Modeling System Reliability using Various Component and System Data Sources

Christine Anderson-Cook
Statistical Sciences Group, D-1
Los Alamos National Laboratory
c-and-cook@lanl.gov

Todd Graves, Earl Lawrence, Scott Vander Wiel, Alyson Wilson
Statistical Sciences Group, D-1
Los Alamos National Laboratory

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Outline

- Connecting to the System Ethnography Model
- Basics of the Bayesian System Model for Estimating and Predicting Reliability
- Estimates from Model
- Current Research on Additional Capability of Model
- Conclusions

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Overview of Model

- Model contains a reliability distribution for each component, as well as how the components are combined to give system
- For basic model:
  - Reliability distribution for each component as a function of age will be estimated from the data and any expert knowledge that we wish to incorporate
  - Components combine serially into whole system (assume that all components need to work for system success)
- Other aspects:
  - Component reliability will be estimated by using both flight and component quality assurance measures
  - Requires surrogacy assumption for integrating data sources
  - Different variants of systems are possible

Translation of Data – Flight Data

- Need to translate flight successes and failures into information about the individual components of the system

SN	Age (months)	Result	Failure Mode
U00866	110	Failure	Missile Battery Fails in Flight
U00867	56	Success	
U00868	87	Success	
...	...	...	
U00843	33	Success	
U00858	91	Success	
U00818	103	Failure	Degraded Roll
U00814	41	Failure	Hangfire
U00803	74	Failure	Unguided Flight

Activity	Failure Mode	Related Hardware	Possible Root Cause
RAM Designation [From Missile Present to ITL (p A-22)]	Missile Not Detected	Ship	Error in Ship Controls
		Ship, Launcher	Error in Ship to Launcher Interface
		Launcher	Error in Launcher
		Umbilical	Error in Launcher to GMRP Interface
RAM Launch [From Successful Missile Ready to Umbilical Separation]	Misfire	Rocket Motor	No/Low RM Thrust
	Hangfire	Canister: Hold Back Latch	HBL not retracted
	Dud	Rocket Motor	RM not fired
		Canister: Squibs	Failed Squibs
		Ship to Launcher	Miscommunition, No Signal
		Launcher to Missile (Umbilical)	Open Wires, Failed Umbilical
	Launch Cover Eject Fails	Canister Squibs	Squibs Failed, Covers did not completely separate
	Low RM Thrust	Rocket Motor	Aged Propellant, Propellant not ignited
	Degraded Roll	Rocket Motor	Low RM Thrust

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	Low RM Thrust	Rocket Motor	Aged Propellant, Propellant not ignited
	Degraded Roll	Rocket Motor	Low RM Thrust

Legend
S = Success
F = Failure
PF = Possible Failure
? = Status Not Tested

At least one of these failed

Once a system fails, no info about components in later phases

Specific component failed

	P1:Missile Assign			P2: Wake Up				P3: Launch			P8: Direct Strike			
Failure Modes	C1	C2	C3	C4	C5	C6	C7	C8	C9	…	C27	C28	C29	C30
Missile Not Detected	PF	PF	PF	?	?	?	?	?	?		?	?	?	?
Misfire	S	S	S	S	S	S	S	F	S		?	?	?	?
Hangfire	S	S	S	S	S	S	S	S	F		?	?	?	?
Dud	S	S	S	S	S	S	S	PF	PF		?	?	?	?
Degraded Pitch	S	S	S	S	S	S	S	S	S		?	?	?	?
…														
Success	S	S	S	S	S	S	S	S	S		S	S	S	S

SN	Age (months)	Result	Failure Mode
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		P1:Missile Assign			P2: Wake Up				P3: Launch			P8: Direct Strike			
SN	**Age (months)**	C1	C2	C3	C4	C5	C6	C7	C8	C9	…	C27	C28	C29	C30
U00866	110	S	S	S	S	S	S	S	S	S		?	?	?	?
U00867	56	S	S	S	S	S	S	S	S	S		S	S	S	S
U00868	87	S	S	S	S	S	S	S	S	S		S	S	S	S
…	…														
U00818	103	S	S	S	S	S	S	S	PF	PF		?	?	?	?
U00814	41	S	S	S	S	S	S	S	S	F		?	?	?	?
U00803	74	S	S	S	S	S	S	S	S	S		?	?	?	?

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Translation of Data – Component Quality Assurance Data

C1			
Age	Value	Lower Spec	Upper Spec
1	12.6	10	15
1	13.1	10	15
2	13.2	10	15
2	14.1	10	15
2	13.4	10	15
3	13.7	10	15
...	...	...	...
6	14.8	10	15

C2			
Age	Value	Lower Spec	Upper Spec
1	1.25	1	2
1	1.33	1	2
2	1.51	1	2
2	1.26	1	2
2	1.44	1	2
3	1.24	1	2
...		...	...
6	1.37	1	2

• • •

C4		
Age	Value	Upper Spec
1	3.12	4
1	3.17	4
2	3.22	4
2	3.41	4
2	3.15	4
3	3.28	4
...	...	...
6	3.18	4

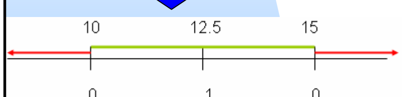
C1		
Age	Value	Lower Spec
1	12.3	10
1	14.3	10
2	15.1	10
2	11.1	10
2	9.7	10
3	10.3	10
...	...	...
6	14.2	10

- Some components may not have any quality assurance data
- Some components may have multiple measures
- Specification limits can be Upper and Lower, Lower Only, Upper Only

Standardizing QA data

For computational convenience, these measures are translated to a standardized scale where 0 is the specification limit, positive values are within specification, and negative values are outside the specification limits

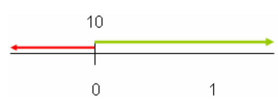
C1			
Age	Value	Lower Spec	Upper Spec
1	12.6	10	15



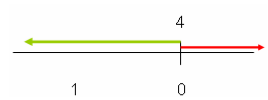
$$\frac{2.5-|X-12.5|}{2.5}$$

C1		
Age	Value	Lower Spec
1	12.3	10

$$X-10$$



C4		
Age	Value	Upper Spec
1	3.12	4



$$4-X$$

Integrating Components of Model into Unified Analysis

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- To combine the data from these different data sources, we need an approach that allows flexibility:
  - Ability to incorporate expert knowledge of system
  - There is a considerably variability in how much data is observed for different pieces of the system
  - Not all components will have quality assurance data
  - The specification limits are thought to be approximations of when the part will fail, but do not necessarily match exactly with the flight data
  - Observed flight failure modes will not necessarily specify the failure of every component
  - There is frequently ambiguity about which component failed during flight testing

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Including flight test data in the posterior distribution

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- Define p_{1i} , p_{2i} , and p_{3i} to be the probability that components 1,2,3 work in the *i*th test
- These are functions of the age of the *i*th missile and of the unknown parameters, which we will define later
- For a very simple system with 2 components, we obtain terms like $(p_{1i}p_{2i})$ ← Both components worked
  $\{p_{1i}(1-p_{2i})\}$, ← Component 1 worked, but comp 2 failed
  and $\{1-p_{1i}p_{2i}\}$, ← At least one of Comp 1 or 2 failed
- For a more complex system, we might obtain
  $(p_{1i}p_{2i}\, p_{3i}p_{4i}\, p_{5i}p_{6i}\, p_{7i}p_{8i})$ ← All 8 components worked
  or $(p_{1i}p_{2i}\, p_{3i}p_{4i}\, (1- p_{5i}p_{6i}))$ ← At least one of C5 or C6 failed

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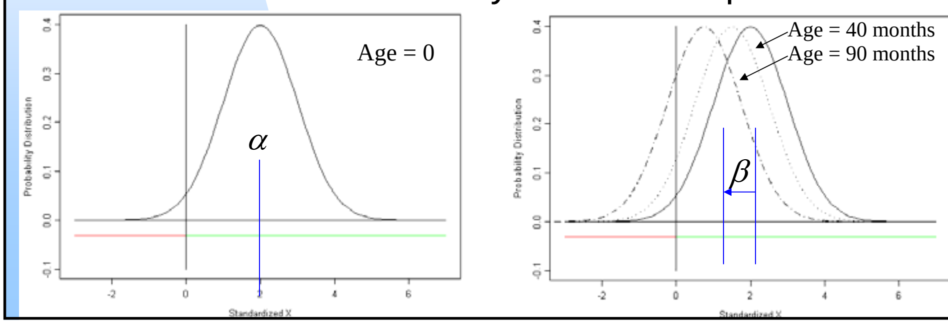
Models for the QA measurements

- Denote the *i*th component QA measurement by C_i. It was taken from a missile with age A_i.
- Assume $C_i \sim N(\alpha_{Li} + \beta_{Li}A_i, \gamma_{Li}^2)$: linear regression
- α's have prior mean to match expected proportion of failures, β's should be negative
- Generates normal density terms in the posterior



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Additional System Covariates

In addition to the system age, A_i, there may be a number of other measures which are thought to potentially affect degradation of the system over time:

- Amount of time spent in storage, S_i
- Number of transfers, T_i, (usage-to-shore)

- Alternate measure in the model add additional parameters of the form

$$C_i \sim N(\alpha_{L_i} + \beta_{1,L_i} A_i + \beta_{2,L_i} T_i + \beta_{3,L_i} S_i, \gamma_{L_i}^2)$$

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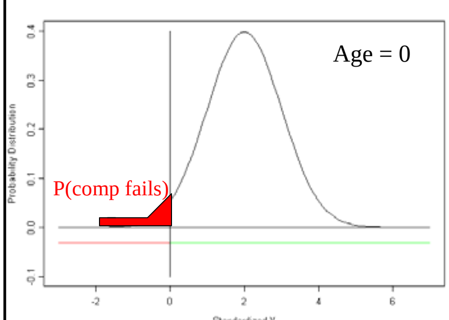
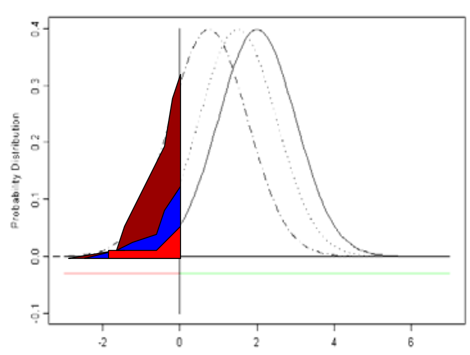
Surrogacy assumption

- In order to combine the information from the QA data and the flight data we need the surrogacy assumption
- This states that the pattern of behavior for the two types of data is assumed to be the same, since there was no systematic strategy used for determining which test was done on the system
- This allows us to write the flight data in terms of the specification formulation
  - Suppose that a launch motor to be flight tested would have attained spec measurements C^1, C^2, C^3, C^4 had those things been measured (and they won't be!)
  - Then the probability (p_{1i}) that the component will succeed in the flight test is assumed to be $\Pi_{j=1}^{4}\, \Phi\{(C^j-\theta_j)/\ \sigma_j\}$, conditionally on the C's

- We don't observe the specific C^1, C^2, C^3, C^4 for flight tested data!
- Fortunately one can integrate them out, so that the probability the component works, unconditionally on the C's, is

$$p_{1i} = \Pi_{j=1}^{4}\, \Phi\{(\alpha_j + \beta_j A_i - \theta_j)/\ (\sigma_j^2 + \gamma_j^2)^{1/2}\},$$



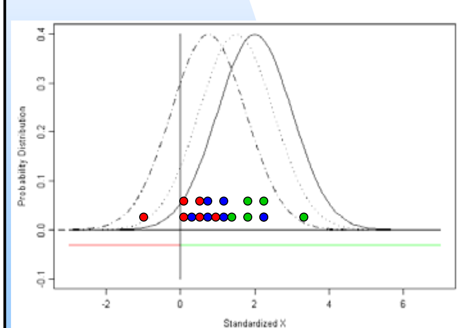


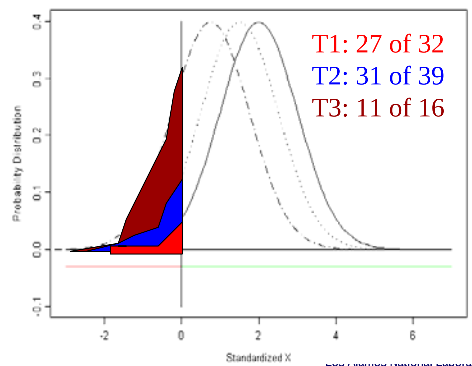
Data & the Surrogacy Assumption

- Both sources of data provide information about the shift of reliability over time

From QA data, we obtain the mean of the characteristic at each time

From the flight data, we obtain a proportion of success/failure at each time





Bayesian Analysis

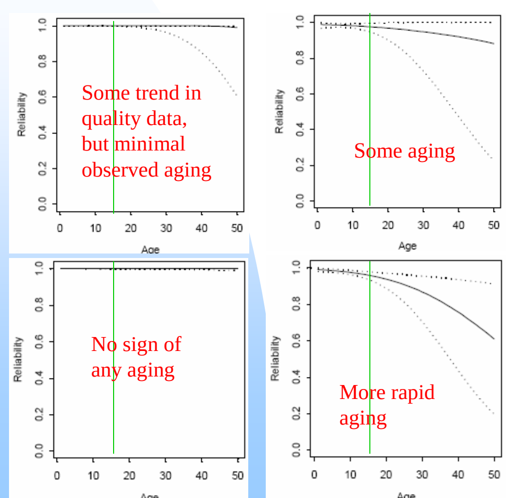
- Capability to easily incorporate expert knowledge about reliability for individual components, through informative priors
- Using special-purpose MCMC programming packages, YADAS
  - http://yadas.lanl.gov
  - Control over algorithm choices
  - “Solves” broader class of mode
- Analysis could also be programmed in other languages as well (eg. R, S-Plus, WinBugs)
- Computationally quite intensive

Model Analysis Outputs

- Component specific reliability estimates
  - For all observed times
  - For future times
- System level reliability estimates
  - For all observed times
  - For future times
- Information about how closely the current specification limits match what has been observed
  - This could be helpful for understanding the actual performance (i.e. what values of some of the quality assurance measures are actually associated with failures)

Component reliability estimates

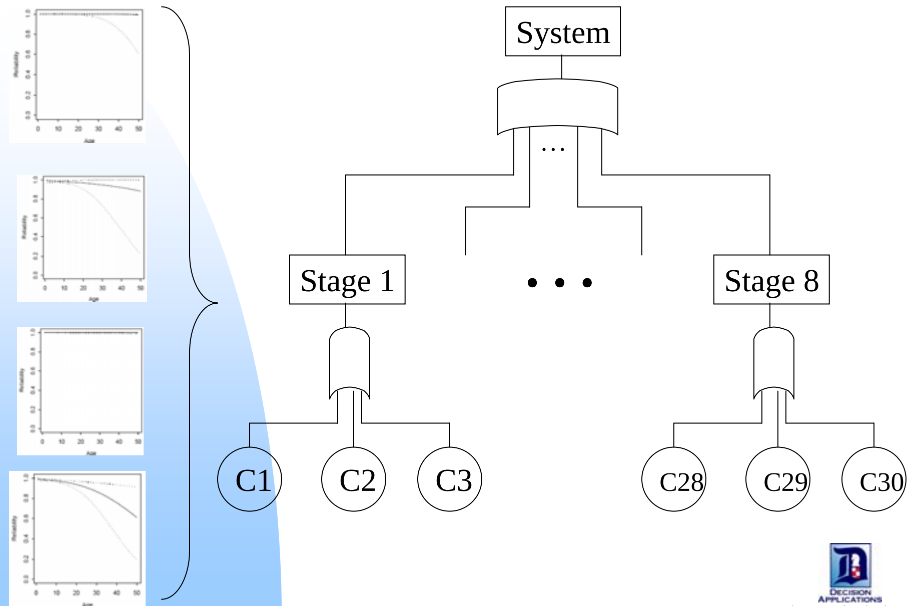
- For each component in the system, we can obtain estimates for its reliability at any age



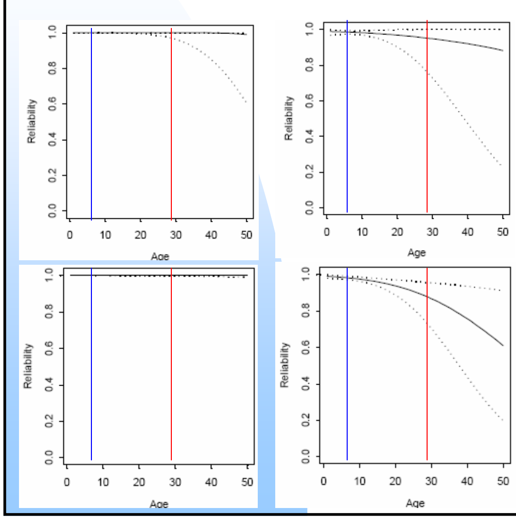
Each component has its own summary with potentially different reliability and precision

It is not uncommon to have many components showing little or no aging, while others are the main drivers of the system reliability

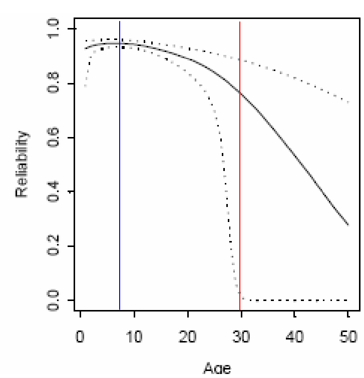
System Reliability Estimate



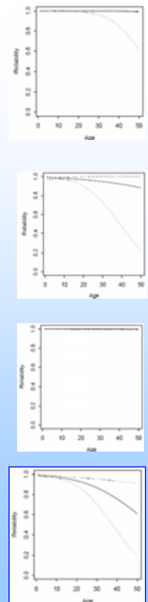
System Reliability at any age is the product of all of the component reliabilities in a serial system



P(system success) = function of component reliabilities

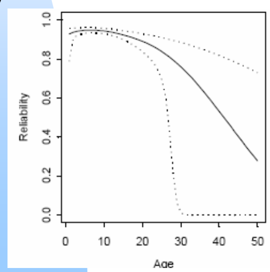


System Reliability for Variants

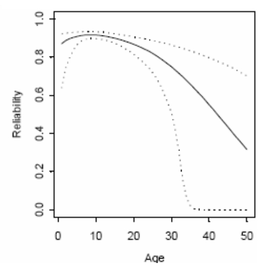


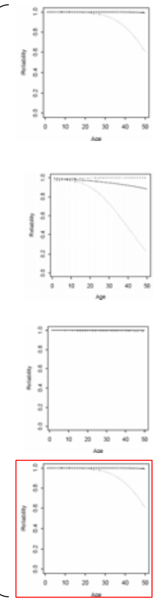
Recall for some systems there will be variants with many common parts, but some that are different. With this approach we can assemble a system estimate for any collection of components

Variant 1



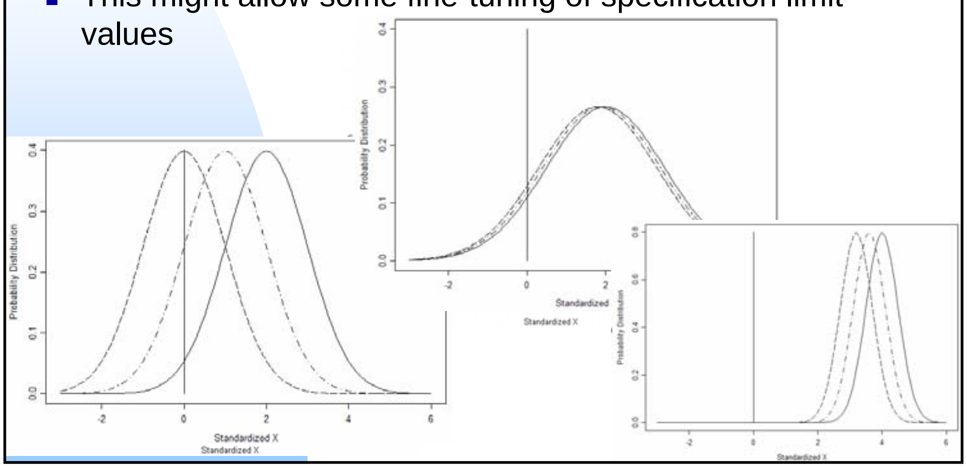
Variant 2





Assessing Specification Limits

- By examining the parameter estimates of the model, we can see what proportion of successes are predicted to fall within the specification limits and outside the limits.
- This might allow some fine-tuning of specification limit values



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Current Research

- There are many enhancements to the model which will make it increasingly flexible for variations in the data. We are currently working to include:
  - Formal assessment methods for additional system level covariates (eg. Storage patterns, usage patterns)
  - More flexible types of quality assurance data (pass/fail, categorical, ordinal data)
  - Incorporating maintenance of components
  - Incorporating accelerated testing data
  - Improving global summaries of stockpile reliability

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Conclusions

- Modeling system reliability as a function of component reliability allows for additional sources of data to be included
- Simulation study currently being conducted to help determine which system and data characteristics are most influential on precision
  - Considered:
    - System complexity
    - Pattern of reliability over time
    - Number of variants
    - Amount and distribution of data over time
    - Amount and distribution of data between different data sources
    - Priors (diffuse, informative and correct, informative and incorrect)
    - Different data used: SF, SF CF, SF CS, SF CF CS

System characteristics (System complexity; Pattern of reliability over time; Number of variants)

Data distribution (Amount and distribution of data over time; Amount and distribution of data between different data sources)

216 combos x 10 reps (first five items)

8 analyses (Priors; Different data used)

SF = system flight
CF = component flight
CS = component spec (QA data)

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Conclusions (continued)

- There can be important advantages (for both accuracy and precision) to incorporating the component flight (CF) and component specification (CS) data
- Collecting CF data is more beneficial for complex systems
- Variability of results is dependent on which combination of system complexity, amount of data and distribution over time we are considering
- Priors need to be carefully chosen to reflect current understanding of component and system reliability (both diffuse and incorrect informative priors can cause problems)
- Cost considerations for the relative cost of collecting these data should also be considered when determining which analysis is best

References

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- C.M. Anderson-Cook, T. Graves, N. Hengartner, R. Klamann, A. Koehler, G. Lopez, and A.G. Wilson, "**Reliability Modeling using Both System Test and Quality Assurance Data**" , Los Alamos National Laboratory Report LA-UR-05-2252 (2005).
- C.M. Anderson-Cook, T. Graves, A. Koehler, E. Lawrence, S. Vander Wiel, and A.G. Wilson, "**Comparing Different System Reliability Estimation Methods**", Los Alamos National Laboratory Report LA-UR-05-9401 (2005).

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