Reliability Engineering and Management in New Product Development

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Topics to be covered

- Reliability Management
- Reliability in Product Design
- Reliability Tools
  - Boundary Diagram
  - Functional Block Diagram / FBD
  - Event Sequence Diagram
- Weibull Analysis

New Product Development

Consumer needs changes

Marketing environment changes

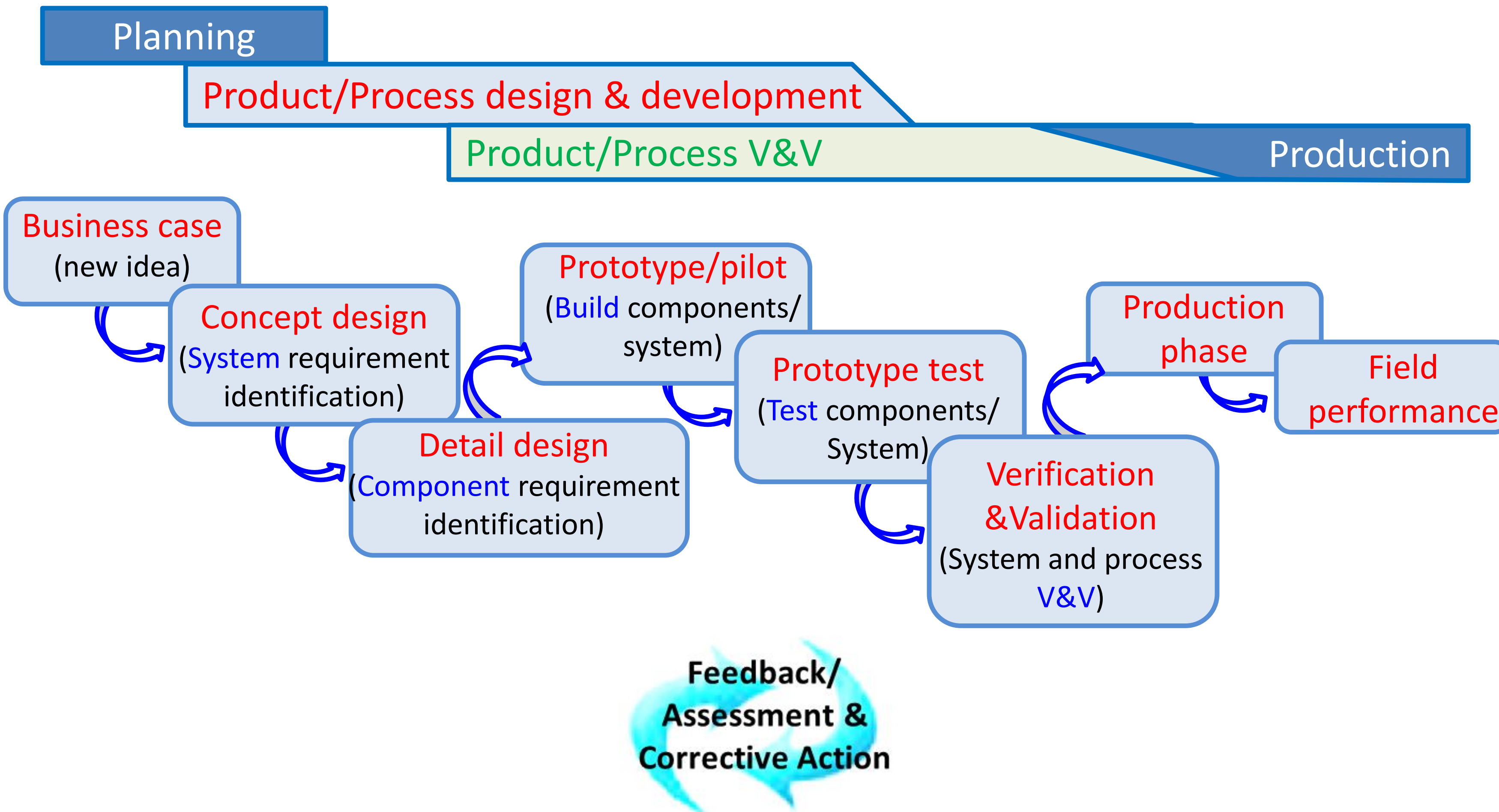
Changing technology

High % of total revenue

Not to lose market share

To stay ahead of Competition

New Product Development



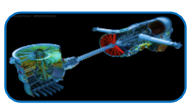
New Product Development

NPD programs are often plagued with:

Cost overruns, Schedule delays, and Quality issues.

Recent news on NPD delays, cost overruns, and quality issues






Product	*Company*	*Issues*	*Year*	*Source*
787 Dreamliner	Boeing Co	***Delay due to a structural flaw***	2009	The Wall Street Journal
Chevy Volt	General Motors	***Cost overrun during design***	2009	CNN Money
The Honda/GE HF120 turbofan engine	Honda	***Design issues:*** An unanticipated test program glitch. A part of the gearbox failed during the test. Rebuild the engine and begin the test again.	2013	Flying
F-35	United Technologies Corp.'s Pratt and Whitney unit	Delays in delivering engines. ***Quality flaws*** and technical issues. Systemic issues and manufacturing quality escapes.	2014	Defence-aerospace.com Bloomberg Business
Sikorsky	US Marine Corps' (USMC's)	A failure in the main gear box and need for ***redesign*** of the component. Problems with wiring and hydraulics systems. Budget constraints.	2015	HIS Jane's 360

New Product Development

NASA's main projects that faced cost and time overrun:

- The International Space Station.

  Prime contract had grown: **25%**

  (from $783M to $986M, the 3rd increase in 2 years).

- The NASA Ares-I launch system.

  Cost overrun: **43%**

  (from $28 billion original estimate to $40 billion)

The **Department of Defense (DoD)**

The set of **96** major new weapon system development programs (2000-2010) have:

- an average development cost growth of **42%**,
- an average delay of **22** months.

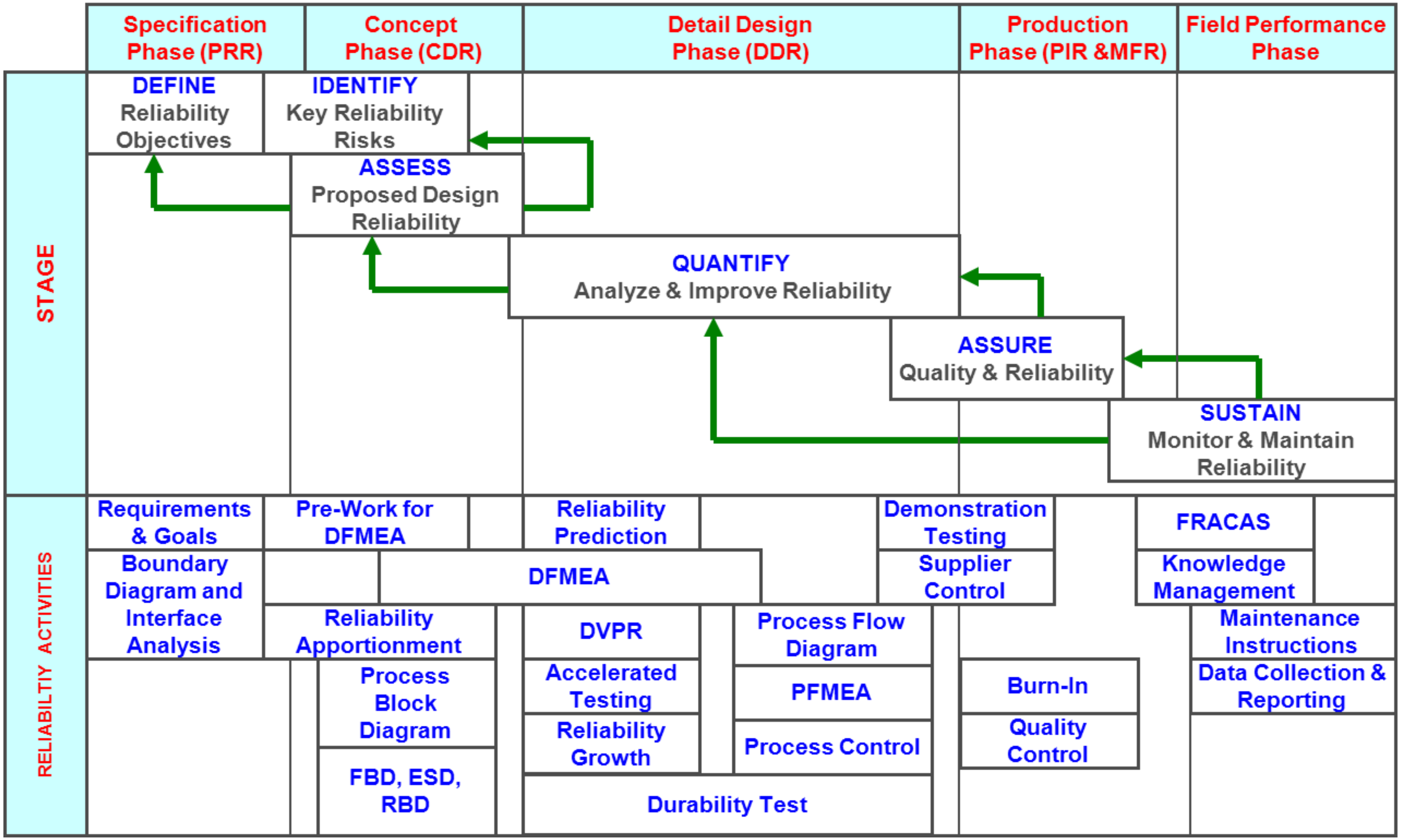
50% of the DOD's NPD programs faced cost overrun.

80% experienced an increase in unit costs from initial estimates.

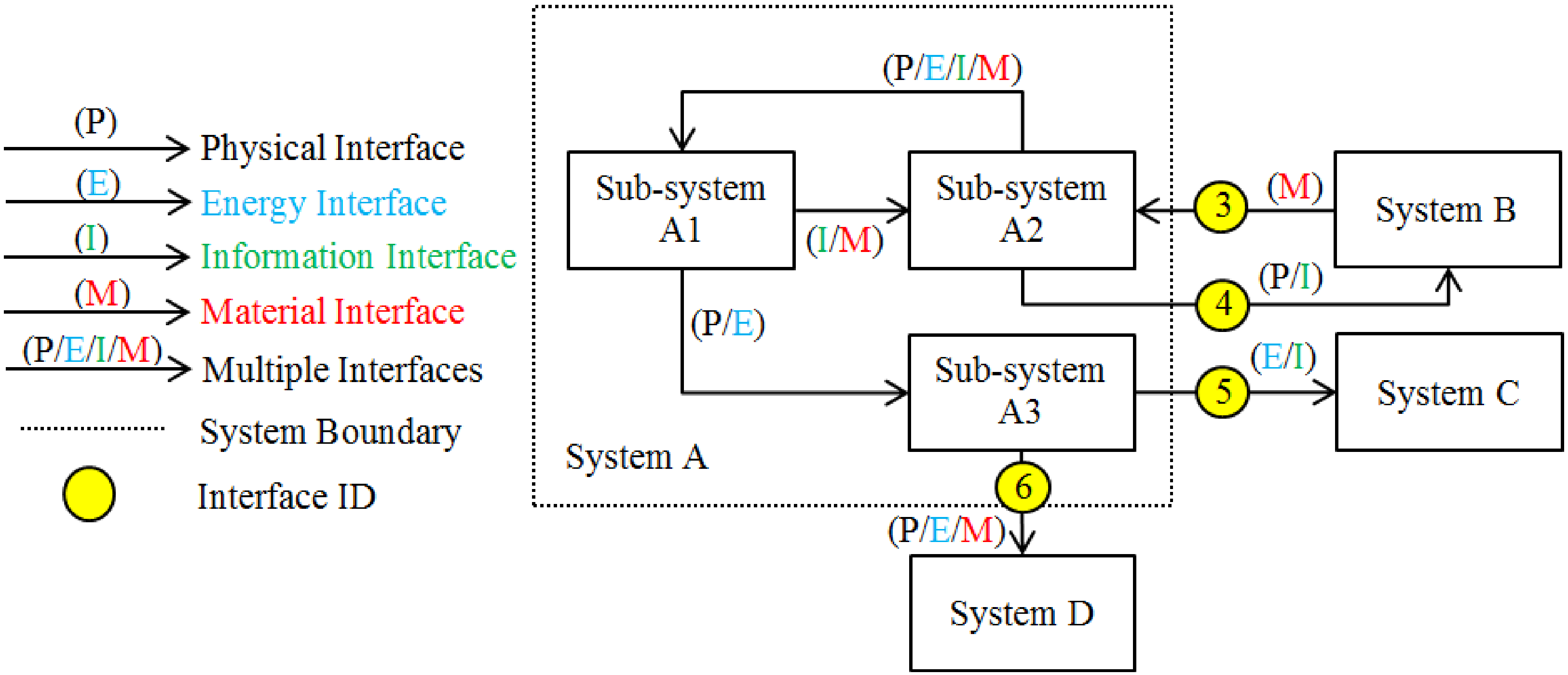
Reliability Management - Plan

- Develop Reliability Program Plan - identifies specific tasks, with start and completion dates, and explains how these tasks are coordinated and integrated with major program milestones for design, manufacturing, and testing;
- Plan need to address
  - Monitoring/Control of Subcontractors and Suppliers;
  - Program Review;
  - Failure Reporting, Analysis, and Corrective Action System (FRACAS);
  - Failure Review Board;
  - Reliability Modeling;
  - Reliability Allocations;
  - Reliability Predictions;
  - Part Derating;
  - Thermal Reliability;
  - Reliability Development/Growth Testing.

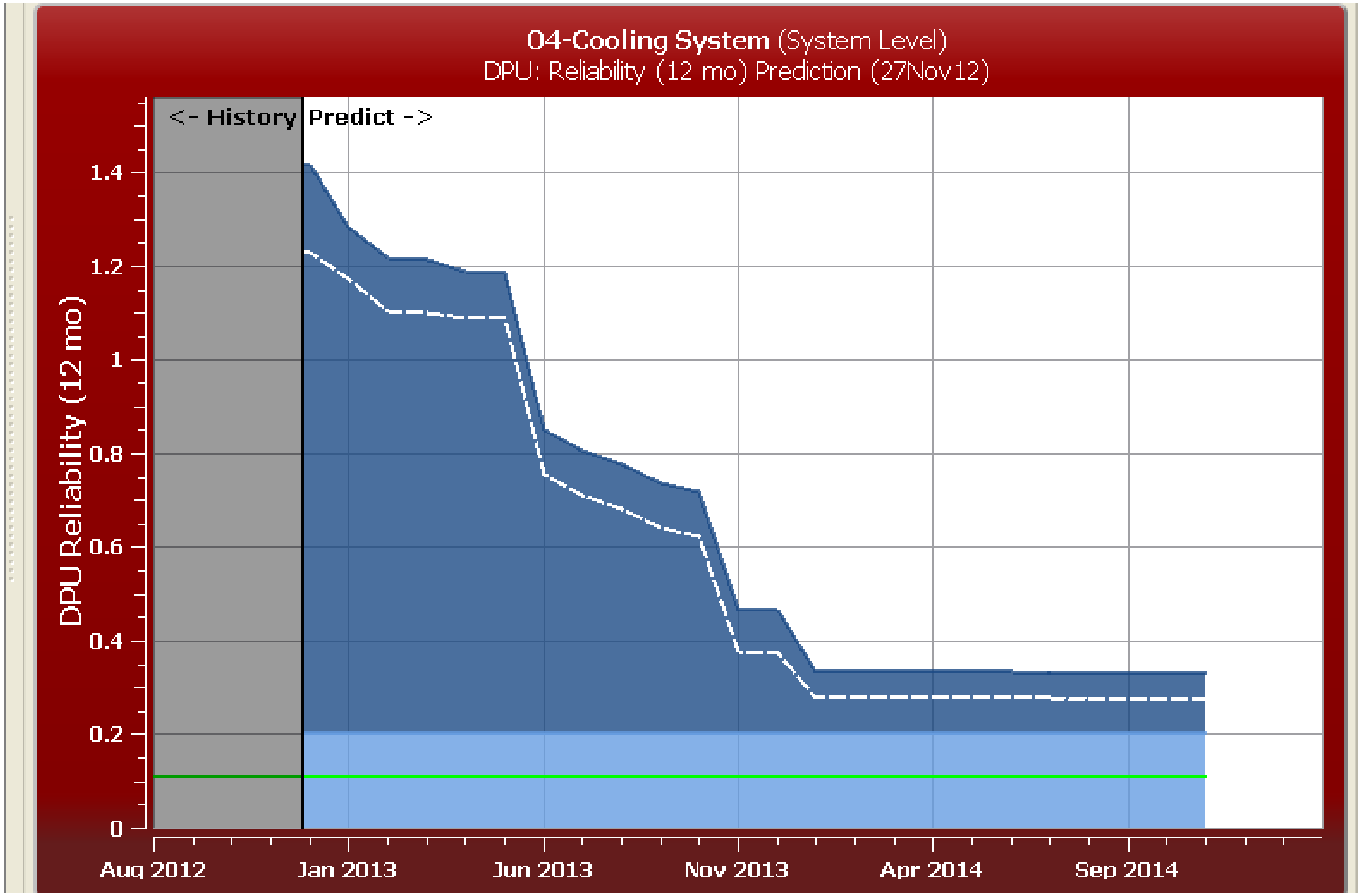
Reliability Management



Boundary Diagram



Reliability Management – Monitoring and Prediction



Reliability in Product Design

Design for Reliability

Purpose – system design to achieve specific reliability goals

Reliability specification should include:

- Definition of product failure
- Conditions in which the product will be stored, transported, operated and maintained
- Definition of time (calendar, cycle)

Reliability Allocation

Goal – allocate the reliability of components such that:

- $H(R_1(\boldsymbol{t}), R_2(\boldsymbol{t}), \ldots, R_{\boldsymbol{n}}(\boldsymbol{t})) \geq R^*(\boldsymbol{t})$

where

$R^*(\boldsymbol{t})$ = goal of the system reliability at time $\boldsymbol{t}$

$R_i(\boldsymbol{t})$ = the reliability allocated to component $\boldsymbol{i}$

$H(.)$ = the function of a system configuration

Reliability Allocation

Available methods

- Minimum cost allocation (similar to what we have done, however treat system reliability as a constraint)

Engineering approaches

- Aeronautical Radio Inc. (ARINC) method
- Advisory Group on Reliability of Electronic Equipment (AGREE) method

Reliability Allocation

ARINC Method – *Proportional allocation*

- Developed in 1951.

Assumption:

- System consists of n independent components connected in series
- Each component has a constant failure rate λ_i such that:
- $\lambda_i * = \mathbf{W}_i \times \lambda_{\mathbf{system}}$
- where $\mathbf{W}_i = \lambda_i / \Sigma\lambda_i$ is the allocation
- weight for the $\boldsymbol{i}^{\text{th}}$ component.

Reliability Allocation

Example - ARINC Method

- A system has 4 components with the failure rates:

$\lambda 1$ = **0.002,** $\lambda 2$ = **0.003,**
$\lambda 3$ = **0.004,** $\lambda 4$ = **0.007.**

The requirement is: the system should keeps functioning with the probability of 0.95 during a 5-hour mission.

Allocate the reliability of these components to meet the requirement.

Solution – ARINC Method

- **<u>Assume the components in the system are connected in series</u>**

$$R(t=5) = 0.95 = e^{-\lambda_{system}\times 5}$$

$$\Rightarrow \lambda_{system} = -0.2\ln 0.95 = 0.01025$$

Since

$$\sum_{i=1}^{4}\lambda_i = 0.016 \quad \Rightarrow\Rightarrow$$

$$\lambda_1^* = 0.002/0.016\times 0.01025$$
$$= 0.00128$$
$$\lambda_2^* = 0.003/0.016\times 0.01025$$
$$= 0.00192$$
$$\lambda_3^* = 0.00256$$
$$\lambda_4^* = 0.00448$$

AGREE Method

- Developed in 1957.

Assumption:

- System consists of n independent modules each having n_i components
- Contribution of the ith module to the system reliability goal is:

$R_i * = [R_{system(t)}]$^(n_i/N)

where **N** = total number of components

$\Sigma \boldsymbol{n_i}$ in the system.

AGREE Method

Assumption (continued):

$1 - R_i^* = 1 - [R_{system(t)}]^{\wedge}(n_i/N) = W_i \times [1 - e(-\lambda_i t_i)]$

where W_i = importance index of the *i*th module (prob. that the system will fail given module ***i*** has failed).

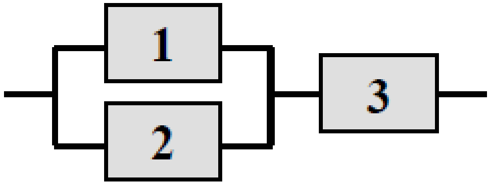
$$\lambda_i^* = -\frac{1}{t_i}\ln\left(1 - \frac{1 - [R^*(t)]^{n_i/N}}{W_i}\right)$$

A system has 4 modules: receiver, power supply, transmitter and antenna. The requirement is: the system should keeps functioning with the probability of 0.99 during 1000 hours.

Module	W_i	t_i hrs	n_i
Receiver	0.8	1000	25
Power supply	1.0	1000	15
Transmitter	0.7	500	23
Antenna	1.0	1000	70

Example - Other Method

- A system has the following structure. The goal is: the system reliability is 0.95.

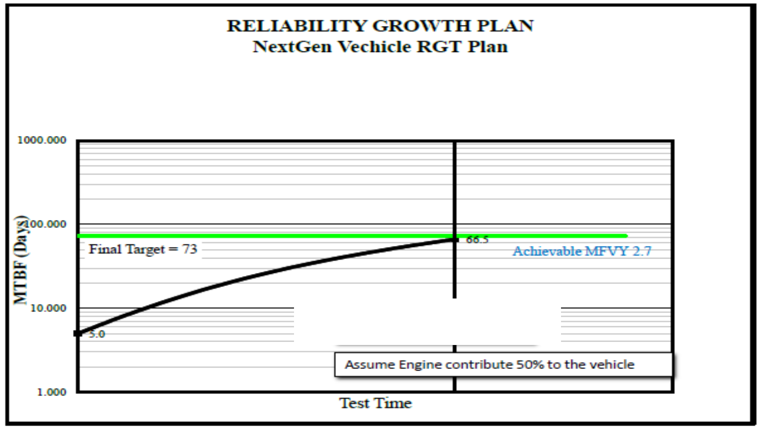


- Idea: allocate the reliability of these components

by balancing the reliability of the subsystems.

- Benefit: avoid over-improving a subsystem
- $R_1 = R_2 = 0.8409$, $R_3 = 0.9747$

Reliability Prediction – Reliability Growth



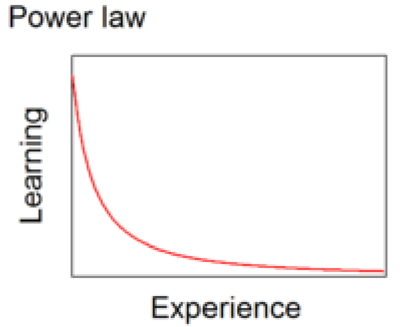
Reliability Growth Test (RGT)

Why Reliability is able to grow?

1. Find root cause for various failure modes
2. Analyze and fix the problems by design change
3. Management involvement
4. Resource investment, e.g., Testing facility, Service manual,...
5. ……………

Reliability Prediction – Reliability Growth

How to model the Reliability Growth?



Duane model - 1962

The cumulative MTBF and the cumulative testing time is linear
a log-log scale – An empirical model

Duane model in terms of cumulative failure rate:

$$ln[C(t)] = \delta - \alpha ln(t)$$

where $C(t) = N(t)/t$ is the cumulative failure rate or average failure rate, δ and α are positive parameters.

$$C(t) = \lambda t^{-\alpha}, \text{ where } \lambda = e^{\delta}$$

Crow AMSAA - 1972

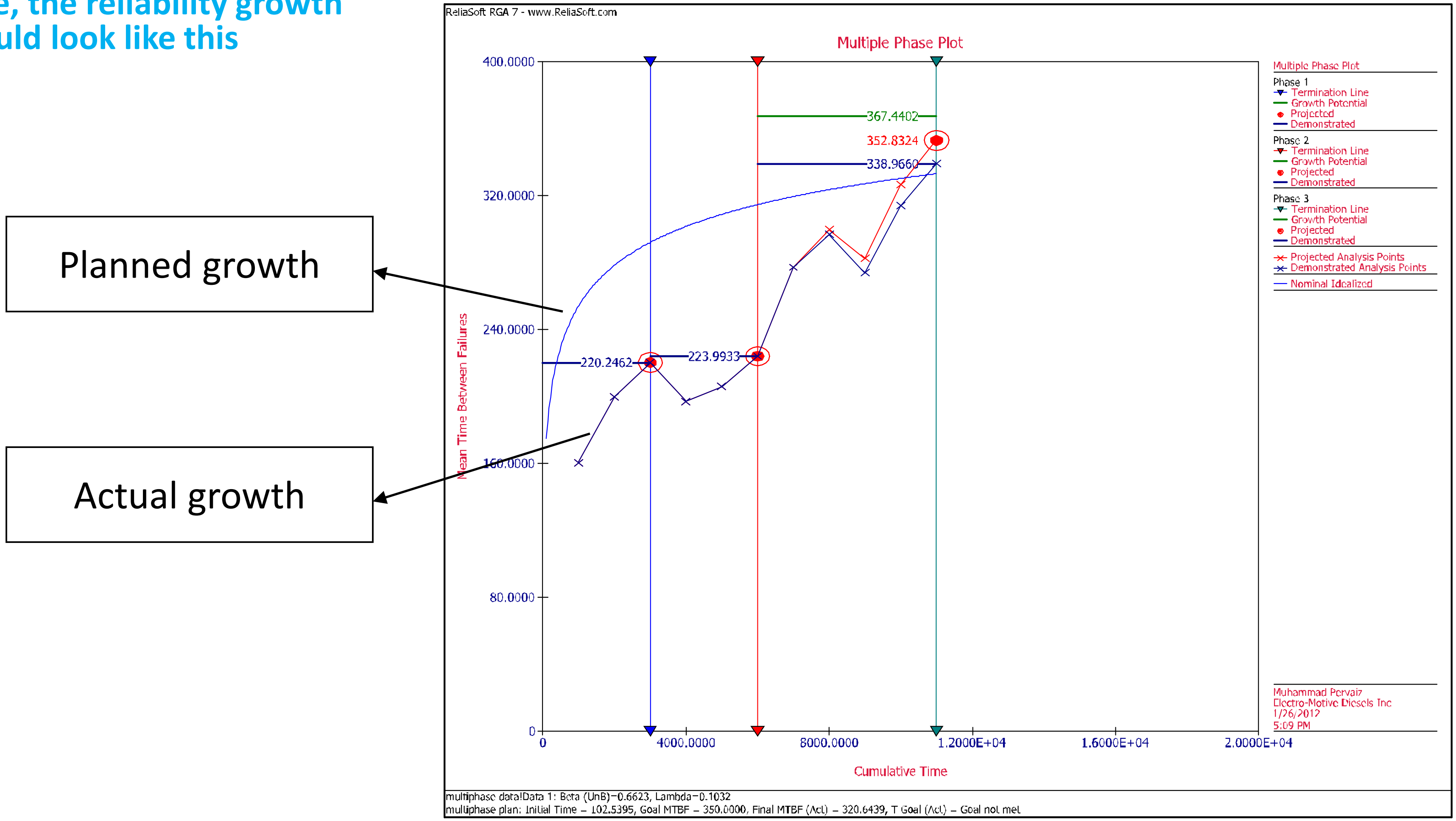
Statistically model the growth process as a non-homogeneous process NHPP – A more generic and statistics-based model

- Maximum likelihood estimator (MLE)
- Goodness-of-fit is discussed

$$r(t) = \lambda\beta\, t^{\beta-1}$$

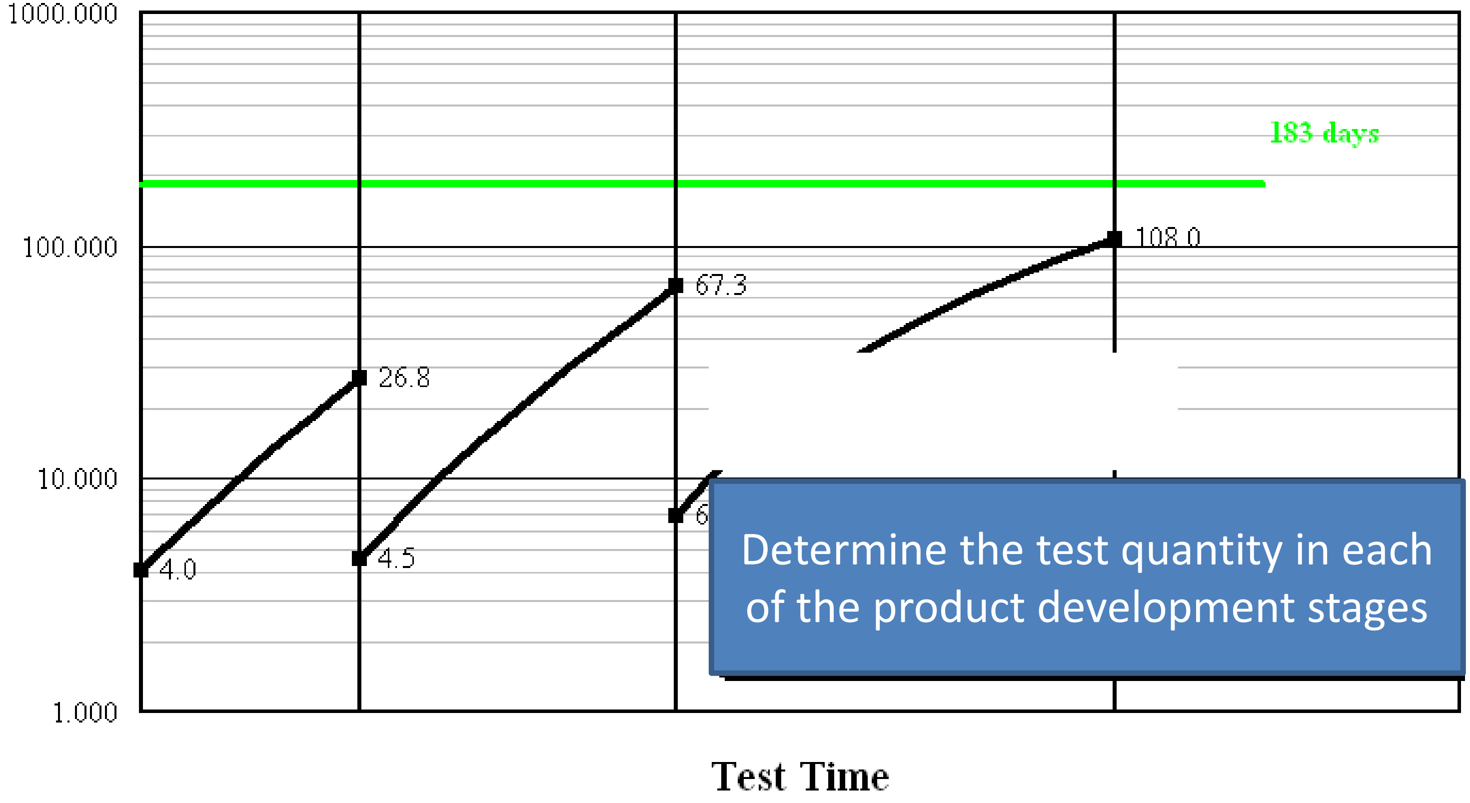
Reliability Prediction – Reliability Growth

After cumulating some testing time, the reliability growth should look like this



Reliability Prediction – Reliability Growth

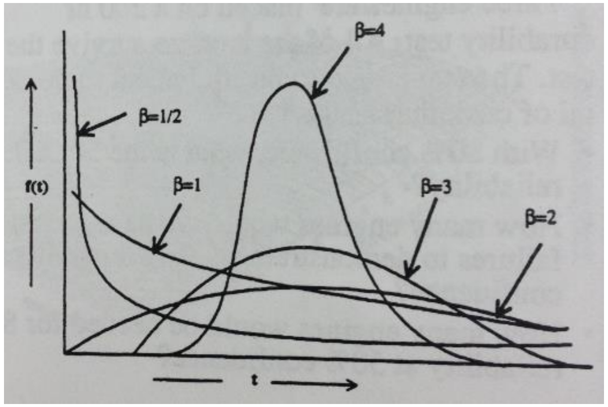
One more example for a multi-stage reliability growth planning



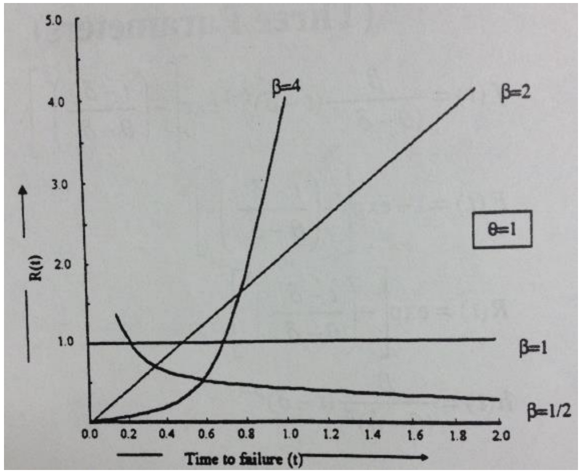
Determine the test quantity in each of the product development stages

Weibull Life Model

- Different Weibull shapes (pdf)



- Different hazard functions



Weibull Life Model

most popular model for IFR and DFR systems

two parameters

- unit-less shape parameter $\beta > 0$
- characteristic life $\quad > 0$ (same units as T)

hazard function

$$\lambda(t) = \frac{\beta}{\eta^{\beta}} t^{\beta - 1}$$

- IFR if $\beta > 1$
- DFR if $\beta < 1$
- CFR if $\beta = 1$ (equivalent to exponential)

Weibull Life Model

other reliability measures

gamma function

$$R(t) = e^{-(t/\eta)^{\beta}}$$

$$MTTF = \eta\, \Gamma\left(1 + \frac{1}{\beta}\right)$$

$$F(t) = 1 - e^{-(t/\eta)^{\beta}}$$

$$f(t) = \frac{\beta}{\eta^{\beta}} t^{\beta-1} e^{-(t/\eta)^{\beta}}$$

Gamma Function

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt$$

Exercise:

$$\Gamma(4.21) = \int_0^{\infty} x^{3.21} e^{-x} dx$$
$$= 3.21\,\Gamma(3.21)$$
$$= 3.21 \times 2.21 \times \Gamma(2.21)$$
$$= 3.21 \times 2.21 \times 1.\cancel{21} \times \Gamma(1.21)$$

0.91558

DEFINITE INTEGRALS

*GAMMA FUNCTION

Values of $\Gamma(n) = \int_0^{\infty} e^{-x} x^{n-1} dx$; $\Gamma(n+1) = n\Gamma(n)$

n	$\Gamma(n)$	n	$\Gamma(n)$	n	$\Gamma(n)$	n	$\Gamma(n)$
1.00	1.00000	1.25	.90640	1.50	.88623	1.75	.91906
1.01	.99433	1.26	.90440	1.51	.88659	1.76	.92137
1.02	.98884	1.27	.90250	1.52	.88704	1.77	.92376
1.03	.98355	1.28	.90072	1.53	.88757	1.78	.92623
1.04	.97844	1.29	.89904	1.54	.88818	1.79	.92877
1.05	.97350	1.30	.89747	1.55	.88887	1.80	.93138
1.06	.96874	1.31	.89600	1.56	.88964	1.81	.93408
1.07	.96415	1.32	.89464	1.57	.89049	1.82	.93685
1.08	.95973	1.33	.89338	1.58	.89142	1.83	.93969
1.09	.95546	1.34	.89222	1.59	.89243	1.84	.94261
1.10	.95135	1.35	.89115	1.60	.89352	1.85	.94561
1.11	.94739	1.36	.89018	1.61	.89468	1.86	.94869
1.12	.94359	1.37	.88931	1.62	.89592	1.87	.95184
1.13	.93993	1.38	.88854	1.63	.89724	1.88	.95507
1.14	.93642	1.39	.88785	1.64	.89864	1.89	.95838
1.15	.93304	1.40	.88726	1.65	.90012	1.90	.96177
1.16	.92980	1.41	.88676	1.66	.90167	1.91	.96523
1.17	.92670	1.42	.88636	1.67	.90330	1.92	.96878
1.18	.92373	1.43	.88604	1.68	.90500	1.93	.97240
1.19	.92088	1.44	.88580	1.69	.90678	1.94	.97610
1.20	.91817	1.45	.88565	1.70	.90864	1.95	.97988
1.21	.91558	1.46	.88560	1.71	.91057	1.96	.98374
1.22	.91311	1.47	.88563	1.72	.91258	1.97	.98768
1.23	.91075	1.48	.88575	1.73	.91466	1.98	.99171
1.24	.90852	1.49	.88595	1.74	.91683	1.99	.99581
						2.00	1.00000

* For large positive values of x, $\Gamma(x)$ approximates the asymptotic series $x^x e^{-x} \sqrt{\frac{2\pi}{x}} \left[1 + \frac{1}{12x} + \frac{1}{288x^2} - \frac{139}{51840x^3} - \frac{571}{2488320x^4} + \cdots\right]$.

Weibull Life Model

example

- Supηose the time to failure of a device is a Weibull random variable having $\beta = 1.8$ and a characteristic life ( ) of 3500 hr.
- What is the *MTTF* of the device?

$$MTTF = 3500\,\Gamma\left(1 + \frac{1}{1.8}\right) = 3500(0.889) = 3113 \text{ hr}$$

- What is the 2000-hr reliability of the device?

$$R(2000) = e^{-(2000/3500)^{1.8}} = 0.694$$

Weibull Life Model

example

- Suppose the device has survived 4000 hr.
- What is the probability that the device survives an additional 2000 hr?

$$R(6000|4000) = \frac{R(6000)}{R(4000)} = 0.255$$

example

- Suppose the device has survived 4000 hr.
- What is the expected value of the remaining life of the device?

$$MTTF(4000) = \int_0^\infty R(t + 4000|4000)\,dt$$

- the integral must be computed numerically

$$MTTF(4000) = 1414\text{ hr}$$

$$MRL(t) = E[T - t|T > t) = \int_0^\infty R(x|t)\,dx$$

Weibull parameter estimation

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

$$\mathrm{R}(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - F(t)$$

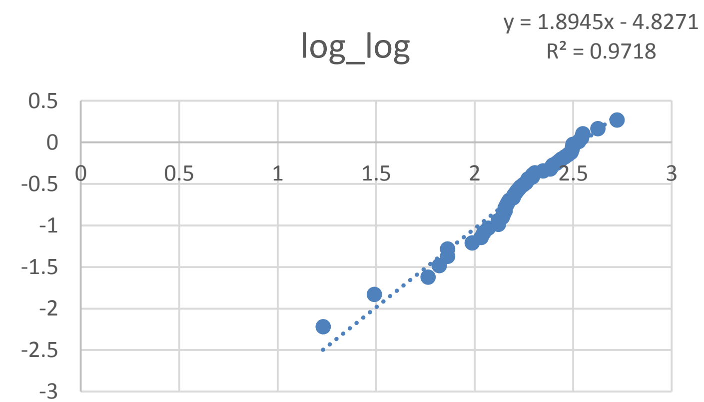
$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}$$

$$\bar{F}(t) = exp[-(\frac{t}{\eta})^{\beta}] = 1 - F(t)$$

take logarithm two times $\Rightarrow$

$$ln[-ln(\bar{F}(t))] = \beta \cdot ln(t) - \beta \cdot ln(\eta)$$

$$\widehat{F}(t_i) = \frac{i - 0.3}{n + 0.4}$$



Weibull parameter estimation

- In Minitab