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A review of reliability prediction methods for electronic devices

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Abstract

A wide range of reliability prediction methods is available today for electronic systems. This article classifies the commonly used and referred to reliability prediction methodologies into some categories easy to understand. A set of selected methods, which are of relevance to many industries, the aerospace industry among others, are reviewed and the possibility they offer to address the stated objectives is assessed. Their respective advantages and shortcomings are the basis for the recommendation we make to use the methods in a combined fashion (simultaneously or successively) along the product development process.

1. Introduction

The nature of the need for a reliability prediction method varies according to the product development stage (e.g., design, development or manufacturing) and its related reliability metric. Some of the objectives are listed here [1,2].

- determine if a reliability requirement is achievable,
- help to achieve a reliable design that meets end-user reliability and safety requirements with justification for the requirements,
- help to achieve a reliable manufacturing process,
- assess potential warranty risks,
- provide inputs to safety analysis,
- establish baseline for logistic support requirements (e.g., maintenance, spares, upgrades).

Several methods have been developed to address these objectives but no unique method can address all the objectives [3]. This paper reviews several methods used in the industry and assesses how they fulfill the aforementioned objectives.

First, the selected methods are presented and then discussed. Next, they are rated according to a list of criteria that are representative of an ideal method. Finally, a comparative table summarizing our viewpoint regarding the management of the objectives is suggested.

2. The concepts for reliability prediction

Table 1 lists the most common reliability prediction methods and their latest update. These methods have been grouped into three types:

- bottom–up statistical methods (BS),
- top–down similarity analysis methods based on external failure database (TD),
- bottom–up physics-of-failure methods (BP).

The first two types use statistical analysis of failure data while the last one refers to the use of physics-of-failure (PoF) models. There had been several articles on the merits and demerits of the statistical methods of reliability predictions [1,4–9]. This article clarifies the different conditions for application of these methodologies.

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Table 1
Non-exhaustive list of assessed reliability prediction methods and their latest updates

BS	SAE[a] reliability prediction method	1987
	Mil-Hdbk-217 [10]	1995
	Telcordia SR-332 [11]	1997
	CNET[b] RDF-93 [12]	1993
	Corrected 1999	
	CNET RDF-2000 [13]	2000
	British Telecom	1995
	HRD-5 [14]	
	Siemens SN29500 [15]	1999
	NTT[c] procedure [16]	1985
	Reliability Analysis Center	2000
	PRISM [17]	
TD	Honeywell In-Service Reliability Assessment Program (HIRAP) similarity analysis method [18], [19]	1999
	REMM Reliability Enhancement Methodology and Modelling [20]	2001
	DERA[d] Transport Reliability Assessment and Calculation System (TRACS) [21]	1999
BP	Airbus–Giat use of manufacturer testing results [22], [23]	1999
	CADMP, calcePWA, calceFAST (CALCE EPSC[e], University of Maryland) software [24], [25], [26]	2001

[a] Society of Automotive Engineers (USA).
[b] Centre National d'Etude des Télécommunications (France).
[c] Nippon Telephone & Telegraph (Japan).
[d] Defence Evaluation and Research Agency (UK Ministry of Defence) – now renamed to DSTL and QinetiQ.
[e] Computer Aided Life Cycle Engineering (CALCE) Electronic Products and Systems Center (USA).

2.1. Bottom–up statistical methods

BS methods use prediction models developed from statistical curve fitting of component failure data, which may have been collected in the field, in laboratory or from manufacturers. The assumption is made that system or equipment failure causes are inherently linked to components whose failures are independent of each other.

The models used in BS methods are mainly based on two types: "parts count analysis" and "parts stress analysis". As shown in the examples given in Table 2, "parts count analysis" models assume that the component operates under typical operating conditions, whereas "parts stress analysis" models require an input of the parameters that are included in the models of the component failure rate, λ [5].

Table 2
Examples of models used in BS methods for microcircuits

Parts count	$\lambda = \lambda_G \Pi_Q \Pi_L$ (Mil-Hdbk-217)	(1)
	$\lambda = \lambda_a \Pi_Q$ (CNET)	(2)
Parts stress	$\lambda = (C_1 \Pi_T + C_2 \Pi_E)\Pi_Q \Pi_L$ (Mil-Hdbk-217F)	(3)
	$\lambda = (C_1 \Pi_t \Pi_T \Pi_V + C_2 \Pi_B \Pi_E \Pi_s)\Pi_L \Pi_Q$ (CNET)	(4)

The factors for failure rate calculations follow:

- λ_G, λ_a are generic or average failure rates (or base failure rates) depending on the device complexity and technology,
- Π_Q, Π_L are quality and device factors depending respectively on the quality of the device as stated by inspection and on the time the device has been manufactured,
- C_1, C_2 are failure rate constants depending on the device complexity (circuit, technology, package and pin count),
- In CNET, Π_B, Π_T and Π_s are respectively package technology factor, technology and function factor and package pin count factor,
- Π_t in CNET and Π_T in Mil-Hdbk-217 are temperature acceleration factors (steady state operating temperature),
- Π_V is a voltage stress factor depending on the ratio of applied voltage to the rated voltage of the component,
- Π_E is an environmental factor depending on a tabulated description of the environment.

These models may be detailed as in the last project of CNET, known as RDF2000, where models have been defined for boards and hybrid circuits as well. The model for microcircuit is now [13]:

$$\lambda = \lambda_{\text{die}} + \lambda_{\text{package}} + \lambda_{\text{overstress}} \quad (5)$$

where

$$(1)\ \lambda_{\text{die}} = (\lambda_1 N \mathrm{e}^{-0.35a} + \lambda_2)\Sigma(\Pi_t \tau) \quad (6)$$

with

- λ_1, base failure rate per transistors,
- N, number of transistor,
- a, manufacturing year minus 1998 (base year),
- λ_2, failure rate depending on technology know-how,
- $\Sigma(\Pi_t\tau)$, sum of all the temperature factors (Π_t) times the time (τ) during which this particular temperature is reached.

$$(2)\ \lambda_{\text{package}} = 2.75 \times 10^{-3}\Pi_\alpha(\Sigma\Pi_n\Delta\tau^{0.68})\lambda_3 \quad (7)$$

with

- Π_α, thermal expansion coefficient difference factor,
- Π_n, thermal cycle factor depending on the number of yearly cycles of the said $\Delta\tau$,
- $\Delta\tau$, amplitude of one thermal variation,
- λ_3, package base failure rate.

(3) $\lambda_{\text{overstress}} = 0$, when the microcircuit is not an interface circuit, otherwise

$$\lambda_{\text{overstress}} = \lambda_{\text{EOS}} \quad (8)$$

with λ_{EOS}, failure constant for electrical discharges (electrical over stress) depending on the application field.

Some users modify BS reliability models with a corrective multiplicative factor. This factor is derived from the user's experience through proprietary field or test data.

Another evolution of these BS methods is the PRISM software where the global model is similar to RDF2000 ($\lambda = \lambda_{\text{die}} + \lambda_{\text{package}} + \lambda_{\text{overstress}}$). PRISM includes terms for failure rates from temperature cycling and solder joint but treats those contributions as constant failure rate without justification. This method also offers the possibility to make a simple similarity analysis, to use field experience databases and to weight the overall quality factor with "Process Grading factors". These factors depend on components, design, manufacturing, supply chain, mechanical fatigue, management, and analysis tools. This is a mix of methods with the implementation of top–down similarity analysis.

Once the failure rate of each component has been computed, the reliability of the board is calculated by summing up all λ. In both the models discussed in this article (Mil-Hdbk-217 and RDF2000), a constant failure rate is associated with the connections and assemblies weighed up by the thermal cycles undergone during the life.

2.2. Top–down similarity analysis methods

Top–down similarity analysis methods based on proprietary databases (TD) use similarity analysis between previous systems or sub-systems with a known level of reliability and newly designed systems.

All failure causes, and not only component failure rates, are considered and therefore, failure cause analysis is of the utmost importance.

A typical TD approach is summarized by the following steps [18,19]:

- collection of failure data from the field,
- assessment of field data (particularly equipment/board failure causes, calculation of the associated reliability),
- determination of failure rates at the circuit card assembly (CCA) level, based on the number of unique CCAs per equipment,
- determination of the failure rates at the piece part and interconnect levels based on the number of piece parts and interconnects per CCA,
- determination of the failure rates for equipment/board failure causes not related to piece parts and interconnects,
- creation of the in-service failure rate database with all previous pieces of information according to the following physical model categories: passives (low/high complexity), interconnections, semiconductor (low/high complexity), manufacturing process, design process, other failure causes,
- comparison of existing to proposed designs or similarity process with the following steps:
  - review products for which field data is available,
  - identify characteristic differences (e.g., design, manufacturing, and so on),
  - quantify the impact of the characteristic differences on each physical model category,
  - incorporate field data (percent of each physical model category, overall end item or assembly failure rates),
  - compute the new item (board, CCA or equipment) failure rate according to:

  $$\lambda = \lambda_p \sum_{a=1}^{n}(D_a \times F_a d) \quad (9)$$

  where λ_p is the field failure rate for the predecessor item, D_a is the distribution percentage for physical model category a, F_a is the difference factor between the new and previous items for category a, and n is the total number of physical model categories.

Other TD methods also use the knowledge of reliability experts to assess and weight the different inputs [21].

2.3. Bottom-up physics-of-failure methods

BP methods requires comprehensive knowledge of the thermal, mechanical, electrical and chemical life cycle environment as well as processes leading to failures in the field in order to apply appropriate failure models.

The first method [22,23] uses the manufacturer's reliability data test results (highly accelerated stress test, temperature humidity bias, temperature cycling, ...) at the components level.

These data are computed with the help of statistical laws (Weibull, χ^2) with confidence levels generally set at 60%. From these failure rates, appropriate acceleration models are applied to derive component failure rates applicable to the life cycle.The acceleration models are the following:

- Arrhenius's law for temperature:

$$\mathrm{AF} = \exp\left(\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right) \tag{10}$$

  where, AF is the acceleration factor, E_a is the activation energy of the failure mechanism, k is the Boltzman constant, T_1 and T_2 are the temperature of use and stress respectively.
- Voltage acceleration:

$$\mathrm{AF} = \exp(\beta(V_2 - V_1)) \tag{11}$$

  where, AF is the acceleration factor, β is a constant depending on technology, V_1 and V_2 are the voltages of use and stress respectively.
- Gunn's law for humidity:

$$\mathrm{AF} = \exp(\beta(\mathrm{RH}_2 - \mathrm{RH}_1)) \tag{12}$$

  where, AF is the acceleration factor, $\beta = 0.08$, RH_1 and RH_2 are the humidity level of use and stress respectively.
- Coffin–Manson based law for thermal cycling fatigue:

$$\mathrm{AF} = \left(\frac{\Delta T_2}{\Delta T_1}\right)^2 \left(\frac{F_1}{F_2}\right)^{0.33} \tag{13}$$

  where, AF is the acceleration factor, ΔT_1 and ΔT_2 are the amplitude of thermal variations of use and stress respectively, F_1 and F_2 are the frequency of the use and stress cycles respectively.

The component failure rate is the sum of all the failure rates (thermal, humidity, voltage, thermal cycling). The board failure rate is the sum of all the failure rate of the components.

The highest level of BP methods (CALCE software) predicts the time to failure of board or component by targeting the most common failure mechanisms at various sites of the component or assembly. Required information includes material characteristics, geometry, environmental, and operational loads. The failure mechanisms and associated failure models used for assembly analysis are

- Thermo-mechanical solder joint fatigue (1st order)

$$\Delta\gamma = F\frac{L_D}{h}\Delta\alpha\Delta T_e \tag{14}$$

  This is the Engelmaier model for Surface mount packages where, $\Delta\gamma$ is the shear strain range, F is a correction factor, L_D is the component length, h is the solder joint height, $\Delta\alpha$ is the thermal expansion coefficient (CTE) difference between component and board, ΔT_e is the thermal cycle range.
  The damage is then assessed by

$$N_f = \frac{1}{2}\left(\frac{\Delta\gamma}{2\varepsilon_f}\right)^{1/c} \tag{15}$$

where N_f is the number of cycles to failure, $\Delta\gamma$ is the calculated shear strain range, $2\epsilon_f$ is the fatigue ductility coefficient (ϵ_f is the strain to fracture), c is the fatigue ductility exponent (material characteristic).

Other second-order strain (as well as damage) models or Finite Element Models exist for more complex packages like BGA (Ball Grid Array).

- Vibration solder joint fatigue

$$Z_0 = \frac{9.8\ G_{in}}{f_n^{1.5}} \tag{16}$$

This is the Steinberg model where, Z_0 is the maximum displacement of the board, G_{in} is the board acceleration input, f_n is the first natural frequency of the board.

The damage is then assessed by Basquin's relationship:

$$ZN_f^b = \text{constant} \tag{17}$$

where Z is the board out-of-plane displacement, N_f is the number of cycles to failure, b is a solder joint material characteristic.

This relationship can be written in the following form:

$$N_f = N_{f_0}\left(\frac{Z_0}{Z}^b\right) \tag{18}$$

where N_f is the unknown number of failures for the applied Z, N_{f_0} is the number of cycles to failure for Z_0—displacement associated with first natural frequency.

A cumulative analysis may also be led through the implementation of Miner's rule:

$$N_f = \frac{0.7}{\left(\frac{f_v/f_{th}}{N_v} + \frac{1}{N_{th}}\right)} \tag{19}$$

where N_f is the solder joint fatigue life, N_v (N_{th}) is the number of vibration (thermal) cycles to failure, f_v (f_{th}) is the frequency of vibration (thermal) cycles.

The reliability of a board is the reliability of the weakest point on the board with the associated failure site (or location), mode, and mechanism identified.

Similarly, the same method is used at the component level [25,26].

3. Discussion on the methods

The discussion focuses on the following areas: the sources of the data, the inputs, the sensitivity of the models and the outputs.

Table 3 lists the sources of data and original environment of all the methods listed previously. The more generic the sources of data and the environment they come from, the better. However, each method considers the environment differently: BS methods use environmental and load fitted factors (for operating mode with or without storage) based on failure modes (not causes) whereas BP methods use load profiles.

This comes from the fact that the environment for the BS methods derives from the failure databases that may be hampered by the following issues:

- a large amount of experimental data is required to set up representative fittings,
- these fittings become pessimistic over time because of data aging and component reliability improvement: HRD-5 and PRISM for example are designed to take this reliability improvement into account but HRD-5 is insensitive to the component technology,
- new technologies are conservatively dealt with, although PRISM and CNET latest issues tend to address this problem,
- extrinsic (e.g. EOS) and intrinsic (e.g. oxide weakness) failures are mixed and are used to get an aggregate figure without mathematical or physical justification.

Similarly, TD methods need a regular updating of their failure in-service databases, which depends on the companies policies and investments. Eventually, all removals need to be analyzed, failures tracked down and failure rates stored for each cause of failures at each level (item, equipment, board, component).

For the Airbus–Giat method, manufacturers' reliability results are needed and their relevance must be checked.

The inputs to the methods are summarized in Table 4. As far as BS methods are concerned, PRISM is somewhat different and allows for further inputs of a different kind: an assessment of the design, manufacturing, supply and testing processes at system or sub-system level may be used to mitigate the overall results (process grading). Similarly, PRISM also allows the direct input of environmental and operational parameters (temperature cycling, shock, relative humidity and vibration frequencies).

However, in most cases with BS methods, the result reflects the reliability of the components, which are no longer the main contributors to the system reliability due to quality improvement and system increased complexity [27,28] (system level failures are overlooked).

Results with TD methods could be refined by a large use of tests and field data.

BP methods like CALCE software need a detailed knowledge of information, which might be considered as proprietary by manufacturers. These methods also require significant time resources. A prior knowledge of failure mechanisms of failed products is also needed to choose models geared to actual failure mechanisms. Similarly, there is an extensive selection of operational and environmental parameters, which also proves to be an advantage to "customize" the method.

The elements that measure the sensitivity of the models are the next issue to be discussed.

Table 3
Sources of data and environment of the reliability prediction methods

Method	Sources of data environment
MIL-Hdbk-217	Military
Telcordia SR-332	Telecom
CNET	Ground Military
RDF-93 and 2000	Civil Equipment
SAE Reliability Prediction method	Automotive
BT-HRD-5	Telecom
Siemens SN29500	Siemens products
NTT procedure	Telecom
PRISM	Commercial—Military
HIRAP	Commercial aviation
REMM	Automotive—Military
TRACS	Military vehicles
Airbus–Giat method	Not specific[a]
CALCE software	Not specific

[a] The validation has only been made on avionics for active components.

Table 4
Inputs to the different reliability prediction methods

Method	Inputs
BS	Part types, count and quality level Application environment System configuration
TD	Failure rates of several similar items Characteristic differences
BP	Material properties Design characteristics Assembly techniques Usage environment Functional loads

In BS methods, the temperature influence is simplified by the use of Arrhenius's equation: the influence of thermal gradients and ramp rates are downplayed. Furthermore, the sensitivity to operational and environmental parameters varies among the methods [5,29] and the predictions are optimistic or pessimistic depending on the application: the appropriate method should hence be carefully selected.

However, the models account for a great deal of components (integrated circuits, capacitors, resistors, transistors, diodes, thyristors, mechanical and electromechanical devices) and their implementation is easy to use.

PRISM has once again another feature: a similarity analysis based on identified failure causes could be led using collected field data.

This is halfway from TD methods, which models account for internal design and manufacturing failures at a higher level (board, equipment or system).

As far as BP methods are concerned, a difference shall be made between Airbus–Giat and CALCE methods. The former considers only intrinsic failures and does consider manufacturing process variations (through manufacturers' data), whereas the latter overlooks intrinsic failures (the electronic function is not described) nor does it consider manufacturing process variation. Otherwise, common characteristics are

- new technologies are not penalized by models,
- models are product-independent (only dependent on materials),
- overstress environmental conditions are not considered.

CALCE method has also some specific patterns: there is an extensive choice of stress and damage models (e.g., depending on packages) and the failure mechanisms are limited to those mainly responsible today for field failure return (assembly solder joint).

The outputs of the methods are quite different. BS methods provide the user with an average failure rate of the average production. Failures are considered to occur randomly and failure rate is therefore considered as constant. This means that screening is assumed efficient enough for the components to reach the constant failure rate domain (NTT, HRD-5, Mil-Hdbk-217). Some models, however, allow refinement of the failure rate in case of an insufficient screening (Telcordia, Siemens, SAE and RDF). The main features of such an output are listed below:

- no failure mechanism is characterized,
- no confidence level is provided,
- an estimate of the probability of the success of the mission is available for further calculation (e.g., maintenance, spare parts),
- no time is given as to when an equipment should be replaced,
- uncertainties remain as to which components are critical [29].

TD methods output a failure rate, which is monitored over time (a constant failure rate is assumed in HIRAP). This failure rate is an average of a given production. Failure causes are identified but no confidence level is provided.

The outputs from BP methods differ between Airbus–Giat and CALCE methods. The former delivers an average failure rate of a given production. The knowledge of failure modes is extensive and specific through the manufacturer's data. Furthermore, some data on the confidence level are given. However, this is limited to a component and board level computation and acceleration models should be carefully selected [30].

The latter of the two methods delivers a time to failure for the component/board. Failure site, mode, and mechanism are identified, which allow for improvements. This figure is, however, limited to component or board and inputs on the distributions on material, geometry and environment is required to obtain confidence level on the results. Furthermore, the use of this time-to-failure metric is not yet included in many traditional availability, maintenance, or safety assessment tools.

4. Comparison criteria and assessment

According to our discussion, Table 5 rates subjectively the characteristics of these methods in view of a set of criteria deemed appropriate. As can be seen no single method addresses all criteria comprehensively: tradeoffs need to be made between the models usability and the required amount of detailed information.

Not all these criteria bear the same significance. Number one, three, five, and eight (marked by an asterisk) seem to be more important to be achieved. Therefore, it clearly appears that TD as well as BP methods should be recommended for their intrinsic characteristics.

Accuracy addresses the meaning of the calculated reliability figure. Relative implies that only a comparison can be performed whereas absolute means that the approach intent is to provide a number typical of the product.

Ease of data exchange grades ability of the approach to allow cross-industrial comparisons of obtained figures and use of databases and models.

Amount of devoted resources evaluates the material and human resources (e.g., software, test equipment, failure analysis equipment) necessary to adequately perform the reliability prediction process.

Time to obtain reliability estimate evaluates the amount of time necessary to adequately perform the reliability prediction process.

Table 5
Comparison criteria for use

Comparison criteria	BS	TD	BP
Accuracy*	Relative	Absolute	Absolute
Ease of data exchange	Easy	Difficult	Easy
Amount of devoted resources*	Small	Important	Extensive[a]
Time to obtain reliability estimate	Short	Short	Long
Ease of customization*	No	Yes	Yes
Traceability	Difficult	Easy	Easy
Repeatability	High	Medium	Low
Ability for evolution*	Difficult	Yes	Yes

[a] If no material, part, or board library is available.

Ease of customization grades ability of the approach to allow for selecting database and models, modeling operational and environmental parameters and plugging in test and field data according to application-specific environment and failures.

Traceability reviews the possibility to trace back the method building process, whether it is through experimental data collection, failure analysis or model development.

Repeatability assesses the reliability prediction variations caused by the subjectivity brought by the user.

Ability for evolution and regular updating evaluates ability of the approach to keep pace with technology changes in theory and in practice.

5. Management of objectives

There is another way to weigh up the different methods. Table 6 rates BS, TD, and BP methods compared to the satisfaction of the objectives stated in the introduction.

This is a subjective evaluation of the methods and their ability to contribute to the overall reliability availability maintainability safety assessment process. However, it shows that BP methods are fit for design trade-off, board qualification, and manufacturing improvements.

BS empirical data-based methods are appropriate for delivering an average reliability figure for an average production, which may be appropriate for the following stages: selection and management of components, figure of merit comparison, warranty, maintenance planning, contract negotiation.

At the current level of availability of tools, TD methods offer a very good trade-off and satisfy most of the objectives, but one should remember they cannot be standardized as most data are proprietary. PRISM could lead the way to TD method standardization. Nevertheless, some methodologies of PRISM, which can be considered as a mix between BS and TD, may avoid the need for large internal failure data collection.

What this table shows is mostly that the purpose of a reliability prediction must be known before choosing a method.

6. Conclusions

Today, empirical and PoF-based reliability prediction methods present both advantages and shortcomings. On the one hand, PoF methods can successfully be used for qualification and quality assurance in order to improve design and manufacturing robustness. On the other hand, statistical methods, based on and enriched by thorough failure cause analysis, external or internal

Table 6
Comparison criteria as management of objectives

Objectives	BS	TD	BP
Determine if a reliability requirement is achievable	Low[a]	Yes	Yes
Help to achieve a reliable design			
• By tracking down overstressed parts	No	No	Yes
• By performing a failure root-cause analysis	No	Yes	Yes
• By comparing design trade-off studies	Yes	Yes	Yes
Help to achieve a reliable manufacturing process	No	No	Yes
Assess potential warranty risks	Low[a]	Yes	No
Provide inputs to safety analysis	Low[a]	Yes	No
Establish baseline for logistic support requirements	Low[a]	Yes	No

[a] Use of external databases makes the reliability figure relative and therefore brings little confidence to subsequent steps of the process.

database and similarity analysis, are fit for rapid assessment and may supply helpful figures for further steps including safety analysis, warranty risk management, and field support.

The tables given in this paper will help to define

- what can be told from the methods used by designers or suppliers,
- which method to use depending on the predefined objectives.

It is our belief that the best reliability prediction could only be achieved by a combined use of different methods, depending on the design, development or manufacturing phase. A specific reliability figure is of less concern compared to the confidence in the effective reliability level of the product to be sold. The use made of the reliability prediction concepts should also be coherent, i.e., based on sound principles, explained to the customer throughout the whole process. This is what is intended in new reliability standards such as IEEE 1413 or SAE J1000. The description of which method is to be used at a given product development stage, the explanation of the reasons why this method is used and the delivery of the results associated to the various applied methods along the process will insure that the reliability requirements have been met.

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