Reliability predictions in product development

Proof Engineering Co

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- Review of reliability theory
- Ways to predict part reliability
- Converting parts reliability into a system reliability
- Ways to improve reliability

Uses of reliability predictions

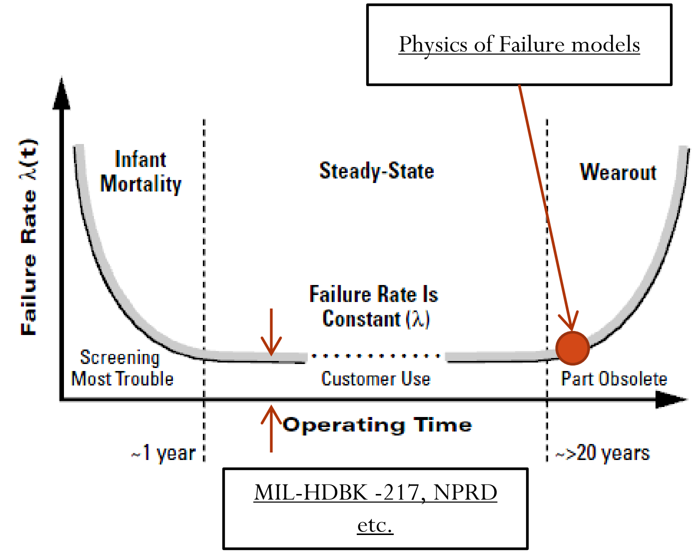
- Internal
  - Compare competing designs
  - Find design weaknesses
  - Objectives for testing
  - Estimate warranty costs
  - Used for marketing purposes
- External
  - Customer requirement
  - Maintenance budgeting

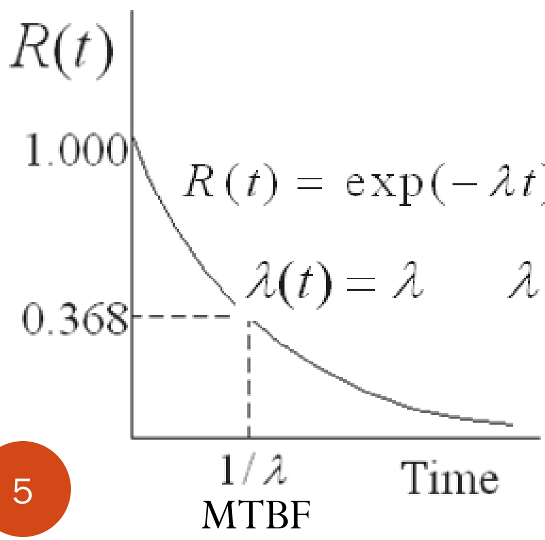
Reliability definitions

- **Reliability** is the probability that a product or service will operate properly for a specified period of time under the design operating conditions without failure.
- **Mean Time To Failure (MTTF):** It is the average time that elapses until a failure occurs.
- **Mean Time Between Failure (MTBF):** It is the average time between successive failures.
- **Failure rate** is the rate of product failures expressed as a function of time. $\lambda = 1/MTBF$

Basic theory

- Reliability models are based on a number of statistical distributions
- Exponential distribution with constant failure rate is very common and simplest to use for hardware





$$R(t) = \exp(-\lambda t) = 1 - F(t)$$

$$\lambda(t) = \lambda \qquad \lambda > 0, \quad t \geq 0$$

Measures	Equivalence	Definitions
$F(t)$	$= 1 - R(t)$	**The cumulative probability distribution function (CDF):** Probability of a component failing at time *t*. Alternately, probability of first failure at or before time *t*. Experimentally, the cumulative percent failure at each observed failure time when plotted versus time (usually on a cumulative probability paper) graphically displays this function.
$R(t)$	$= 1 - F(t)$	**Reliability function:** Probability of a component surviving a time *t*. Alternately, the number of units surviving at time t divided by the initial number of units.
$f(t)$	$= \frac{dF(t)}{dt}$	**Probability density function (PDF):** Probability of failure at an instant (a time period that is infinitesimally small). Experimentally, it is the instantaneous slope at time *t* found on the CDF plot.
$\lambda_{Cum}(t)$	$= F(t)/t$	**Cumulative failure rate:** Cumulative failure rate of a component at time *t*. Experimentally, this is cumulative percent failure at time *t* divided by the observed failure time *t* for each observed failure point when plotted versus time (usually on log-log paper) graphically displays this function. A linear relationship can exist to the hazard rate (see Appendix A).
$\lambda(t)$	$= \frac{f(t)}{R(t)} = -\frac{1}{R(t)}\frac{dR(t)}{dt}$	**Instantaneous failure rate, hazard rate, or just the failure rate:** Probability of failure in unit time of a device that is still working. The instantaneous rate of failure for devices of a population that have survived to time *t*.
MTBF & MTTF	$= \frac{1}{\text{Constant Failure Rate}} = \frac{1}{\lambda}$	**Mean Time Between Failure (MTBF), Mean Time To Failure (MTTF):** Expected length of time a system/unit will be operational. MTBF is the preferred term instead of MTTF when repairs are involved. Both are the inverse of the failure rate when the failure rate is constant.
A	$= \frac{\text{Up Time}}{\text{Up Time} + \text{Down Time}}$	**Availability:** In steady-state operation, this is the probability that the system is up and running over time. For "inherent availability," up time is usually the MTBF and down time is usually the Mean Time To Repair (MTTR) a system. "Noninherent availability" can include complex factors such as standby time, logistic time, and administrative time (also see Chapter 11 on operational availability).

Parts reliability modeling

Goal – determine failure rate ($MTBF^{-1}$) of a part

- Method I –Parts Count (MIL-HDBK-217 for electrical components, NPRD 2011 for mechanical components). Based on historical part failure rates, assigns "default" failure rates depending on part category.
- Method II – Parts Stress (MIL-HDBK-217 for electrical components, NSWC for mechanical components -Adjusts default failure rates with factors that account for stress, temperature complexity, etc.

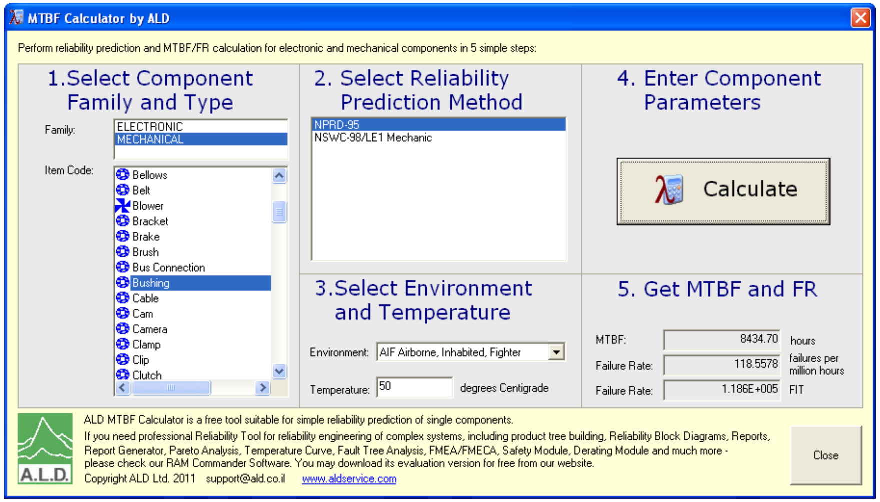
  $$\lambda_{ss} = \lambda_G * \pi_Q * \pi_S * \pi_T$$

  λ_{ss} = Steady State Failure rate; λ_G = Generic or Base Failure Rate

  π_Q = Quality Factor; π_S = Stress Factor; π_T = Temperature Factor
- Method III – Physics of failure modeling. Based on detailed simulation of physical failure modes and lifecycle usage conditions.

Parts count reliability prediction

- Electrical components use Mil-HDBK 217
- Mechanical components use NPRD 2011
- Classify part in suitable category (i.e. bracket)
- Read failure rate
- Convert to needed environment if data in needed environment is not available



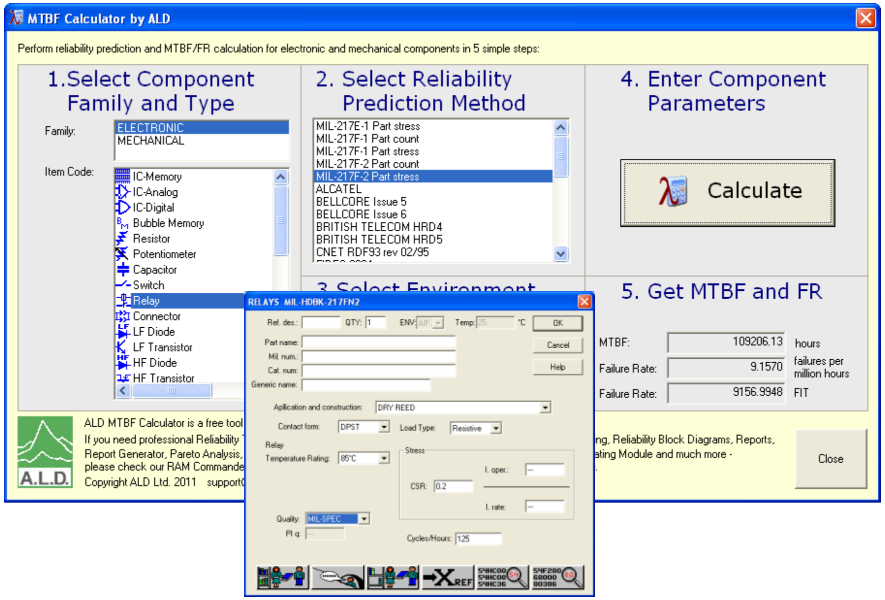
Recommend to use ALD MTBF calculator (freeware) for Mil-HDBK 217

Recommend to use electronic copy of NPRD 2011 from

Reliability Information Analysis Center, RIAC ($175)

Parts stress reliability prediction

- Electrical components use Mil-HDBK 217
- Mechanical components use NSWC 2011
- Classify part in suitable category (i.e. bracket)
- Perform calculations or software to obtain failure rate

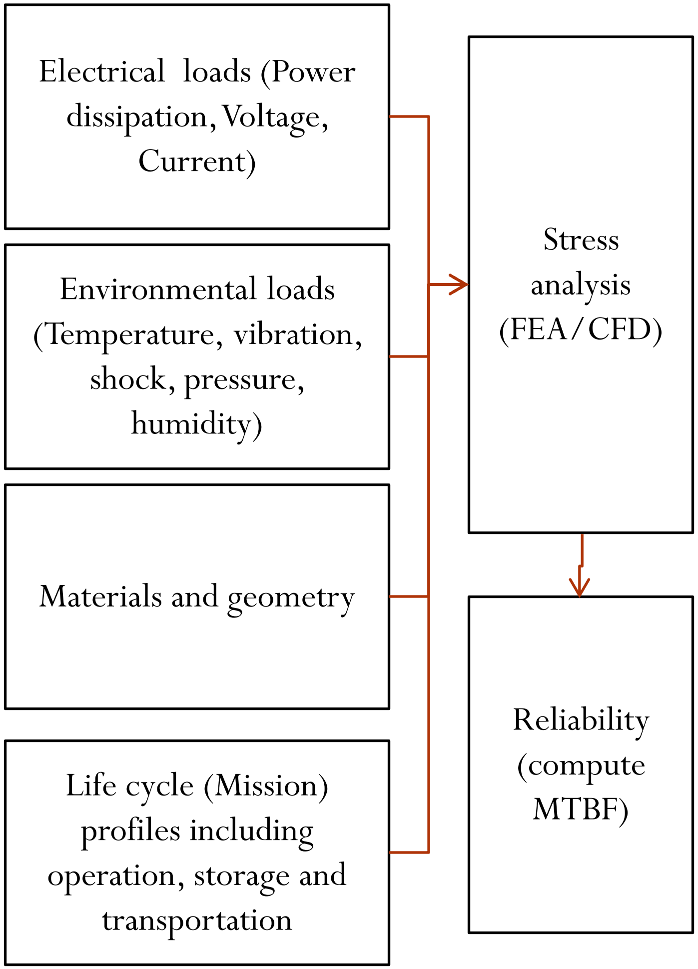


Recommend to use ALD MTBF calculator (freeware) for Mil-HDBK 217

Recommend to use NSWC 2011 Handbook of Reliability Prediction Procedures for Mechanical Equipment from Naval Surface Warfare Center (public domain with registration)

Physics of failure (POF) predictions

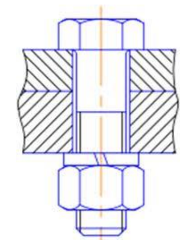
- Define realistic product requirements.
- Define the design usage environment.
- This usage profile defines the mechanical, thermal, electrical and chemical loads over time.
- Identify potential failure sites and failure mechanisms.
- Characterize the materials and the manufacturing and assembly processes, including defects.
- Design to the usage and process capability. The design stress spectra must be based on the anticipated life-cycle usage conditions.



Comparison of methods

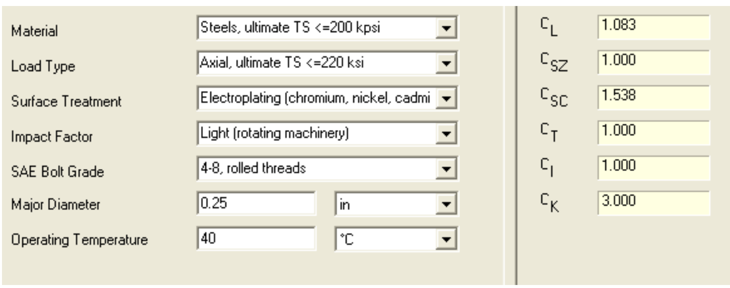
Part count (NPRD 2011)

λ=2.1 failures/million hours



Example -1/4 screw
Preloaded to 30 ksi, 5 ksi oscillating stress, 100 cycles per hour, 40 deg C operating temperature, A286 alloy.

Part stress (NSWC)



Material	Steels, ultimate TS <=200 kpsi		C_L	1.083
Load Type	Axial, ultimate TS <=220 ksi		C_{SZ}	1.000
Surface Treatment	Electroplating (chromium, nickel, cadmi		C_{SC}	1.538
Impact Factor	Light (rotating machinery)		C_T	1.000
SAE Bolt Grade	4-8, rolled threads		C_I	1.000
Major Diameter	0.25	in	C_K	3.000
Operating Temperature	40	°C		

λ=0.505 failures/million hours

Physics of failure

Reliability Model = fatigue (crack growth)
Predicted life =2.5e8 cycles =2.5e6 hrs

λ=0.4 failures/million hours

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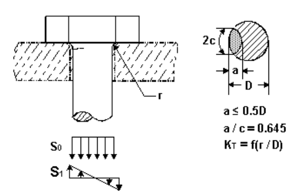


Shear or Machine Bolt - Machined Fillet

Environmental factors

- Environment classification per MIL-HDBK-217
- Reliability is drastically affected by the operational environment
- “Part count” reliability data for different operational environments may be converted
- “Part stress” or physics of failure based predictions account for the operating conditions implicitly

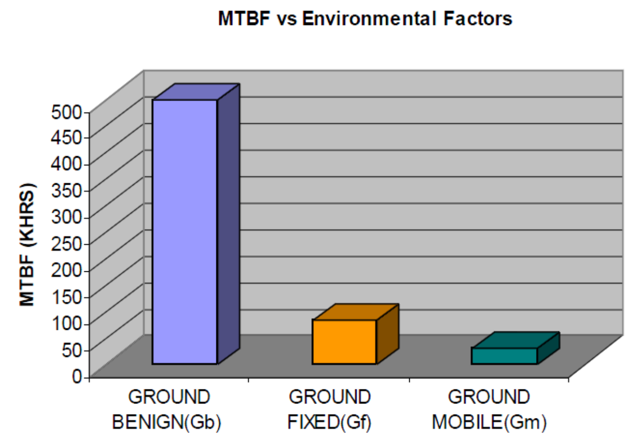
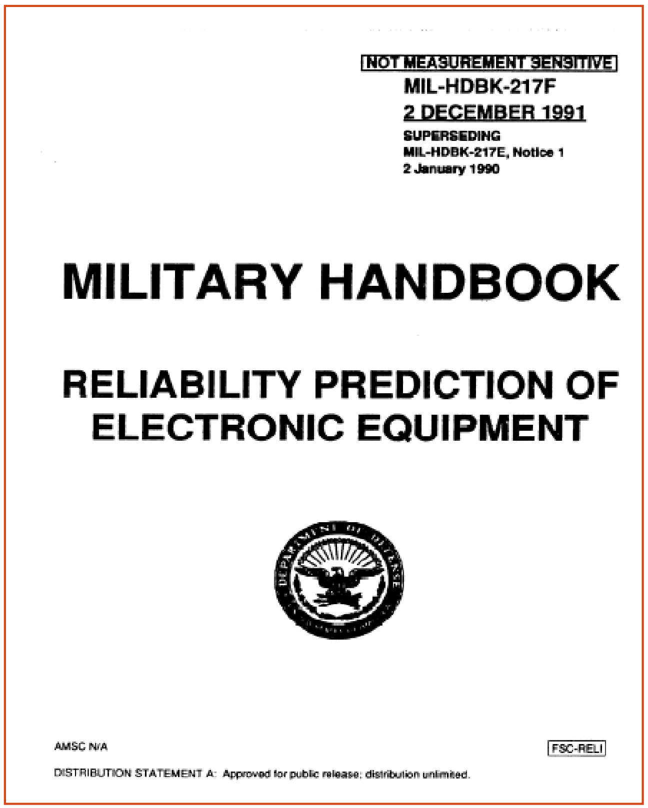


Table 1 is an update to Table 6.3.3-2 "Environmental Conversion Factors" in the RAC publication "Reliability Toolkit: Commercial Practices Edition".

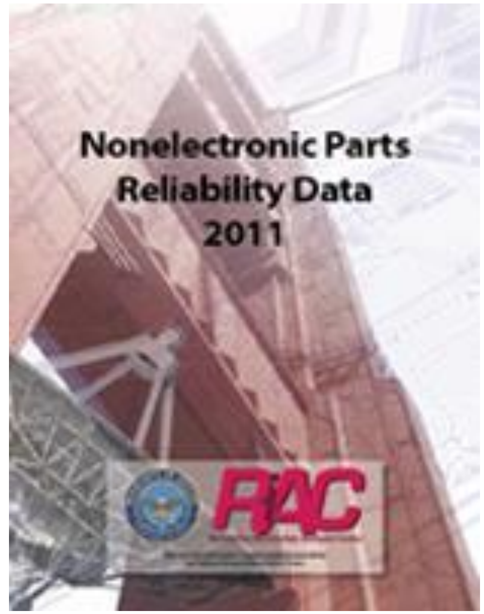
Table 1. Environmental Conversion Factors

To From	**217 ⇒**	**GB**	**GF**	**GM**	**NS**	**NU**	**AIC**	**AIF**	**AUC**	**AUF**	**ARW**	**SF**
217 ⇓	**SD-18 ⇓⇒**	**Protected**	**-**	**-**	**Normal**	**Severe**	**Normal**	**-**	**Severe**	**Severe**	**Severe**	**-**
GB	Protected	X	0.5	0.2	0.3	0.1	0.3	0.2	0.1	0.1	0.1	1.1
GF	-	2.0	X	0.4	0.6	0.3	0.6	0.4	0.2	0.1	0.2	2.0
GM	-	5.0	2.5	X	1.4	0.7	1.4	0.9	0.6	0.3	0.5	5.0
NS	Normal	3.3	1.7	0.7	X	0.5	1.0	0.7	0.4	0.2	0.3	3.3
NU	Severe	10.0	3.3	1.4	2.0	X	2.0	1.4	0.9	0.5	0.7	10.0
AIC	Normal	3.3	1.7	0.7	1.0	0.5	X	0.7	0.4	0.2	0.3	3.3
AIF	-	5.0	2.5	1.1	1.4	0.7	1.4	X	0.6	0.4	0.5	5.0
AUC	Severe	10.0	5.0	1.7	2.5	1.1	2.5	1.7	X	0.6	0.8	10.0
AUF	Severe	10.0	10.0	3.3	5.0	2.0	5.0	2.5	1.7	X	1.4	10.0
ARW	Severe	10.0	5.0	2.0	3.3	1.4	3.3	2.0	1.3	0.7	X	10.0
SF	-	0.9	0.5	0.2	0.3	0.1	0.3	0.2	0.1	0.1	0.1	X

Accepted failure rate data sources



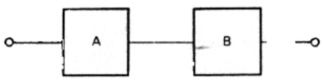
Electronic parts count



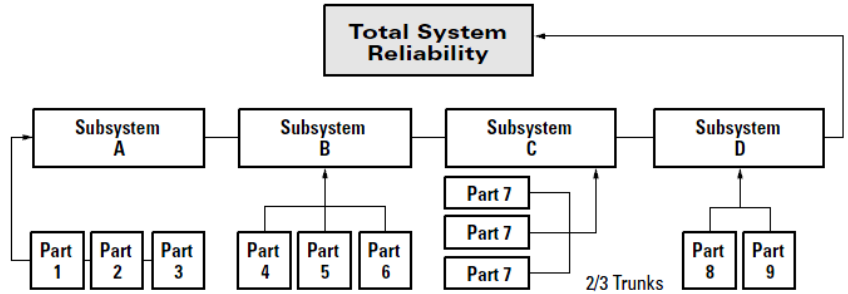
Mechanical parts count

Mechanical parts stress

System reliability - series systems



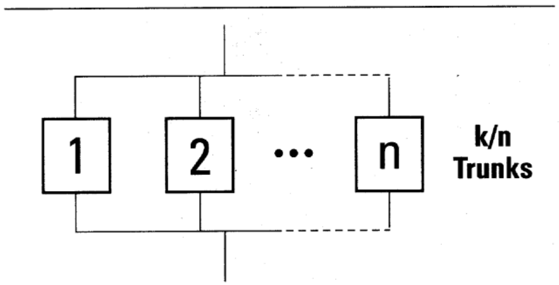
$$R_S = \prod_{i=1}^{n} R_i$$



The failure rate of the system is simply the sum of the failure rates of the individual devices

$$\lambda_{system} = \lambda_1 + \lambda_2 + \lambda_3 + \cdots + \lambda_n$$

System reliability – parallel systems

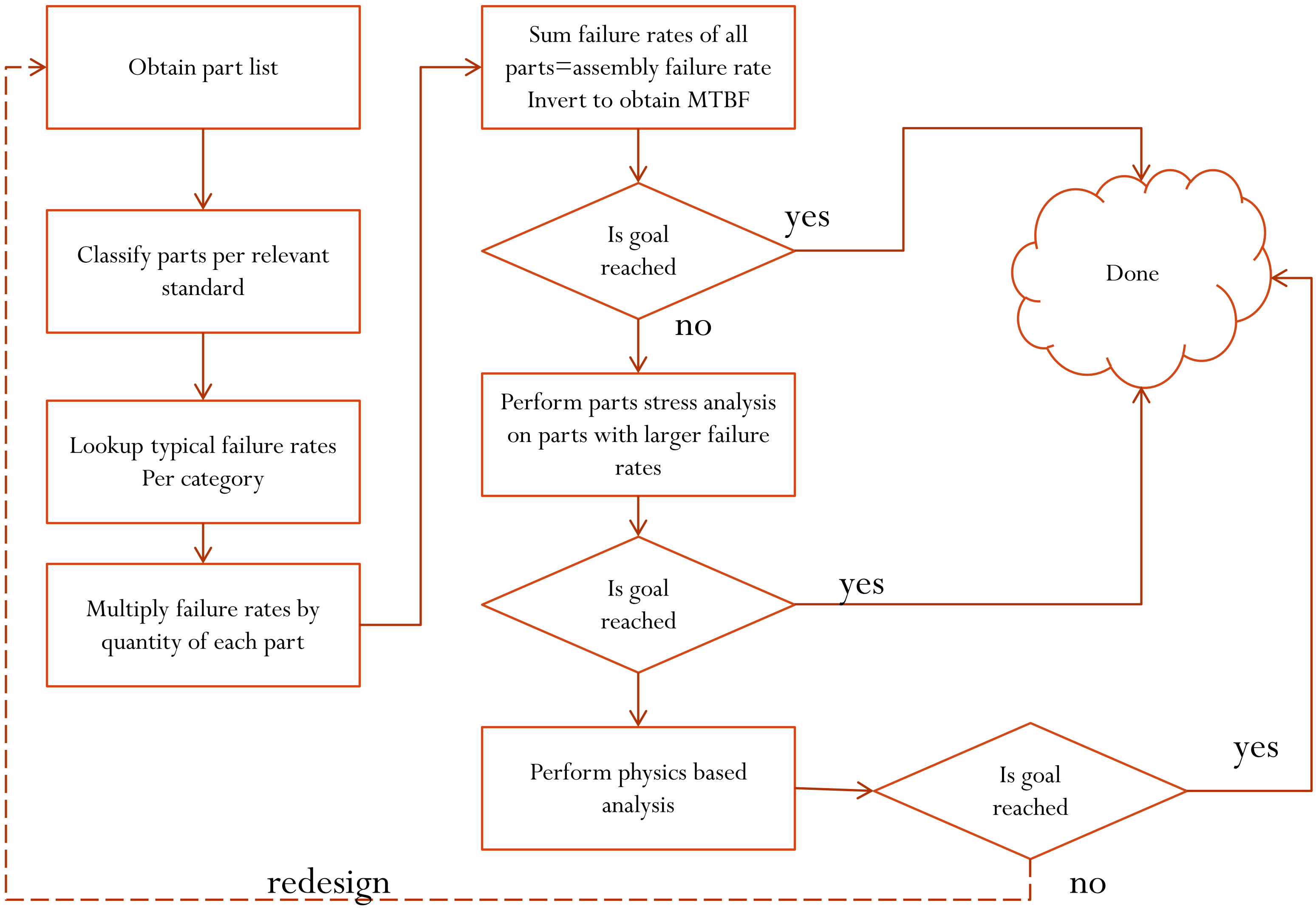


$$\lambda_{eff\ k/n} = \frac{\lambda}{\sum_{i=k}^{n} \frac{1}{i}}$$

Parallel components are accounted in redundant systems

n	k	λeff
1	1	λ
2	1	(2/3)λ
2	2	2λ
3	1	(6/11)λ
3	2	(6/5)λ
3	3	3λ
4	1	(12/25)λ
4	2	(12/13)λ
4	3	(12/7)λ
4	4	4λ
5	1	(60/137)λ
5	2	(60/77)λ
5	3	(60/47)λ

Prediction procedure



Confidence of reliability predictions

- All predictions are only estimates
- Part count methods are very conservative (for properly designed equipment)
- Part stress methods may dictate failure models that do not govern
- Physics based modeling is probably best but does not include human factors, unexpected operating conditions etc
- Can not predict faults not considered

Ways to improve reliability predictions

- Reduce part count by combining parts
- Use parts stress or physics of failure models
- Redundant systems (last resort)
- Consider if part's fault necessarily leads to failure in operation of the system

Reliability software

- Many on the market
- Most seem to focus on electronic components and lag the latest mechanical databases (often a rigid requirement)
- We use spreadsheets combined with ALD MTBF calculator and NPRD electronic database