Reliability & Manufacturability

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Reliability Engineering

- Product quality and reliability are among the most important factors for determining success in a high-technology market.
- Reliability is a measure of the probability that a system will continue to function properly.
- Producing reliable products requires a comprehensive approach that affects all aspects of the design and manufacturing process – so, all engineers benefit from a basic understanding of some of the terminology and methodologies in use.

Design for Reliability (DFR)

- DFR describes the processes by which the reliability of the final product is taken into account and ensured during the design phase.
- DFR activities begin at product inception and continue throughout the design process.
- DFR includes procedures for gathering data from manufacturing, product support and other groups, and putting these data into a database that contains all of the "local" knowledge available to assist with future designs.
- DFR leads to fewer design iterations, reduced costs, and increased profits.

Reliability & Manufacturability

- Many failures are caused by defects or stresses introduced during the manufacturing process.
- These kinds of problems are often caused by a system not being as easy to manufacture as possible.
- Therefore, reliability and manufacturability have significant correlation.
- The fundamental idea is that the process of design is far more inclusive than just considering the raw performance of some prototype; good engineering considers manufacturing, testing, useful life, even packaging, shipping and eventual recycling and disposal of the product.

Causes of System Failure

- Systems may fail for many reasons. For example:
  - The design may be faulty
  - The system may be stressed beyond its specified limits
  - Variations in the components comprising the system may be too large
  - The system might wear out (mechanical & electrical)
  - There may be an unanticipated sequence of events
  - There may be inadequate quality control in the manufacturing processes
- Let's examine the failure modes further and see how we might prevent them:

Faulty Design

- The classic example of a faulty design leading to a catastrophic failure is the Tacoma Narrows bridge collapse in 1940.
- If the designers had considered all of the possible resonances and how they might be excited (e.g., by wind or traffic), the collapse might have been avoided.

http://www.youtube.com/watch?v=P0Fi1VcbpAI&feature=related

Faulty Design Continued

- Faulty designs also include those designs that do not properly take into account the manufacturing processes or normal usage.
  - Design for manufacturability (DFM), for example, takes into account the assembly process and sequence to ensure that components will not be damaged by later steps in the process. For example, the designer should ensure that a part is not damaged by the heat of wave soldering or solder reflow, or by the chemicals used to clean a board, or by the physical stress of a later step in the assembly process.
  - Logic circuits often generate a lot of noise on the power supplies, which may adversely affect other circuits.

Faulty Design Continued

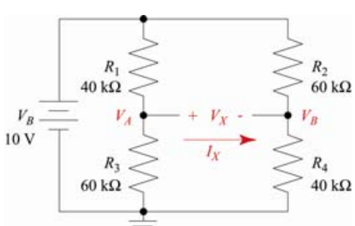
- Faulty designs also include those designs that do not properly take into account the manufacturing processes or normal usage.
  - Both wired and wireless communication circuits (e.g., ethernet, 802.11) can interfere with the operation of electronic equipment and other communication services. That is why many products must meet FCC specifications (all electronic products are subject to the Part 15 rules for unintentional emission of RFI).
  - Even electrical motors, relays and other systems can generate RFI and must meet Part 15 rules.

A Design may be Stressed Too Far

- Part of a good design includes building in reasonable safety margins and providing clear operating instructions or safeguards to be sure that parts aren’t stressed to the point of failure.
- Simple examples include:
  - fuses
  - diodes to prevent damage if a battery is installed backwards
  - thermal shutdown circuits
  - alarms and warning lights

Component Variations may be Too Large

- All components have non-zero tolerances (e.g., most resistors are ±10%, some caps are +50%/ -20%, in IC design we talk about PVT analysis)
- Conservative designs allow for unlikely combinations of component values
  - The strictest requirement is true “worst-case analysis” For example:



$$V_{X\max} = V_{Bat\max}\left(\frac{R_{3\max}}{R_{1\min}+R_{3\max}} - \frac{R_{4\min}}{R_{4\min}+R_{2\max}}\right)$$

Such extreme combinations become nearly impossible for any reasonable number of parameters.

The System May Wear Out

- Mechanical components can wear out:
  - rotating machines can have bearings & bushings fail
  - switches and connectors can have contact surfaces scratched off or springs become too weak
  - pieces with stress applied can fracture or deform
- Electrical components can “wear out” as well:
  - metal lines on an IC can become open circuits due to metal migration
  - electrolytic capacitors can have their fluids evaporate away, which raises ESR, which raises heat & evaporation; eventually the safety seal pops
- Some of these failure mechanisms increase rapidly with increasing temperature.

Preventing Wear Out

- There are a number of ways of preventing or delaying wear out failures:
  - the number of mechanical components can be minimized
  - systems can be designed for easy maintenance
  - higher quality components can be used (e.g., cheap aluminum electrolytic caps may fail in 1-3 years in a power supply, but good quality caps can last 20 years)
  - the number of wires and connectors can be minimized
  - power dissipation and other causes of elevated temperature can be avoided, minimized or cooled
  - parts can be derated

An Unanticipated Sequence of Events

- This failure mode is most likely in software, or programmed systems, but it can occur in hardware as well.
  - One example is a “crowbar” circuit used to short the outputs of a DC power supply when regulation is lost; if the power supply is unexpectedly used to charge a high-current-capacity battery (e.g., a car battery) and it shorts the output, the battery may supply enough current to destroy the crowbar circuit.
  - This kind of failure can only be avoided by carefully thinking through all possible uses (and abuses) of a product.

Inadequate Quality Control

- A supplier may change the material used in some component without telling you and this may cause a problem that didn’t exist before
  - For example; a supplier might change the material used to coat an electrolytic capacitor and it might react with a cleaning solution used on the PCBs during manufacturing and compromise the hermetic seal on the component, which would lead to early failures
- This kind of error can be avoided by closely monitoring all suppliers and by continued careful incoming parts inspection

DFR Procedures

- The following seven DFR activities have been found to significantly increase product reliability (listed in approximate order of increasing efficacy):
  - Failure modes and effects analysis (FMEA)
  - Component stress derating
  - Supplier qualification testing
  - Making reliability goals a company priority
  - Supplier process audits
  - Worst-case analysis
  - Thermal design and measurement

Failure Modeling

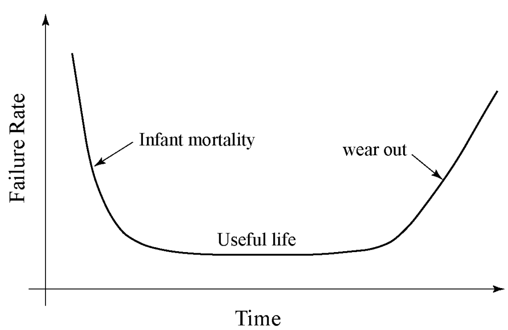
- There are two general classes of systems: those that can be repaired and those that cannot.
- For repairable systems reliability is usually expressed as:
  - Rate of occurrence of failures (ROCOF), which is also called the *failure rate*, λ
  - Or, mean-time between failures (MTBF)
  - If λ is constant, then $\lambda = MTBF^{-1}$

Failure Modeling

- There are two general classes of systems: those that can be repaired and those that cannot.
- For non-repairable systems, reliability is expressed as:
  - mean-time to failure (MTTF)
  - Or, the *hazard rate*, λ (λ is also called the failure rate)
  - If λ is constant, then we again have $\lambda = MTTF^{-1}$

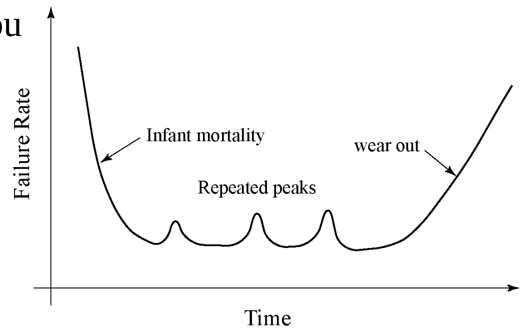
Failure Modeling

- The most commonly used model for the failure rate of a system is the "bathtub curve." It has three regions as shown:
  - Infant mortality: early failures caused by faulty components or manufacturing
  - Useful life: a region where most failures have already occurred
  - Wear out (old age): the region where parts start to wear out and failures increase



Failure Modeling

- Many people now say that the "bathtub curve" is not an accurate model.
- Instead, there is a repetition of peaks and valleys if the failure rate is plotted over time.
- This is what you would expect to happen if you have done a good job of making the system very reliable!



Failure Analyses

- There are so-called "parts-count" reliability prediction methods; all are modifications of the original given in MIL-HDBK-217
  - Parts-count predictions of MTBFs are notoriously inaccurate, but may still be useful for comparing systems and to help engineers think through possible failure modes
- Fault-Tree Analysis (FTA)
  - Identify possible faults and enumerate all of the possible causes of each fault
  - Done in a top-down fashion and represented by a logic diagram that looks like an inverted tree

Design for Reliability (DFR)

- A common approach to DFR is:
  - Do a FTA to think through and enumerate all possible failure modes
  - Develop an initial estimate of the failure rate using some form of parts-count reliability prediction (which can be used to compare different approaches)
  - Build prototypes
  - Do extensive stress testing to identify the dominant failure mechanisms
  - Modify the design (or manufacturing process etc.) to correct failure mechanisms
  - Repeat previous three steps

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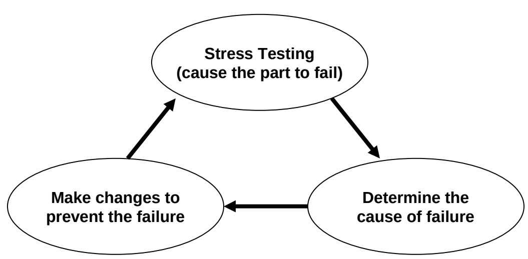


Stress Testing

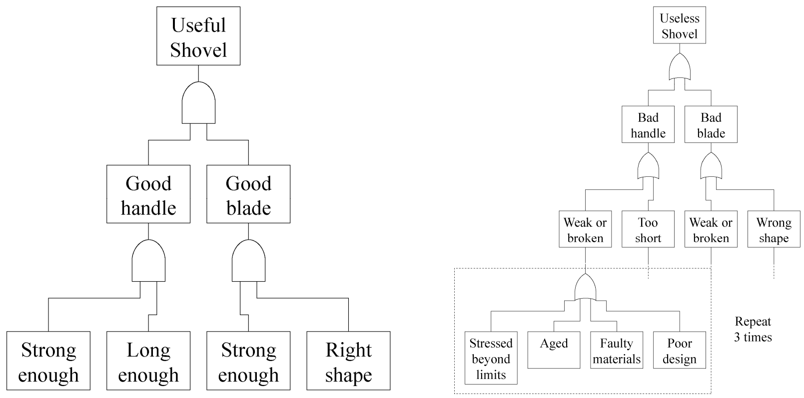
- The primary goal of most stress testing is to induce failures so that the underlying causes can be determined. They are called
  - highly accelerated stress test (HAST)
  - stress-life test (STRIFE)
  - highly accelerated life test (HALT)
- Common types of stress are:
  - vibration
  - elevated temperature and/or humidity
  - rapid thermal cycling
  - power cycling
  - increased load
  - increased or decreased supply voltage

Fault Tree Analysis

- It is sometimes easier to generate a fault tree by first considering a "success tree"
- You then invert every logic function to get the fault tree
- As an example; consider a shovel. What is needed for it to be usable?
  - A good handle (i.e., strong enough and long enough)
  - A good blade (i.e., the right shape and strong enough)
- Let's draw both a success tree and a fault tree for the shovel:

Fault Tree Example

- (a) a the success tree and (b) a the fault tree



Parts-Count Reliability Prediction

- As noted before, there are several common objections to parts-count reliability prediction:
  - Only a small proportion of failures in modern electronic equipment are caused by components failing (but others strongly disagree with this objection)
  - Supposedly "high-grade" components are no longer any more reliable than commercial-grade components
  - Many failures do not have the exponential dependence on temperature assumed by such analyses
  - Other parameters used in these analyses as multipliers on the basic failure rates are of doubtful validity
  - The models don't take many important factors into account (e.g., electromagnetic interference, assembly problems)

Note that all of these can be fixed!

Parts-Count Reliability Prediction

- We begin by defining the *reliability function* (or survival probability) $R(t)$
- $R(t_1)$ is the probability of the system having no failures from $t = 0$ (the time the system begins to be used) until time t_1. In other words, it is the probability that the system continues to function properly for that length of time.
- Let's find a relationship between $R(t)$ and the failure rate of a system, λ

Parts-Count Reliability Prediction

- Consider a large number of identical systems with failure rate λ
- Suppose that at time t there are N of the systems still working properly
- In the next small time dt (i.e., from t to $t + dt$) the number of systems expected to fail is dN where

$$\frac{dN}{dt} = -\lambda N$$

- Rearranging, we get the differential equation:

$$\frac{dN}{N} = -\lambda dt$$

Parts-Count Reliability Prediction

- Solving the differential equation yields

$$\ln N = -\lambda t - C_1$$

- or

$$N = C_2 \exp(-\lambda t)$$

- If there are N_0 items at $t = 0$, then $C_2 = N_0$ and we have

$$N = N_0 \exp(-\lambda t)$$

- Finally, the reliability function is the probability that N of the original N_0 systems are still operating at time t, which is $R(t) = \frac{N}{N_0} = \exp(-\lambda t)$

Parts-Count Reliability Prediction

- Now consider a system with M components that are all critical (i.e., the failure of any one of them will cause the system to fail)
- This is called a *series* system and the system reliability function is (the failures are assumed to be independent)

$$R_{sys}(t) = \prod_{i=1}^{M} R_i(t)$$

- Note that this is just multiplying independent probabilities

Parts-Count Reliability Prediction

- Now consider a system with *M* components that must *all* fail for the system to fail
- This is called a *parallel* system and the system reliability function is found below

$$\text{Probability of failure} = 1 - R_{sys}(t) = \prod_{i=1}^{M} \left\{1 - R_i(t)\right\}$$

$$\text{Therefore } R_{sys}(t) = 1 - \prod_{i=1}^{M} \left\{1 - R_i(t)\right\}$$

- Then, find λ: $R(t) = \exp(-\lambda t)$

$$\Rightarrow \lambda = \frac{-\ln R(t)}{t}$$

Parts-Count Reliability Prediction

- Finally, remember that if λ is constant, then MTBF = λ^{-1}
- We can combine the equations for series and parallel blocks and find the MTBF of complex systems using a reliability block diagram
- The estimates of the failure rates of the individual components in the system are calculated based on their nominal failure base rates, λ_0, and other factors
- The other factors take into account the product quality, environment, temperature and so forth – see the handout