Software Quality Engineering:

Testing, Quality Assurance, and Quantifiable Improvement

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Chapter 22. Software Reliability Engineering

- Concepts and Approaches
- Existing Approaches: SRGMs & IDRMs
- Assessment & Improvement with TBRMs
- SRE Perspectives

What Is SRE

- *Reliability:* Probability of failure-free operation for a specific time period or input set under a specific environment
  - ▷ Failure: behavioral deviations
  - ▷ Time: how to measure?
  - ▷ Input state characterization
  - ▷ Environment: OP

- Software reliability engineering:
  - ▷ Engineering (applied science) discipline
  - ▷ Measure, predict, manage reliability
  - ▷ Statistical modeling
  - ▷ Customer perspective:
    - – failures vs. faults
    - – meaningful time vs. development days
    - – customer operational profile

Assumption: SRE and OP

- Assumption 1: OP, to ensure software reliability from a user's perspective.

- OP: Operational Profile
  - ▷ Quantitative characterization of the way a (software) system will be used.
  - ▷ Test case generation/selection/execution
  - ▷ Realistic assessment
  - ▷ Predictions (minimize discontinuity)

- OP topics in SQE book:
  - ▷ Chapter 8: Musa's OP
    - – flat list with probabilities
    - – tree-structured OP
    - – dev. procedures: Musa-1/Musa-2
  - ▷ Chapter 10: Markov chains and UMMs (unified Markov models)

Other Assumptions in Context

- Assumption 2: Randomized testing
  - ▷ Independent failure intervals/observations
  - ▷ Approximation in large software systems
  - ▷ Adjustment for non-random testing
    $\Rightarrow$ new models or data treatments

- Assumption 3: Failure-fault relation
  - ▷ Failure probability $\sim$ # faults
  - ▷ Exposure through OP-based testing
  - ▷ Possible adjustment?
  - ▷ Statistical validity for large s/w systems

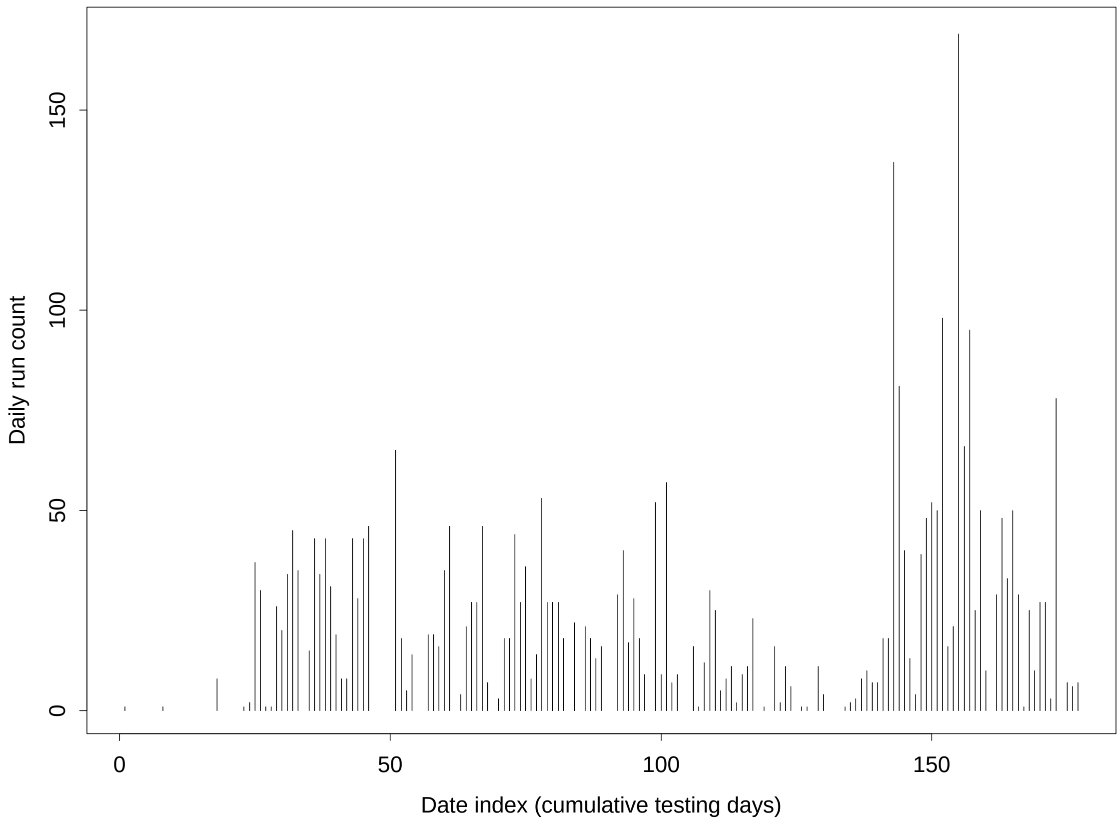
Other Assumptions and Context

- Assumption 4: time-reliability relation
  - ▷ time measurement in SRGMs
  - ▷ usage-dependent vs. usage-independent
  - ▷ proper choice under specific env.

- Usage-independent time measurement:
  - ▷ calendar/wall-clock time
  - ▷ only if stable or constant workload

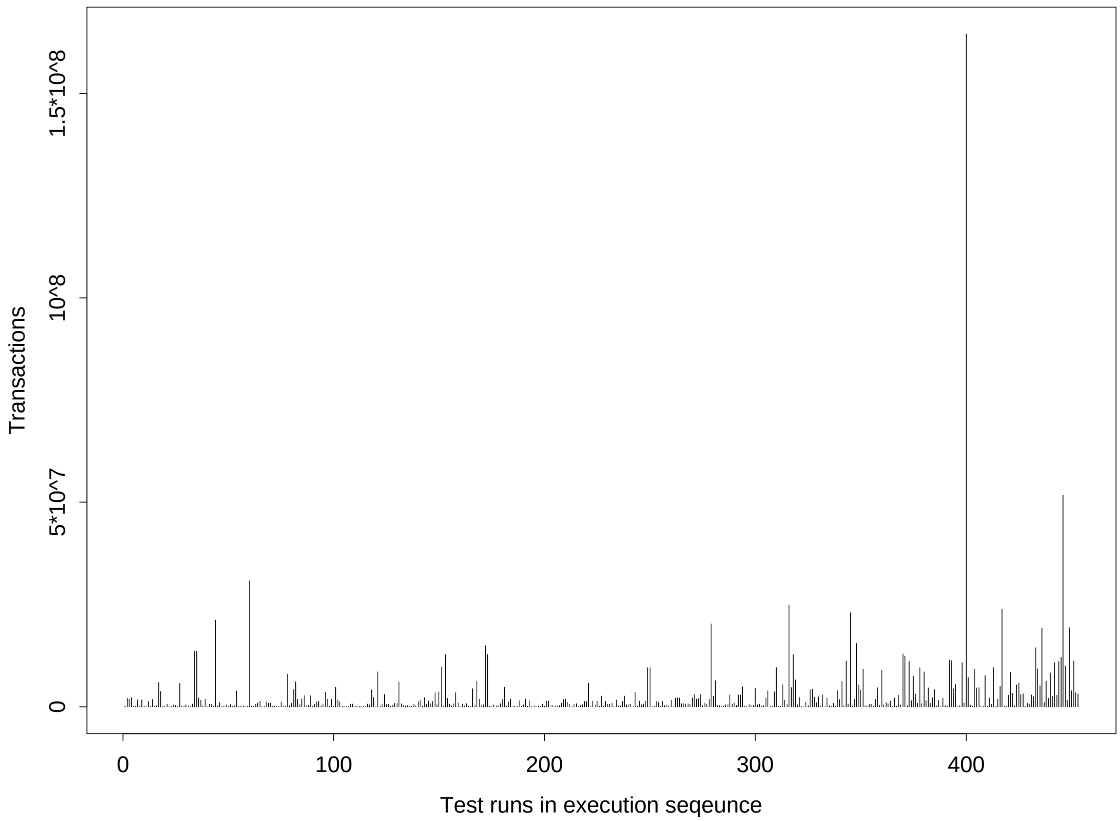
- Usage-dependent time measurement:
  - ▷ for systems with uneven workload
  - ▷ execution time – Musa's models
  - ▷ alternatives: runs, transactions, etc.

Workload for Products D



- Fig 22.1 (p.374): IBM product D workload
  - ▷ number of test runs for each day
  - ▷ wide variability
  - ▷ need usage-dependent time measurement
    – # of runs used

Workload for Products E



- Fig 22.2 (p.375): IBM product E workload
  - ▷ number of transactions for each run
  - ▷ again, wide variability
  - ▷ need usage-dependent time measurement – # of transactions used

Input Domain Reliability Models

- IDRMs: Current reliability snapshot based on observed testing data of n samples.

- *Assessment* of current reliability.

- *Prediction* of future reliability (limited prediction due to snapshot)

- Management and improvement
  - ▷ As acceptance criteria.
  - ▷ Risk identification and followups:
    - reliability for input subsets
    - remedies for problematic areas
    - preventive actions for other areas

Nelson's IDRM

- Nelson Model:
  - ▷ Running for a sample of n inputs.
  - ▷ Randomly selected from set E:

$$E = \{E_i : i = 1, 2, \ldots, N\}$$

  - ▷ Sampling probability vector:

$$\{P_i : i = 1, 2, \ldots, N\}$$

  - ▷ $\{P_i\}$: Operational profile.
  - ▷ Number of failures: f.
  - ▷ Estimated reliability:

$$R = 1 - r = 1 - \frac{f}{n} = \frac{n - f}{n}$$

  - ▷ Failure rate: r.

- Repeated sampling without fixing.

IDRM Applications

- Nelson model for a large s/w system
  - succ. segments: Table 22.1 (p.376)

Segment	rn Range	$\hat{R}_i$	$\hat{\lambda}_i$
1	$0 < rn \leq 137$	0.241	0.759
2	$137 < rn \leq 309$	0.558	0.442
3	$309 < rn \leq 519$	0.176	0.824
4	$519 < rn \leq 1487$	0.454	0.546
5	$1487 < rn \leq 1850$	0.730	0.270
6	$1850 < rn \leq 3331$	0.930	0.070

- Nelson model for web applications
  - daily error rates: Table 22.2 (p.377)

Daily Error Rate	min	max	mean	std dev	rse
errors /hits	0.0287	0.0466	0.0379	0.00480	0.126
errors /day	501	1582	1101	312	0.283

Other IDRMs and Applications

- Brown-Lipow model:
  - ▷ explicit input state distribution.
  - ▷ known probability for sub-domains E_i
  - ▷ f_i failures for n_i runs from subdomain E_i

$$R = 1 - \sum_{i=1}^{N} \frac{f_i}{n_i} P(E_i)$$

  - ▷ would be the same as Nelson model for representative sampling

- IDRM applications
  - ▷ overall reliability at acceptance testing
  - ▷ reliability snapshots over time: in Nelson model examples earlier
  - ▷ reliability for input subsets: in TBRMs

Time Domain Measures and Models

- Reliability measurement
  - ▷ Reliability: time & probability
  - ▷ Result: failure vs. success
  - ▷ Time/input measurement
  - ▷ Failure intensity (rate): alternative
  - ▷ MTBF/MTTF: summary measure
- S/w reliability growth models (SRGMs):
  - ▷ Reliability growth due to defect removal based on observed testing data.
  - ▷ Reliability-fault relations
  - ▷ Exposure assumptions
  - ▷ Data: time-between-failure (TBF) vs. period-failure-count (PFC) models

Basic Functions (Time Domain)

- Failure distribution functions:
  - ▷ $F(t)$: cumulative distribution function (cdf) for failure over time
  - ▷ $f(t)$: prob. density function (pdf) $f(t) = F'(t)$

- Reliability-related functions:
  - ▷ Reliability function $R(t) = 1 - F(t)$

$$R(t) = P(T \geq t) = P(\text{no failure by } t)$$

  - ▷ Hazard function/rate/intensity

$$z(t)\Delta t = P\{t < T < t + \Delta t | T > t\}$$

- Jelinski-Moranda (de-eutrophication) model:

$$z_i = \phi(N - (i - 1))$$

Other Basic Definitions

- MTBF, MTTF, and reliability
  - ▷ Mean time to failure (MTTF)

$$\text{MTTF} = \int_0^\infty t f(t) dt = \int_0^\infty R(t) dt$$

  - ▷ Mean time between failures (MTBF)
    = MTTF for memoryless process
    – similarly defined
  - ▷ good summary measure of reliability

- Reliability-hazard relation:

$$R(t) = e^{-\int_0^t z(x) dx}$$

$$z(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)}$$

Other Basic Functions

- Overall failure arrival process:
  (as compared to individual failures)

- NHPP (non-homogeneous Poisson process):
  - ▷ Most commonly used for modeling
  - ▷ Probability of n failures in $[0, t]$:

$$P(N(t) = n) = \frac{m(t)^n}{n!} e^{-m(t)}$$

  - ▷ $m(t)$: mean function
  - ▷ Failure rate/intensity $\lambda(t)$:

$$\lambda(t) = m'(t) = \frac{dm(t)}{dt}$$

- Other processes: Binomial, etc.

Commonly Used NHPP Models

- Goel-Okumoto model

$$m(t) = N(1 - e^{-bt})$$

  - N: estimated # of defects
  - b: model curvature

- S-shaped model:

$$m(t) = N(1 - (1 + bt)e^{-bt})$$

  - allow for slow start
  - may be more descriptive

- Musa-Okumoto execution time model:

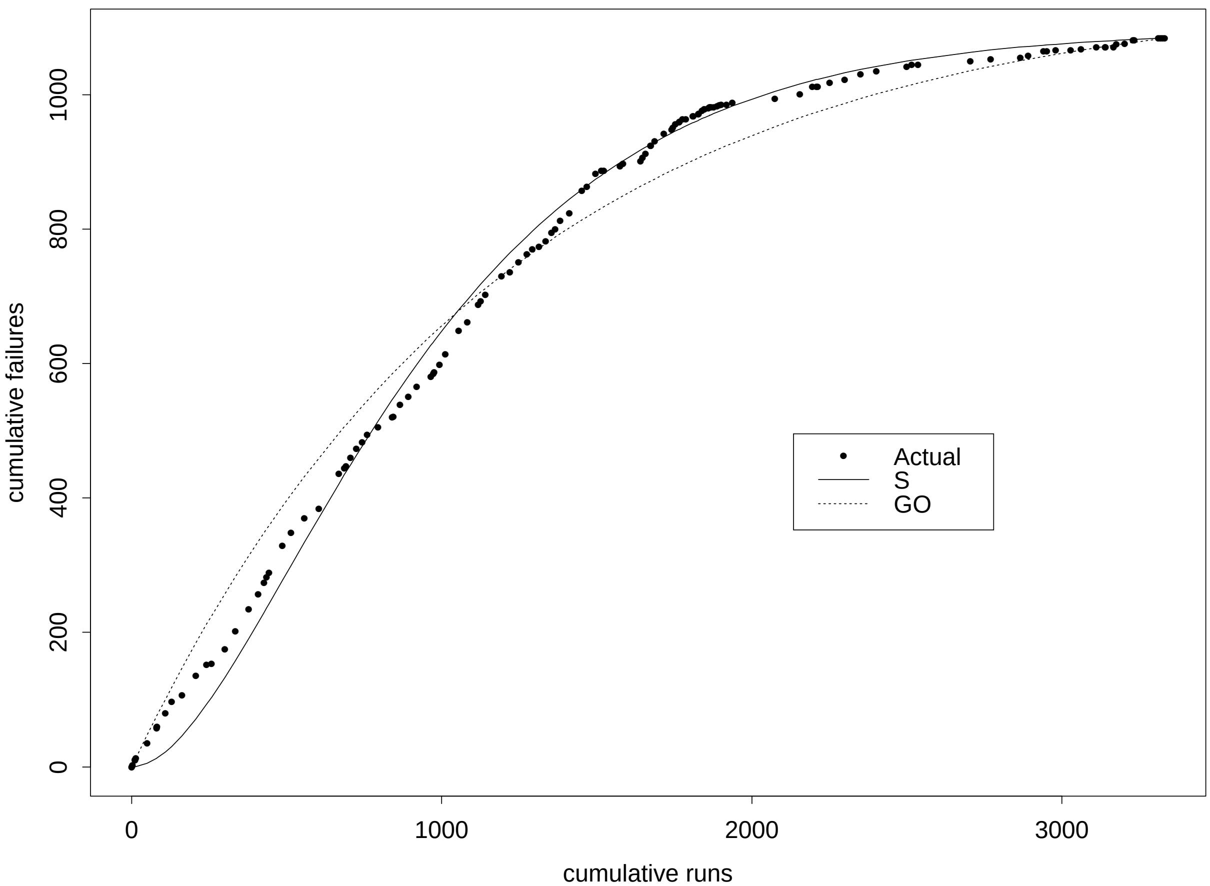
$$m(\tau) = \frac{1}{\theta} \log(\lambda_0 \theta \tau + 1)$$

  - emphasis: execution time τ

SRGM Applications

- *Assessment* of current reliability
- *Prediction* of future reliability and resource to reach reliability goals
- Management and improvement
  - ▷ Reliability goals as exit criteria
  - ▷ Resource allocation (time/distribution)
  - ▷ Risk identification and followups:
    - reliability (growth) of different areas
    - remedies for problematic areas
    - preventive actions for other areas

SRGM Application Example



- SRGM example: Fig. 22.3 (p.380)
  - ▷ IBM product D, # of runs as workload
  - ▷ Goel-Okumoto (GO) and S-shape SRGMs

Assessing Existing Approaches

- Time domain reliability analysis:
  - ▷ Customer perspective.
  - ▷ Overall assessment and prediction.
  - ▷ Ability to track reliability change.
  - ▷ Issues: assumption validity.
  - ▷ Problem: how to improve reliability?

- Input domain reliability analysis:
  - ▷ Explicit operational profile.
  - ▷ Better input state definition.
  - ▷ Hard to handle change/evolution.
  - ▷ Issues: sampling and practicality.
  - ▷ Problem: realistic reliability assessment?

TBRMs: An Integrated Approach

- Combine strengths of the two.

- TBRM for reliability modeling:
  - ▷ Input state: categorical information.
  - ▷ Each run as a data point.
  - ▷ Time cutoff for partitions.
  - ▷ Data sensitive partitioning
    $\Rightarrow$ Nelson models for subsets.

- Using TBRMs:
  - ▷ Reliability for partitioned subsets.
  - ▷ Use both input and timing information.
  - ▷ Monitoring changes in trees.
  - ▷ Enhanced exit criteria.
  - ▷ Integrate into the testing process.

TBRMs

- Tree-based reliability models (TBRMs): TBM using all information.

- Response: Result indicator r_{ij}.
  - ▷ $r_{ij} = 1$ for success, 0 for failure.
  - ▷ Nelson model for subsets:

$$s_i = \frac{1}{n_i} \sum_{j=1}^{n_i} r_{ij} = \frac{n_i - f_i}{n_i} = \hat{R}_i \qquad \text{or}$$

$$s_i = \frac{\sum_{j=1}^{n_i} t_{ij} s_{ij}}{\sum_{j=1}^{n_i} t_j} = \frac{\sum_{j=1}^{n_i} r_{ij}}{\sum_{j=1}^{n_i} t_j} = \frac{S_i}{T_i} = \hat{R}_i.$$

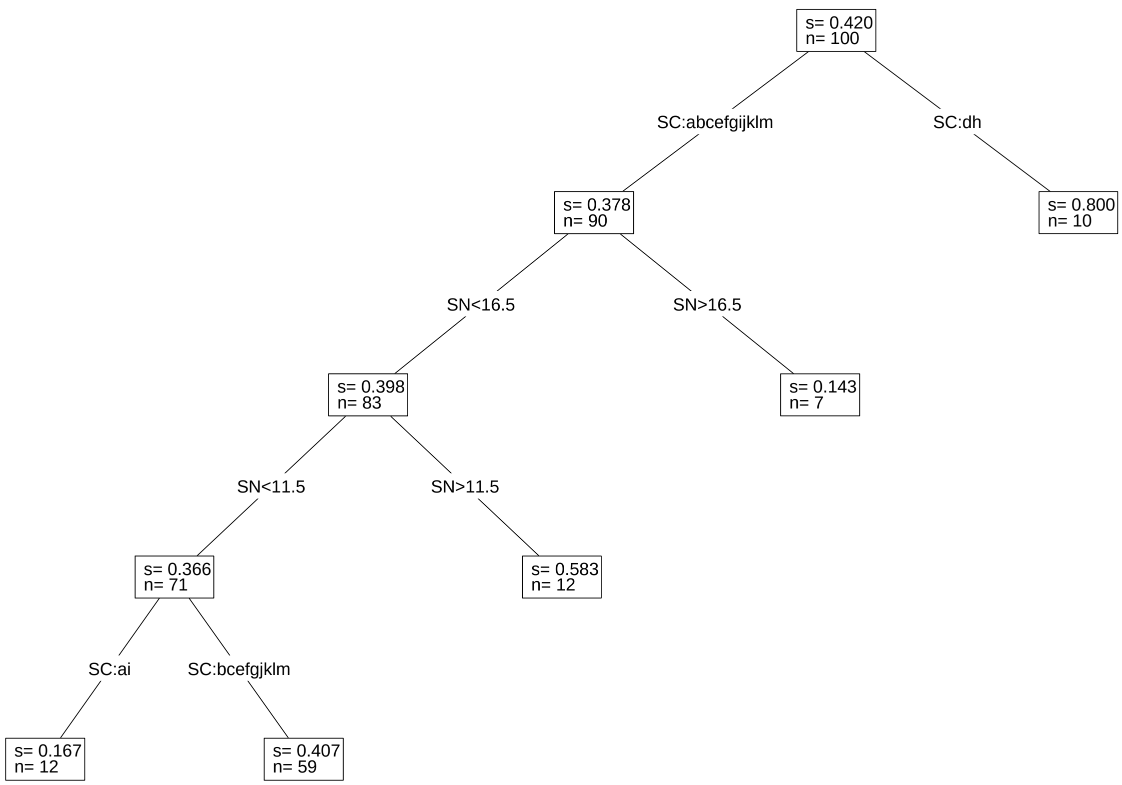
- Predictors: Timing and input states.
  - ▷ Data sensitive partitioning.
  - ▷ Key factors affecting reliability.

TBRMs: Interpretation & Usage

- Interpretation of trees:
  - ▷ Predicted response: success rate. (Nelson reliability estimate.)
  - ▷ Time predictor: reliability change.
  - ▷ State predictor: risk identification.

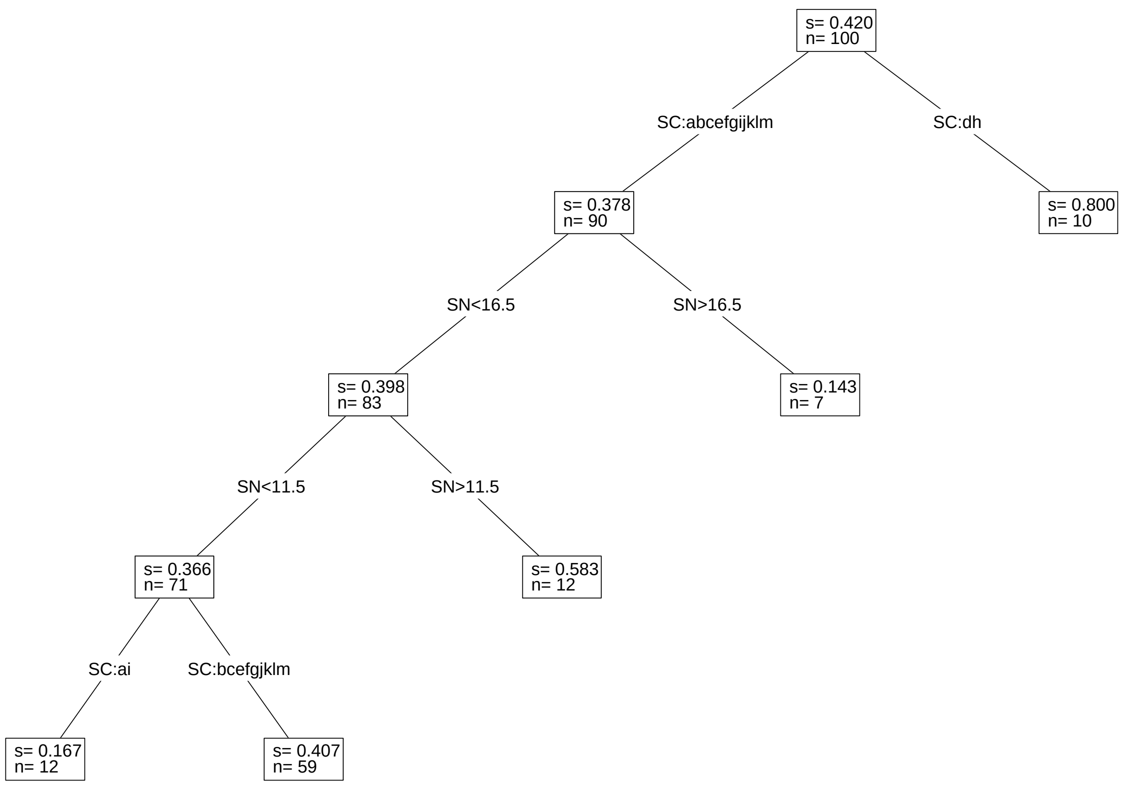
- Change monitoring and risk identification:
  - ▷ Change in predicted response.
  - ▷ Through tree structural change.
  - ▷ Identify high risk input state.
  - ▷ Additional analyses often necessary.
  - ▷ Enhanced test cases or components.

TBRMs at Different Times



- Fig 22.4 (p.383): an early TBRM.
  - ▷ high-risk areas identified by input
  - ▷ early actions to improve reliability

TBRMs at Different Times



- Fig 22.5 (p.383): a late TBRM.
  - ▷ high-risk areas ≈ early runs
  - ▷ uniformly reliable ⇒ ready for release

TBRM Impact

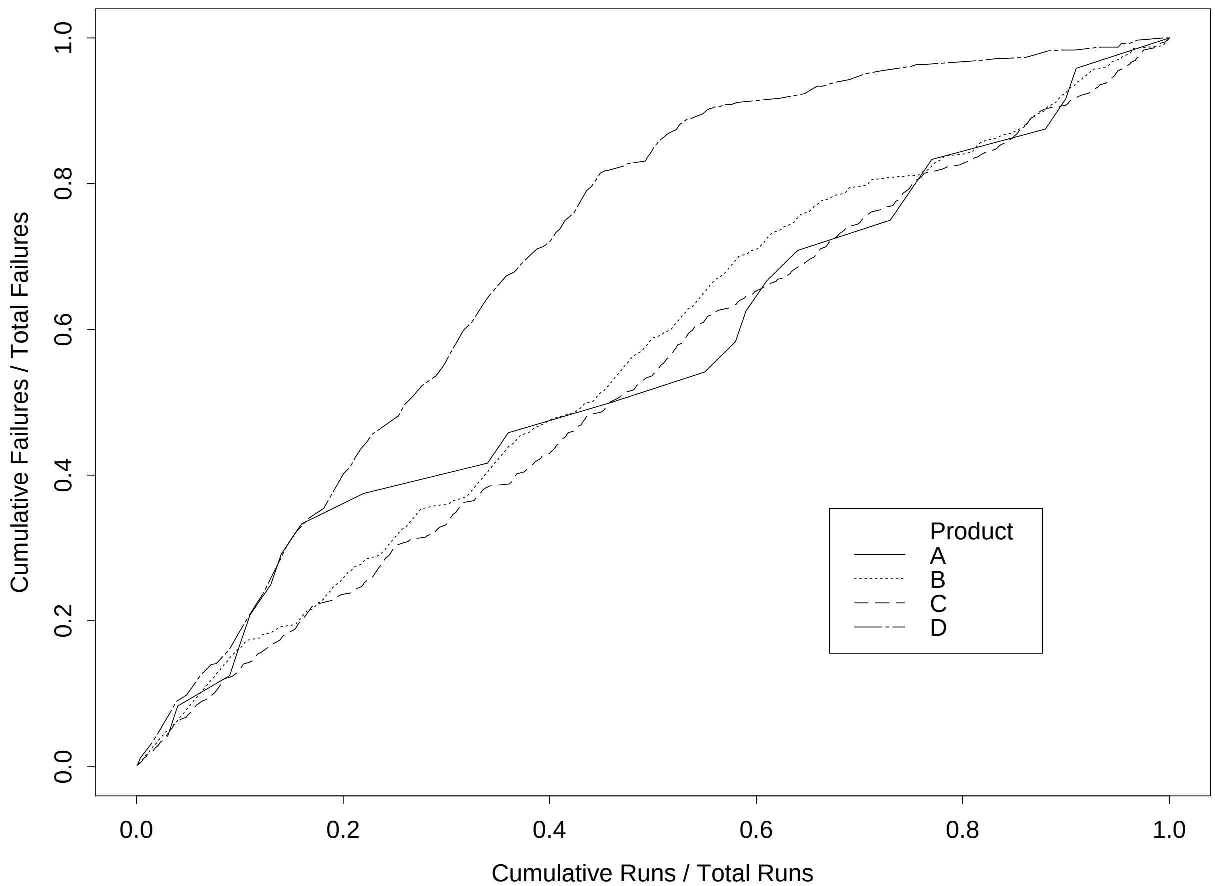
- Evaluation/validation with SRGMs:
  - ▷ Trend of reliability growth.
  - ▷ Stability of failure arrivals.
  - ▷ Estimated reliability: see below

- Quantitative impact evaluation:
  - ▷ Product purity level ρ at exit:

$$\rho = \frac{\lambda_0 - \lambda_T}{\lambda_0} = 1 - \frac{\lambda_T}{\lambda_0}$$

- Important: deployment
  – all successor products at IBM

TBRM Result Comparison



- Fig 22.6 (p.384): TBRMs used in D
  - ▷ better reliability growth in D
  - ▷ compare to A, B, and C (no TBRMs)

TBRM Result Comparison

- Table 22.3 (p.384):
  quantitative comparison with ρ

Purification Level ρ	Product A	Product B	Product C	Product D
maximum	0.715	0.527	0.542	0.990
median	0.653	0.525	0.447	0.940
minimum	0.578	0.520	0.351	0.939

Where: $\rho = \frac{\lambda_0 - \lambda_T}{\lambda_0} = 1 - \frac{\lambda_T}{\lambda_0}$

λ_0: failure rate at start of testing

λ_T: failure rate at end of testing

Integrated Approach: Implementation

- Modified testing process:
  - ▷ Additional link for data analysis.
  - ▷ Process change and remedial actions.
- Activities and Responsibilities:
  - ▷ Evolutionary, stepwise refinement.
  - ▷ Collaboration: project & quality orgs.
  - ▷ Experience factory prototype (Basili).
- Implementation:
  - ▷ Passive tracking and active guidance.
  - ▷ Periodic and event-triggered.
  - ▷ S/W tool support

Implementation Support

- Types of tool support:
  - ▷ Data capturing
    - – mostly existing logging tools
    - – modified to capture new data
  - ▷ Analysis and modeling
    - – SMERFS modeling tool
    - – S-PLUS and related programs
  - ▷ Presentation/visualization and feedback
    - – S-PLUS and Tree-Browser

- Implementation of tool support:
  - ▷ Existing tools: minimize cost
    - – internal as well as external tools
  - ▷ New tools and utility programs
  - ▷ Tool integration
    - – loosely coupled suite of tools
    - – connectors/utility programs
  - ▷ Overall strategy: Ch.18 (Section 18.4)

SRE Perspectives

- New models and applications
  - ▷ Expand from "medium-reliable" systems.
  - ▷ New models for new application domains.
  - ▷ Data selection/treatment

- Reliability improvement
  - ▷ Followup to TBRMs
  - ▷ Predictive (early!) modeling for risk identification and management

- Other SRE frontiers:
  - ▷ Coverage/testing and reliability
  - ▷ Reliability composition and maximization