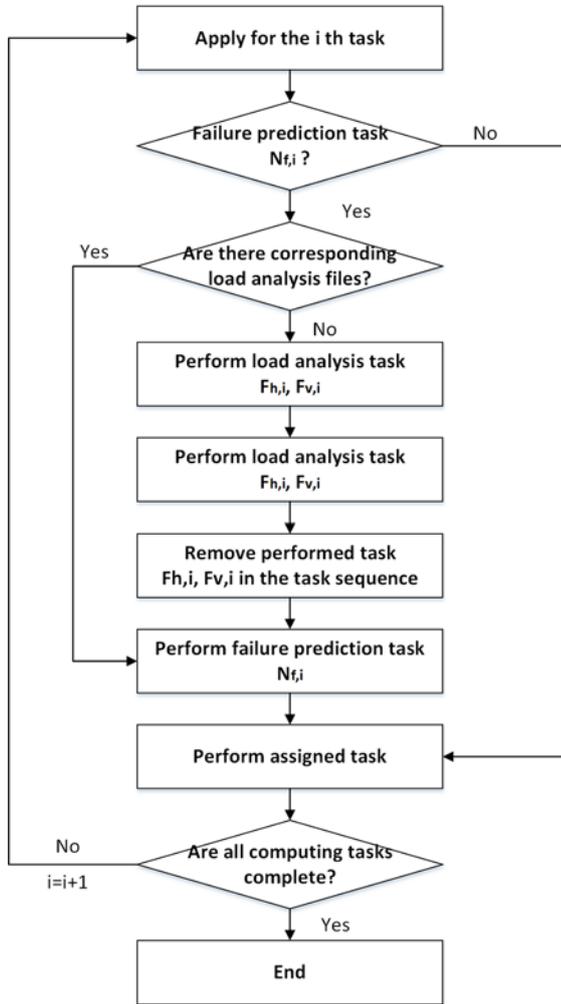


Fig. 6. The task assignment process

### 3.5. Model validation

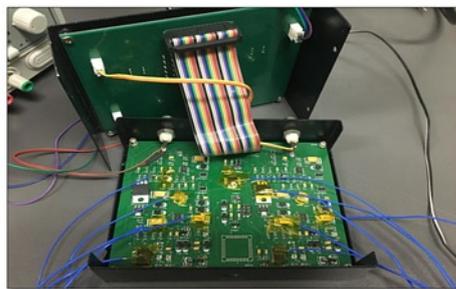
The validation of digital simulation models is an important phase to promote the accuracy of assessment results. Through a consistency test between the simulation and physical test results, simulation credibility can be validated. Therefore, the simulation validation module provides the interface between the software and special hardware. Fig.7 shows the schematic diagram of the thermal and vibration tests. The hardware contains two types of channels to receive the thermal and vibration test data. The thermal test applies temperature sensors to collect temperature data. According to the thermal simulation results, certain high-temperature devices are selected as test objects to complete the thermal validation. The vibration test applies the hammer modal test to perform vibration validation. A displacement sensor is equipped on the tested circuit board. Then, the circuit board is hit multiple times with a hammer equipped with an acceleration sensor to collect feedback signals. The feedback signals are applied to calculate the various order modes of the circuit board. Then, the test data are inputted into the SV module. Based on the TIC and MACmodel validation functions, the module will automatically report the validation results of important devices. The product model will be revised based on validation results until the simulation results approach the test results. After determining the accuracy of the model, the simulation model can be applied to simulation analysis under other conditions, thus eliminating the conditional limitations of physical experiments.

### 4. Case study

As shown in Fig. 8, the filter module for an industrial communication system is selected as the validation case. The filter module is used to filter the interference signal and ensure the accuracy of the communication signal and the normal operation of the communication system. Table 3 displays some important device data. These devices are used to construct the filter circuit and perform the filter function. In the actual task environment, the filter module is not greatly affected by vibration, so this case only focuses on thermal effects. Fig. 9 is a partial task profile, which provides temperature and task time data for simulation analysis.

According to the above information, the CAD model of the filter module is established in the PM module, as shown in Fig. 10. In the modeling process, the model is properly simplified such that some non-important information is ignored. After completing the simulation model, the accuracy of the model needs to be verified. Here, a

**Thermal test**



**Vibration test**

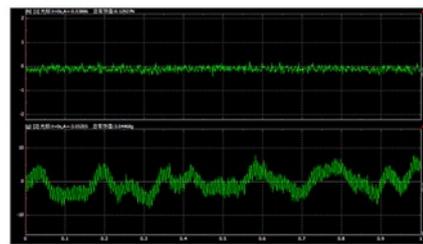


Fig. 7. Schematic diagram of the thermal and vibration tests



Fig. 8. Filter module

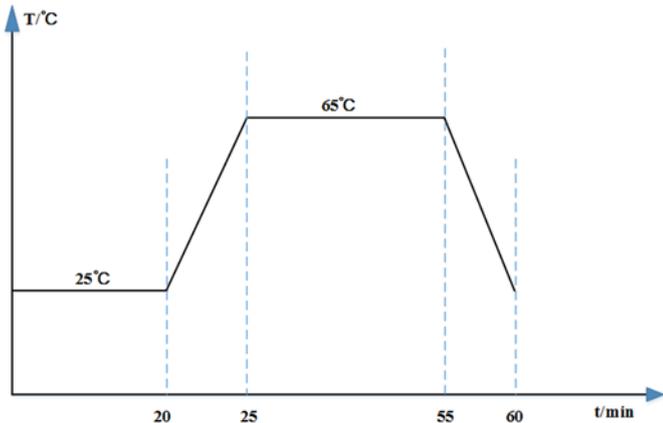


Fig. 9. Temperature profile

thermal test is adopted to verify the model by comparing the thermal simulation results under the same environmental conditions. The thermal test is carried out under normal temperature conditions, that is, 25°C. High-power devices are selected as test objects by the test equipment. The SV module receives the hardware monitoring signal and displays the temperature results. The TIC is 0.04, and the model accuracy is satisfactory. The test results are shown in Table 4.

Then, based on the CAD model, thermal simulation analysis can be carried out. The corresponding simulation result is shown in Fig. 11. For electronic products, heat has a great impact on reliability. The red marks in Fig. 11 indicate regions with high heat generation. Generally, the devices in this region have a great

probability of potential failure. The amount of heat may lead to welding spot fatigue or open circuiting of the device. In the blue region, the two devices have a metal package, so they can achieve better heat dissipation.

After completing the thermal simulation analysis, failure prediction and reliability analysis can be sequentially executed. The expected lifetime of the filter module is assumed to be 5.5 years. The filter module runs 12 times a day according to the task profile, as shown in Fig. 9. As shown in Fig. 13(a), compared with the other devices, the red devices have a lower lifetime. For example, the TTF of C7 is  $1.27 \times 10^5$  h. The underlying failure mechanism is first-order thermal fatigue. The devices marked in red can generate higher heat themselves, which easily causes thermal fatigue failure of the lead and welding spot. The devices in the white box are surface-mount devices that are close to high temperature areas and may have a life expectancy lower than the design value due to thermal fatigue failure. Then, based on the device failure prediction result, the reliability analysis result of the filter module can be obtained, as shown in Fig. 14(a). The MTTF of the filter module is  $4.14 \times 10^4$  h, which is below the expected lifetime. Therefore, with a first round of reliability analysis completed, the analysis results can provide useful information for product reliability design improvements in the design stage. For the thermal design of circuit boards, there are generally three improved measures that can be adopted:

- a) Choose other devices with better heat dissipation performance, such as metal-packaged devices.
- b) Modify the layout of the original devices.
- c) Introduce forced-cooling measures, such as air or liquid cooling.

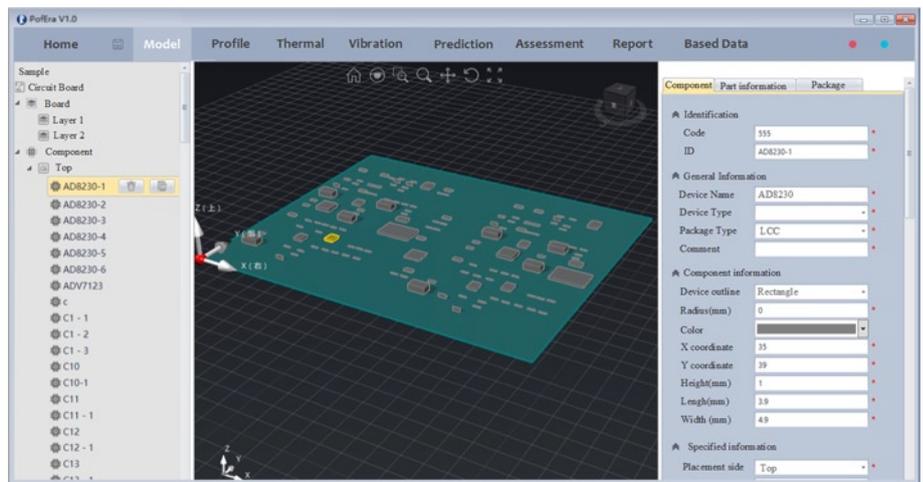


Fig. 10. The CAD model of the filter module

Table 3. Part of the device information

No.	Value	Device type	Length*Width *Height(mm)	Weight(g)	Power Consumption(W)
C1	100 pF	Capacitor	5.2*2.7*1.8	0.8	0.001
C2	47 μF	Capacitor	5.2*2.7*1.8	0.8	0.001
C3	0.22 μF	Capacitor	5.2*2.7*1.8	0.8	0.001
D1	/	Diode	2.5*1.7*1	0.1	0.001
D2	/	Diode	2.5*1.7*1	0.1	0.001
R1	5 kΩ	Resistor	2.2*1*0.7	0.06	0.001
R2	5.5 kΩ	Resistor	2.2*1*0.7	0.06	0.001
R3	25 kΩ	Resistor	2.2*1*0.7	0.06	0.001
AD620AN	/	Operational Amplifier	4.9*3.9*1.5	0.4	0.3

Table 4. Part of the device information

Number	Measurement (°C)	Simulation (°C)
C6	43	45
C7	43.5	47
D1	35	30
D2	30	32
R1	26	29
R2	27.5	29.6
AD620AN	28	29.6

In this paper, we assume that the air-cooling measure is selected to achieve better heat dissipation and improve the product reliability. Then, a new thermal simulation and reliability analysis are carried out. The corresponding analysis results are displayed in Figs. 12-14. It can be seen from Fig. 12 that the heat concentration region disappears. Compared with Fig. 11, the maximum temperature is reduced by approximately 4°C. The TTF of C7 is increased to  $2.12 \times 10^5$  h. The TTF is 66.9% higher than the predicted lifetime without improved measures. The prediction lifetimes of other devices have also increased. The MTTF of the filter module is raised to  $5.23 \times 10^4$  h, which is an improvement of approximately 26.3%. In addition, it can be seen from Fig. 14 that the initial inflection point of the reliability curve has been delayed to  $3.0 \times 10^4$  h.

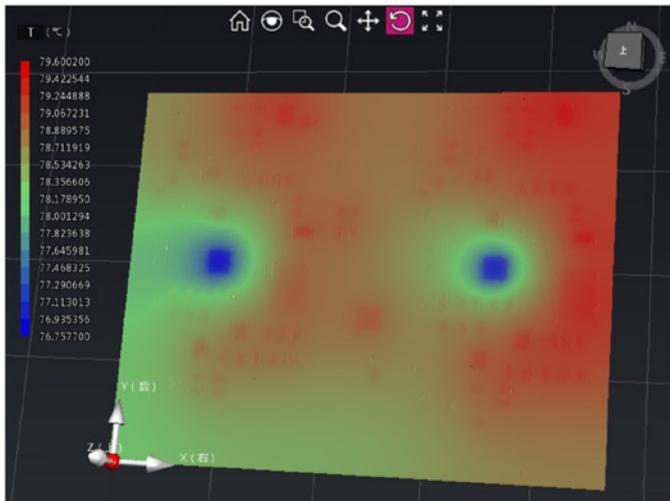


Fig. 11 The thermal simulation result of the filter module

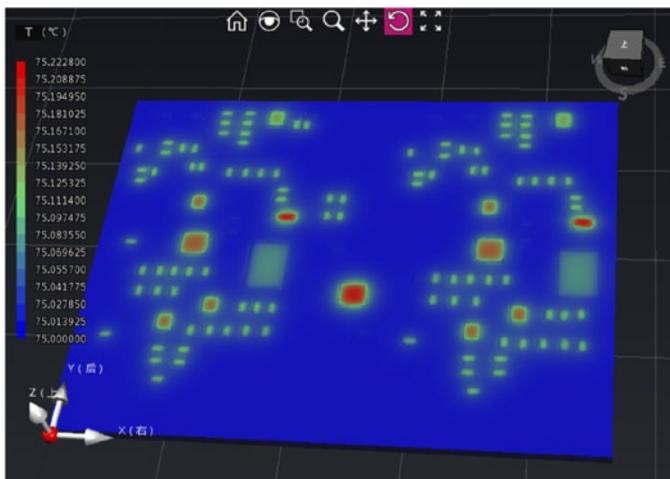


Fig. 12. The thermal simulation result with the improved measure

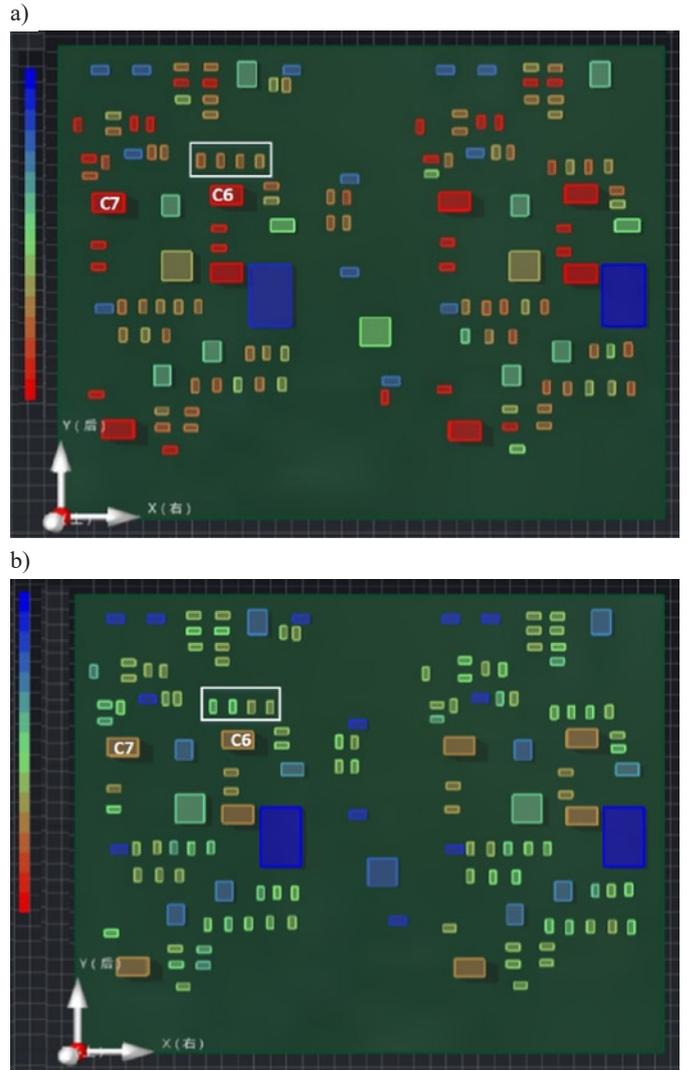


Fig. 13. Failure prediction result (a) without the improved measure (b) with the improved measure

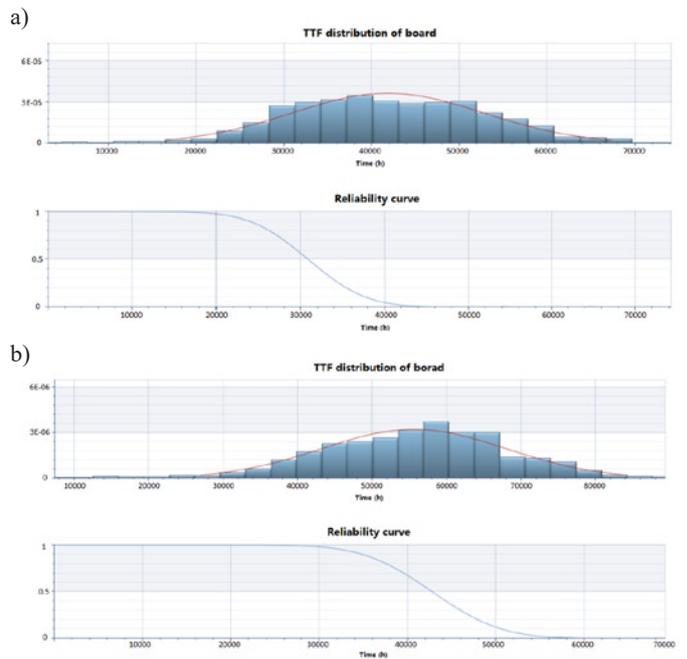


Fig. 14. Reliability analysis result (a) without the improved measure (b) with the improved measure

To validate the prediction accuracy, the errors between the prediction and measurement data need to be calculated. Therefore, the root-mean-square error (RMSE) is selected as the evaluation criterion to evaluate the prediction performance as follows:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (l_{pre}(i) - l_{true}(i))^2}, \quad (9)$$

where  $l_{pre}(i)$  is the predicted lifetime of devices and  $l_{true}(i)$  is the true lifetime of devices.

As a widely used industrial product, we have collected the historical lifetime data of some filter module devices. These historical lifetime data can be used as the true lifetime data to evaluate the prediction accuracy. Then, we select eight typical devices and calculate the RMSE. As shown in Fig. 15, the average RMSE is 0.318. The small error value indicates that the prediction accuracy is high. The fluctuation of the curve is gentle, which indicates that the prediction results are more stable.

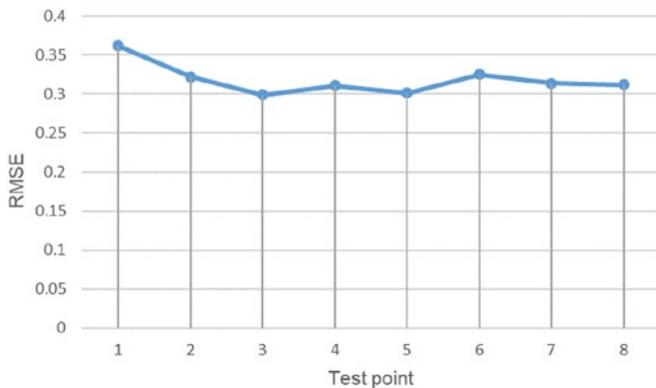


Fig. 15. Prediction error for the filter module

To compute the efficiency of parallel computing in this system, we choose serial computing under the same preconditions as the comparison object. The preconditions are as follows: First, the thermal condition and MonteCarlo simulation number ( $N=1000$ ) in the failure prediction are the same for parallel computing and serial computing. Second, a computer with a quad-core CPU and 64 GB memory is used to execute parallel computing and serial computing. Therefore, under the same precondition, the calculation efficiency is compared according to the calculation time. The following efficiency function is designed to evaluate the improvement of computational efficiency:

$$CE_i = \frac{t_i}{\sum_{i \in s} t_i}, \quad (10)$$

where  $s = (s_p, s_s)$  represents parallel computing and serial computing, respectively.  $t_i$  is the computational time of parallel computing or serial computing. The smaller the value of  $CE$ , the higher the computational efficiency. As shown in Fig. 16, the horizontal axis represents the number of simulation tasks. When the number of simulation tasks is 1, the computing efficiency of parallel computing and serial computing are equal. As the number of simulation tasks increases, the computing efficiency of parallel computing gradually increases, and the computing efficiency of serial computing gradually decreases. The average value of  $CE_{s_p}$  is 0.298, and the average value of  $CE_{s_s}$

is 0.702. Therefore, parallel computing is 40% more efficient than serial computing.

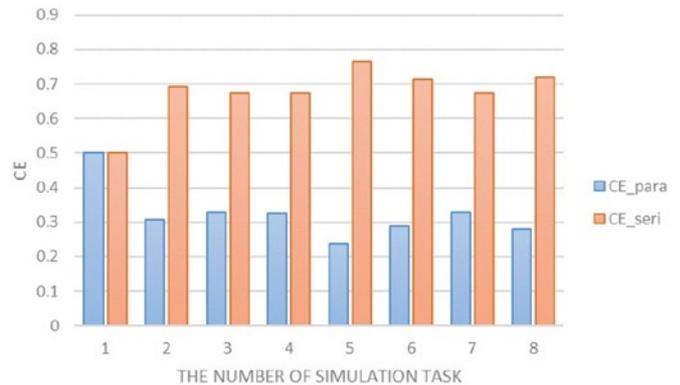


Fig. 16. The computational efficiency of parallel computing and serial computing

## 5. Conclusion

In this paper, the physics-of-failure and computer-aided simulation fusion approach as well as a corresponding software system are presented. The software system applies the PoF approach and computer-aided simulation method. Based on the integrated technology, the CAD, CFD and FEA techniques are integrated into the application system. This provides convenient and accurate access to the PoF method in engineering applications for electronic product reliability.

In the software system, the API programs have a significant impact on providing integration between the information and function modules in a uniform data format. Based on the API programs, the different function modules can not only complete their functions independently but also perform information interchange in the same software environment. Information conversion among different commercial software programs is avoided. Moreover, thermal and vibration testing are also integrated into the system framework, which allows the system to combine hardware and software simultaneously. The simulation validation and corresponding hardware tests can improve the accuracy of the reliability analysis. Therefore, with the integrated technique, the software reduces the application difficulty of the PoF approach in the engineering field. Because of the integration of advanced simulation techniques, the accuracy of the reliability analysis is also improved. Parallel computing is applied to the integration system to improve computational efficiency. Finally, based on the method and system of this paper, the remaining useful life can be evaluated by inputting the life load profile obtained from actual operation, and thus, health management can be realized.

### Acknowledgement

The authors would like to thank the National Natural Science Foundation of China (No. 61673037) for support.

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