SimBRS WD 43

Fleet Maintenance Simulation for Unmanned Ground Vehicles

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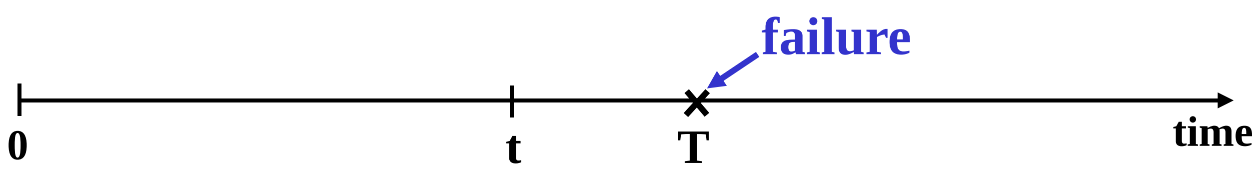
Overview

- What is reliability ?
- Basics of reliability methods for repairable and non-repairable systems
- Estimation of PDF of Time Between Failures (TBF) using limited, censored data
- System reliability and reliability allocation
- Fleet Maintenance Simulation (FMS) Tool
- Unmanned ground vehicle (UGV) system example

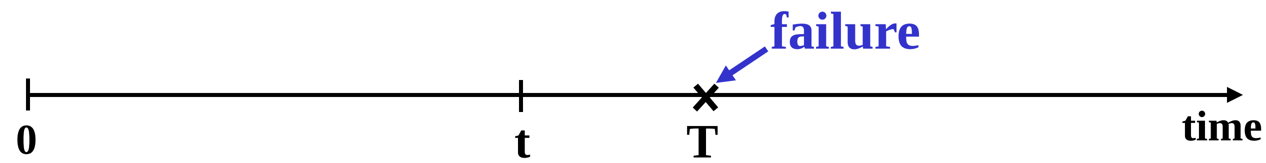
What is Reliability?

Reliability at time t is the probability that the system has not failed before time t.



$$\boxed{R(t) = P(T > t) = 1 - P(T \le t)}$$

Reliability of Non-Repairable Systems



$$R(t) = P(T > t) = 1 - P(T \le t) \Rightarrow \boxed{R(t) = 1 - F(t)} \qquad \textbf{(1)}$$

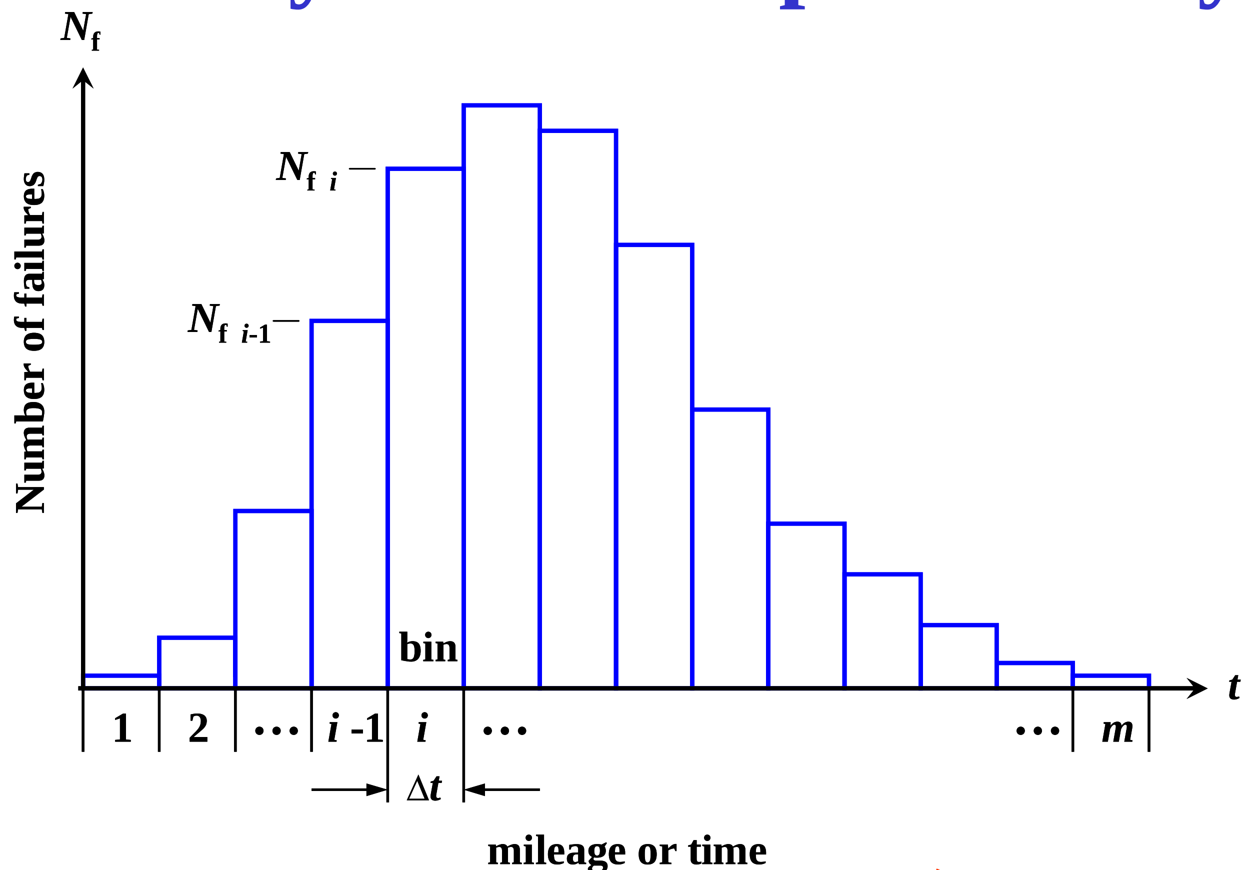
Failure Rate

$$\lambda(t) = \frac{P(t < T \le t + dt / T > t)}{dt} = \frac{P(t < T \le t + dt)}{dt * P(T > t)} =$$

$$= \frac{F(t + dt) - F(t)}{dt * R(t)} \Rightarrow \boxed{\lambda(t) = \frac{f(t)}{R(t)}} \qquad \textbf{(2)}$$

From (1) and (2) we get : $\boxed{R(t) = \exp[-\int_0^t \lambda dt]}$

Reliability of Non-Repairable Systems



$$N_f = \sum_{i=1}^{m} N_{f_i}$$

$$\left.\lambda_i = \frac{f_i}{1-F_i} = \frac{f_i}{1-\sum_{j=1}^{i-1}\frac{N_{f_j}}{N_f}} = \frac{N_{f_i}}{\left(N_f - \sum_{j=1}^{i-1} N_{f_j}\right)\Delta t}\right\} \Rightarrow$$

$$H_i = \sum_{j=1}^{i} \lambda_j \Delta t$$

$$\boxed{R_i = e^{-H_i}}$$

Reliability Calculation

All we need for calculating the reliability of a system (non-repairable or repairable) is the system PDF of time to failure (TTF)

We use :

- **Data to estimate the PDF of TTF for each component**
- **Monte Carlo simulation to estimate the PDF of TTF for the system**

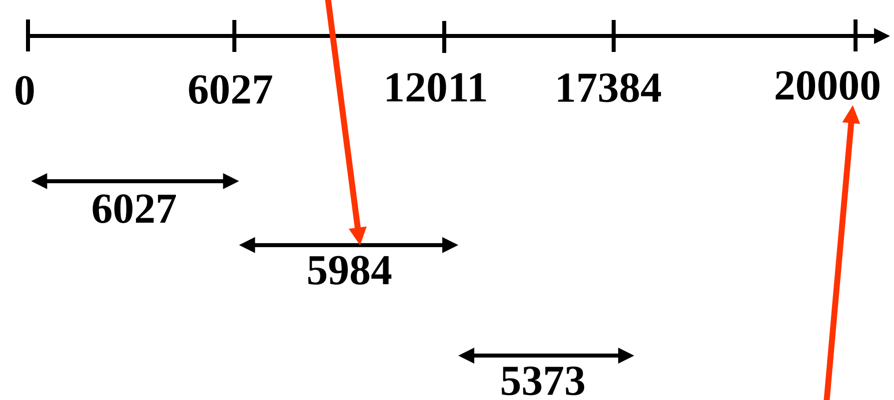
Estimation of the PDF of the TTF (TBF) using Limited, Censored Data

Censored MLE Approach

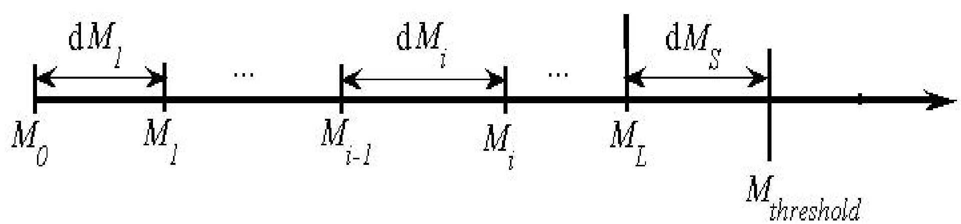
Limited Data / Notation

Original data Vehicle#	Original data mileage	Updated data Vehicle#	Updated data mileage
10	741	1	10247
4	5273	2	9044
7	6027	2	8977
5	7398	3	13984
6	7495	3	4064
2	9044	4	5273
1	10247	4	9747
8	12008	5	7398
7	12011	5	7611
9	12014	6	7495
10	12074	6	7516
3	13984	7	6027
5	15009	7	5984
6	15011	7	5373
4	15020	8	12008
7	17384	9	12014
2	18021	10	741
3	18048	10	11333

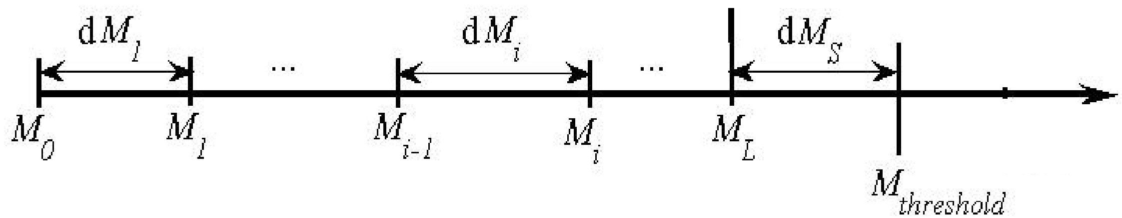
Time Between Failures (TBF)



Censoring Mileage

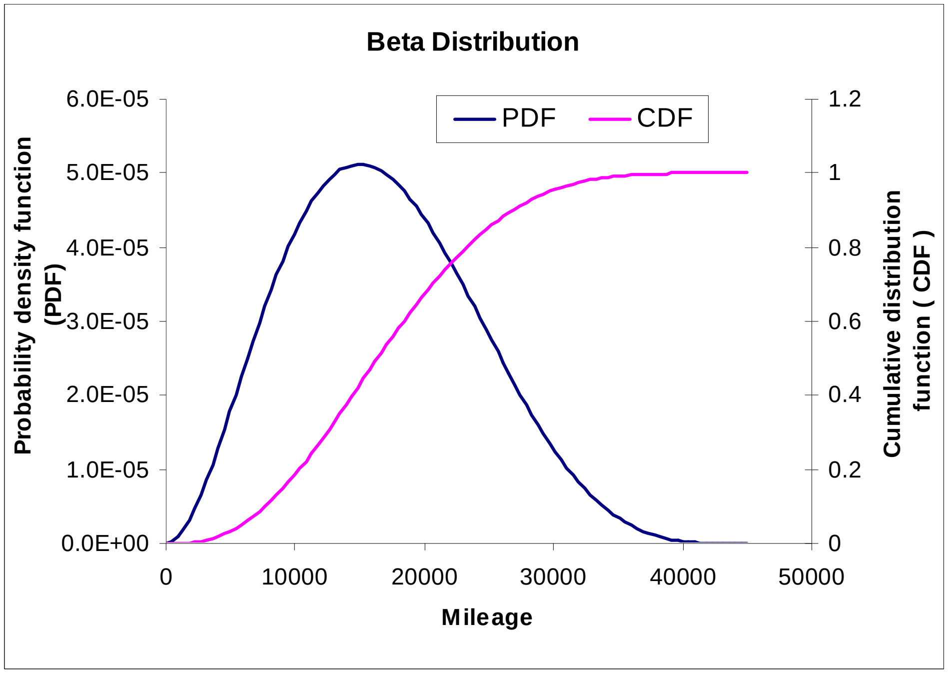


Observation / Assumption



$$\boxed{\mathrm{d}M_i = X_i \sim \beta(A, B, p, q), \quad (A \le X_i \le B, \text{ and } p > 0, q > 0)}$$

$$\boxed{f(x, A, B, p, q) = \beta(p,q)^{-1} (x - A)^{p-1} (B - x)^{q-1} / (B - A)^{p+q-1}, \quad (A \le x \le B, \textit{ and } p > 0, q > 0)}$$



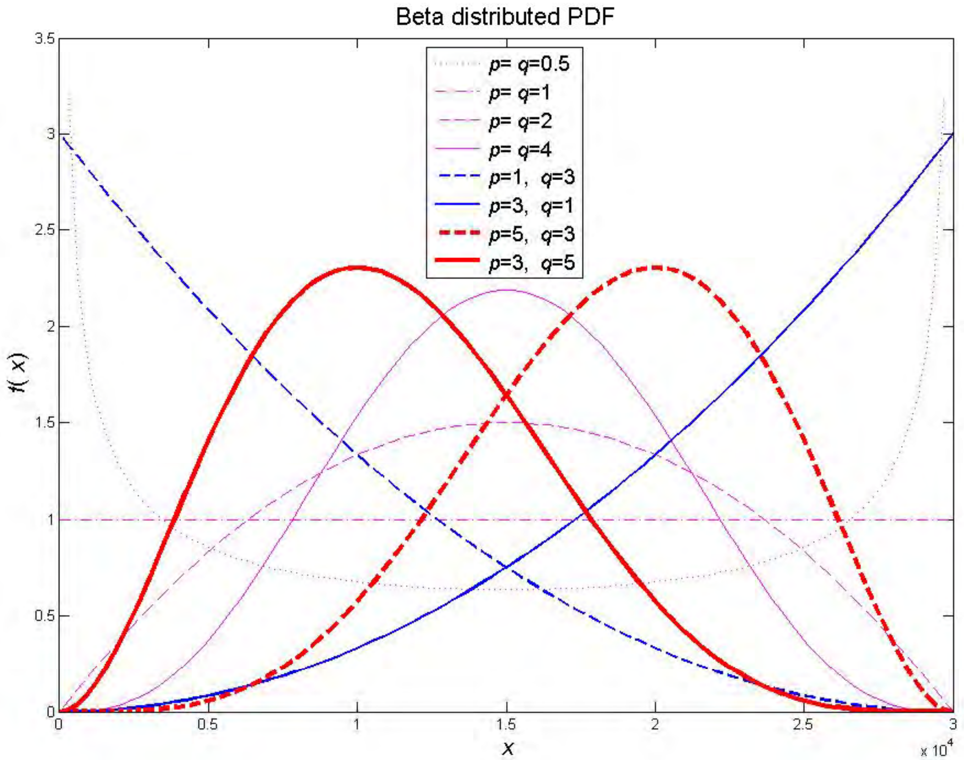
A = 0

B = 45,000 miles

p = 3, q = 5

Observation / Assumption

- **Beta distribution family is used to model TBF.**



A=0, B = 30000

$$f(x, A, B, p, q) = \beta(p,q)^{-1}(x-A)^{p-1}(B-x)^{q-1}/(B-A)^{p+q-1}, \quad (A \le x \le B, \text{ and } p > 0, q > 0)$$

MLE Approach

Determines parameters (*A, B, p, q*) of "most likely" Beta distribution using available data.

Censored MLE

# of recorded failures

# of survivals

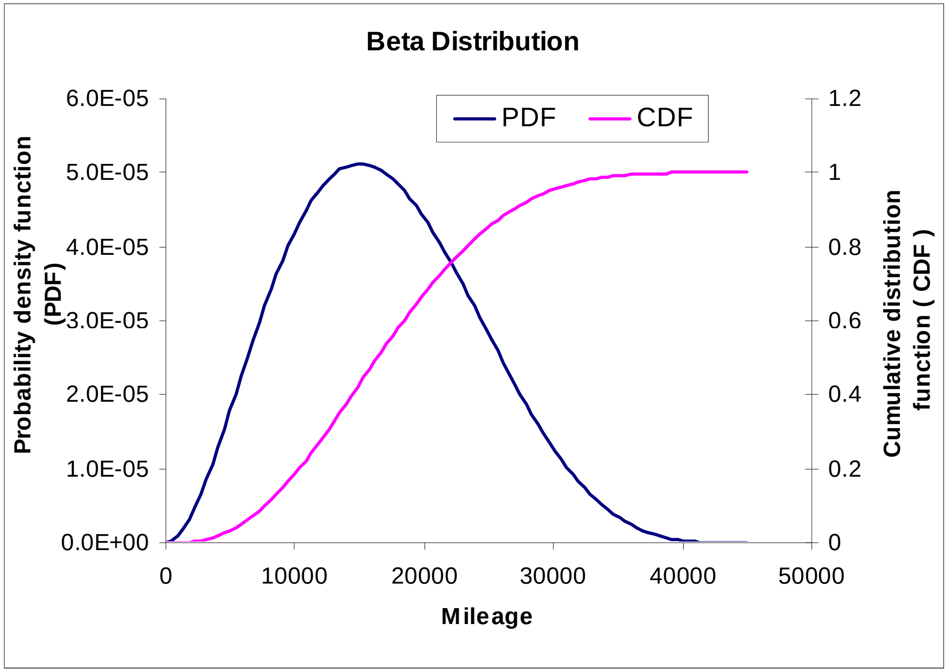
$$\underset{A,B,p,q}{Max} \prod_{i=1}^{N_F} f\left(x_i, A, B, p, q\right) \prod_{j=1}^{N_s} \left[1 - F\left(x_j, A, B, p, q\right)\right]$$

Beta PDF

Beta CDF

If Only MTBF is Available

$$\boxed{f(x,A,B,p,q) = \beta(p,q)^{-1}(x-A)^{p-1}(B-x)^{q-1}/(B-A)^{p+q-1}, \quad (A \le x \le B, \ and \ \ p>0, q>0)}$$



$$\mu = MTBF$$

Assume constant COV

Then for:

$$\bar{\mu} = \frac{\mu - A}{B - A} \quad \textbf{and} \quad \bar{\sigma} = \frac{\sigma}{B - A}$$

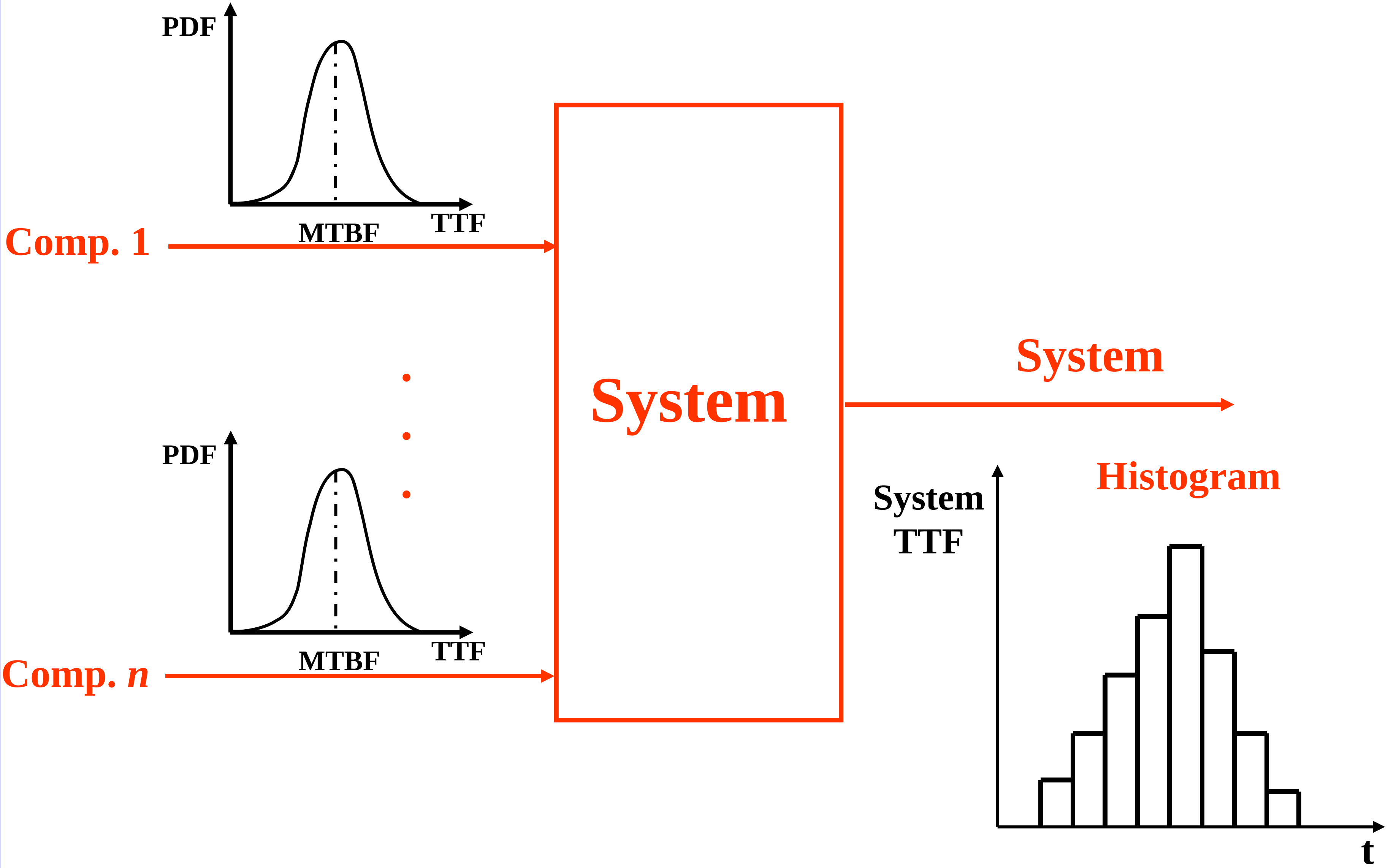
We get:

$$p = \bar{\mu}\left(\frac{\bar{\mu}(1-\bar{\mu})}{\bar{\sigma}^2} - 1\right),$$

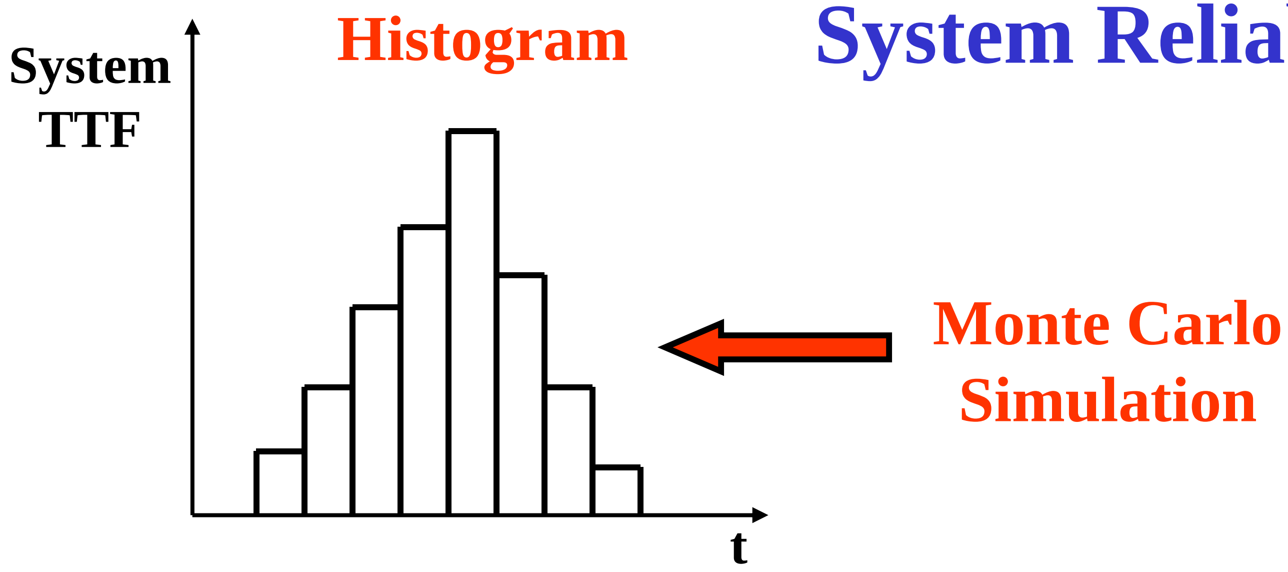
$$q = (1-\bar{\mu})\left(\frac{\bar{\mu}(1-\bar{\mu})}{\bar{\sigma}^2} - 1\right)$$

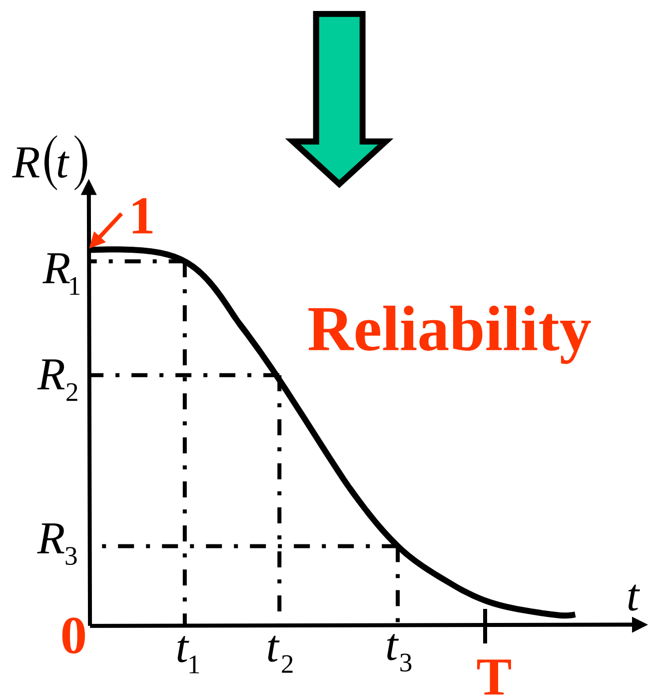
System Reliability and Reliability Allocation

System Reliability



System Reliability

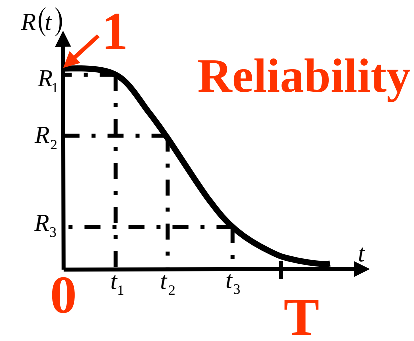




<u>For System :</u>

$$MTBF = \int_0^\infty R(t)\,dt$$

Reliability Allocation



Specify system (vehicle) reliability

Optimization

Determine required reliability of EACH component

This optimization problem DOES NOT have a unique solution

Reliability Allocation

One way to get a unique solution is to trade-off reliability and associated cost

$$\min_{\underline{R}_{comp}} \ Cost$$

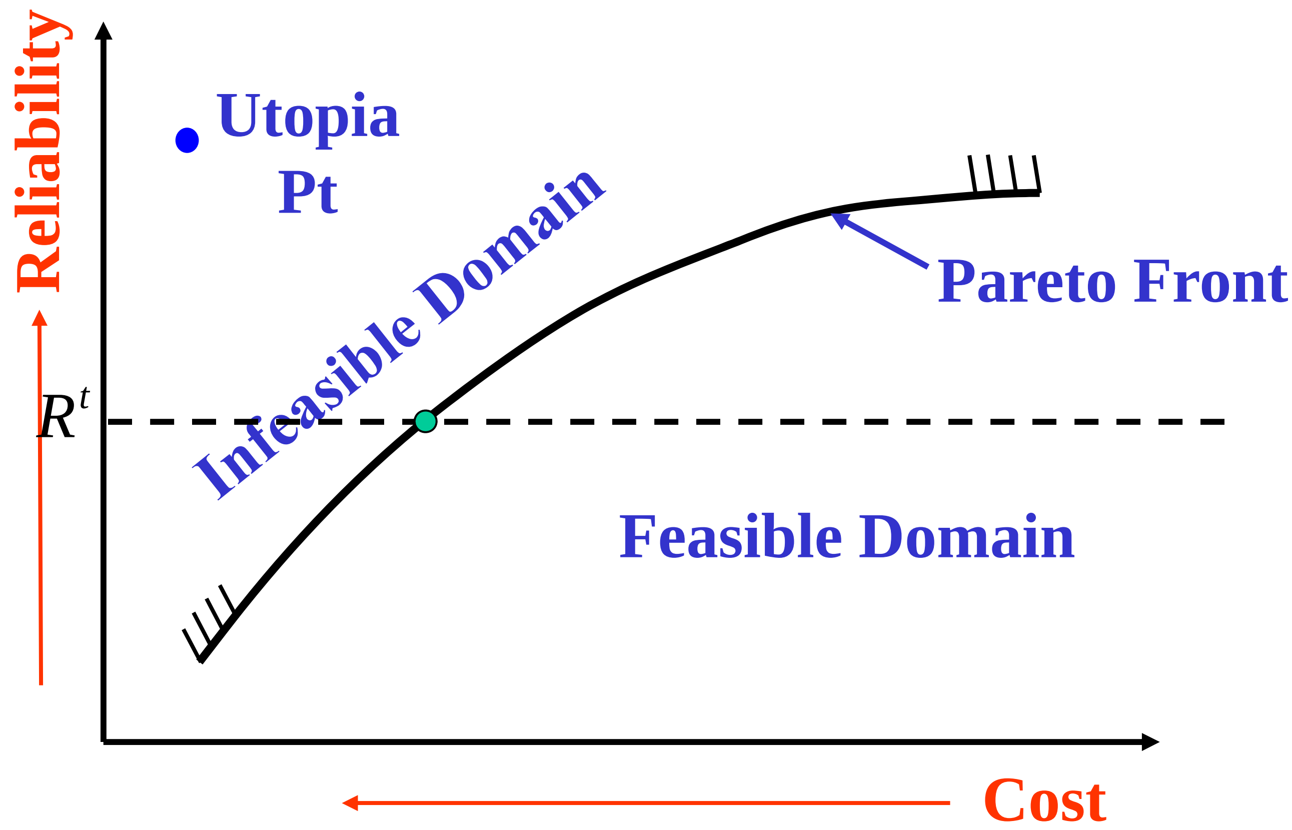
Target system reliability

s. t. $$System \ \ \mathrm{Re}\, liability = R^t$$

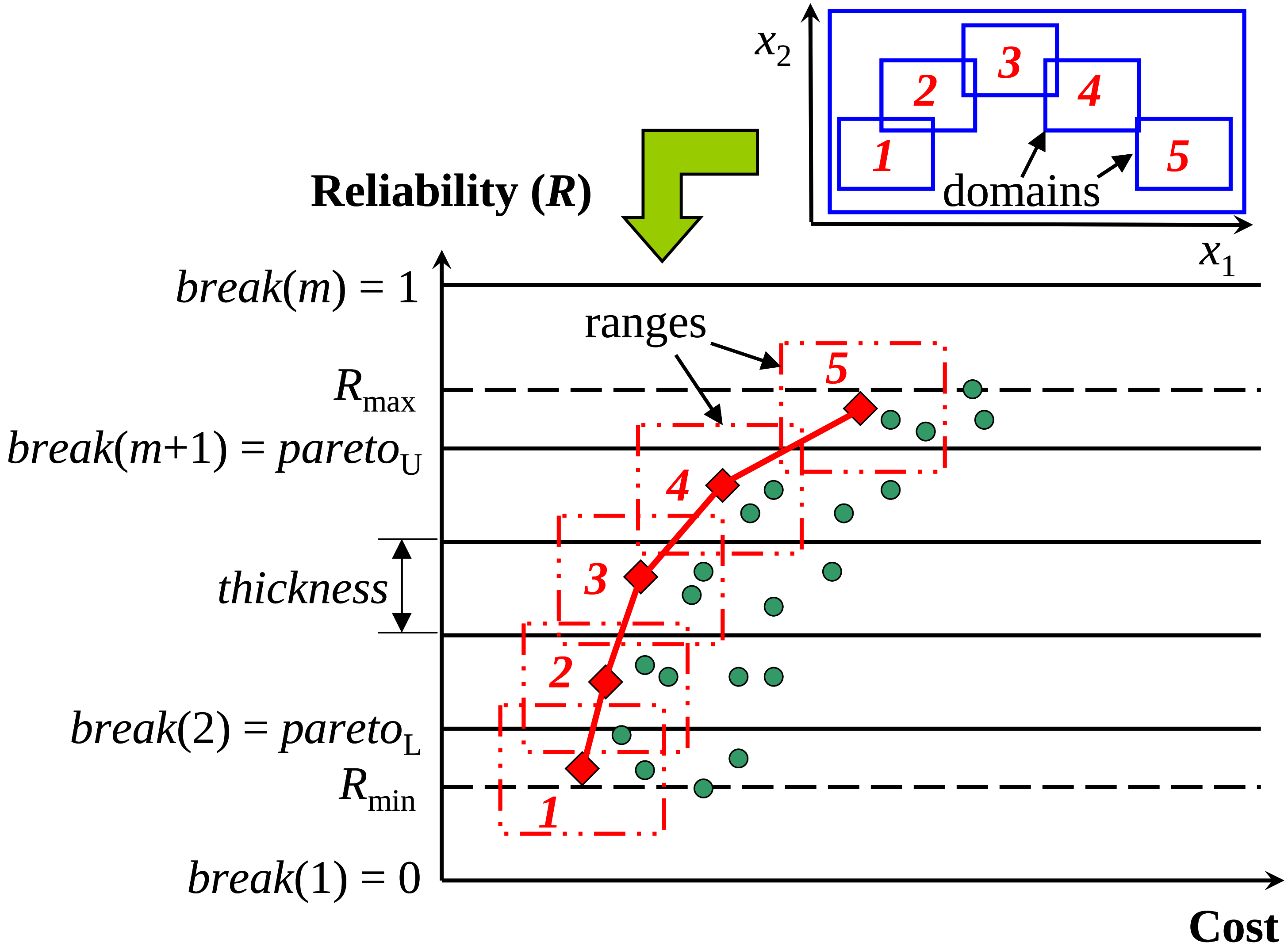
By varying R^t **, we get the so called "Pareto Frontier."**

Reliability vs Risk of Failure (Cost)

We want to maximize Reliability and simultaneously minimize Risk of failure (cost)



Reliability – Cost Pareto Front Calculation

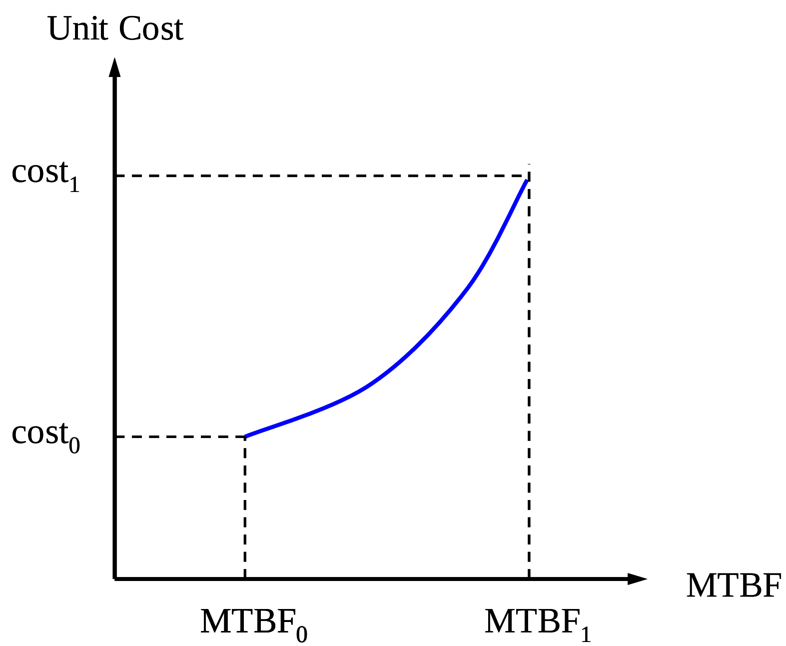


Reliability-Cost Relation

$$\text{cost} = \text{cost}_0 \, e^{k(\text{MTBF}/\text{MTBF}_0 - 1)}$$ **: For each component**

$$\text{Cost} = \sum_{i_C=1}^{N_C} \left[\text{cost}_0 \, e^{k(\text{MTBF}/\text{MTBF}_0 - 1)} (1 + \text{failure counts}) \right]_{i_C}$$

For system with Nc components

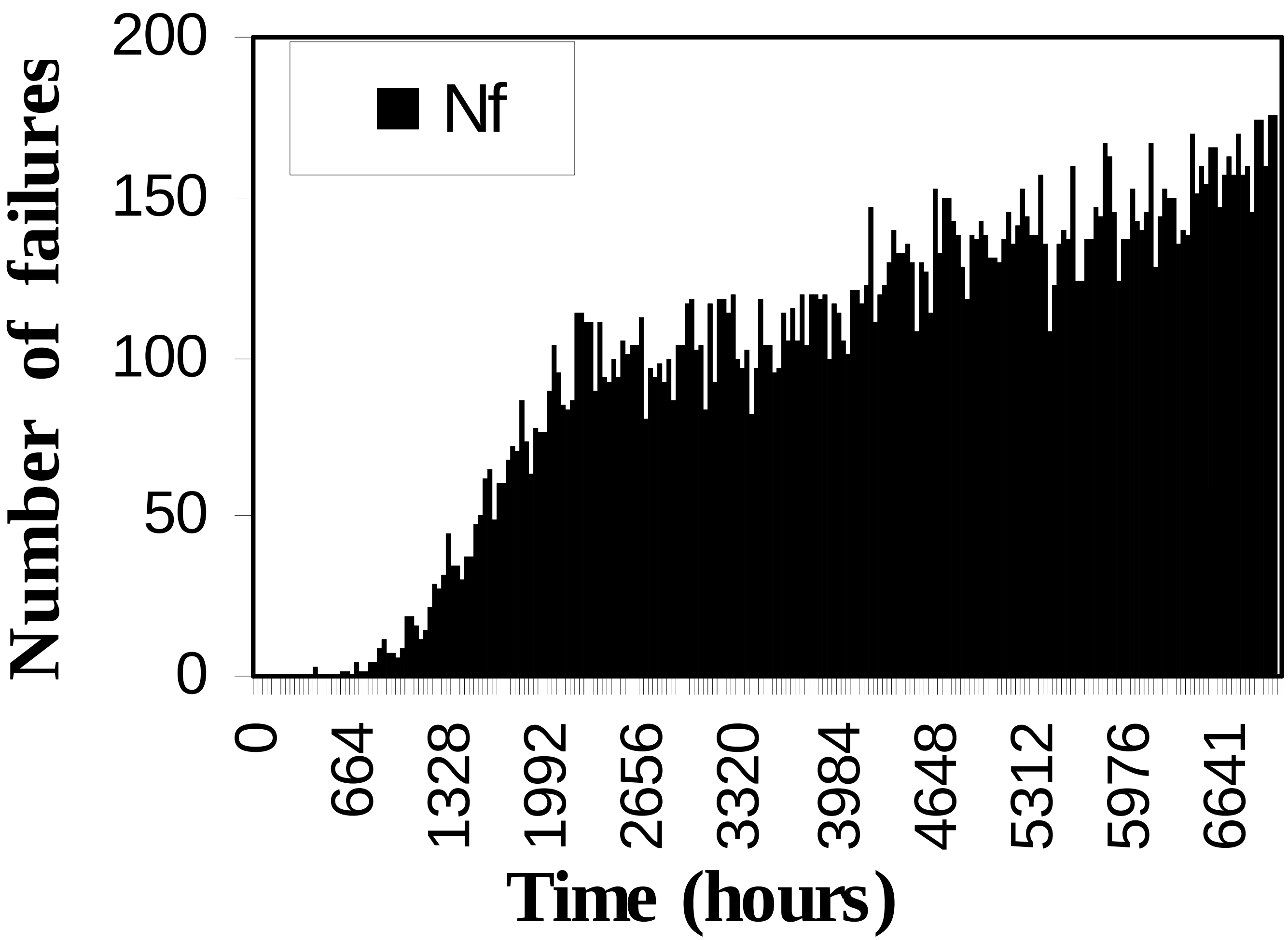


Example : Fifteen-Component System in Series

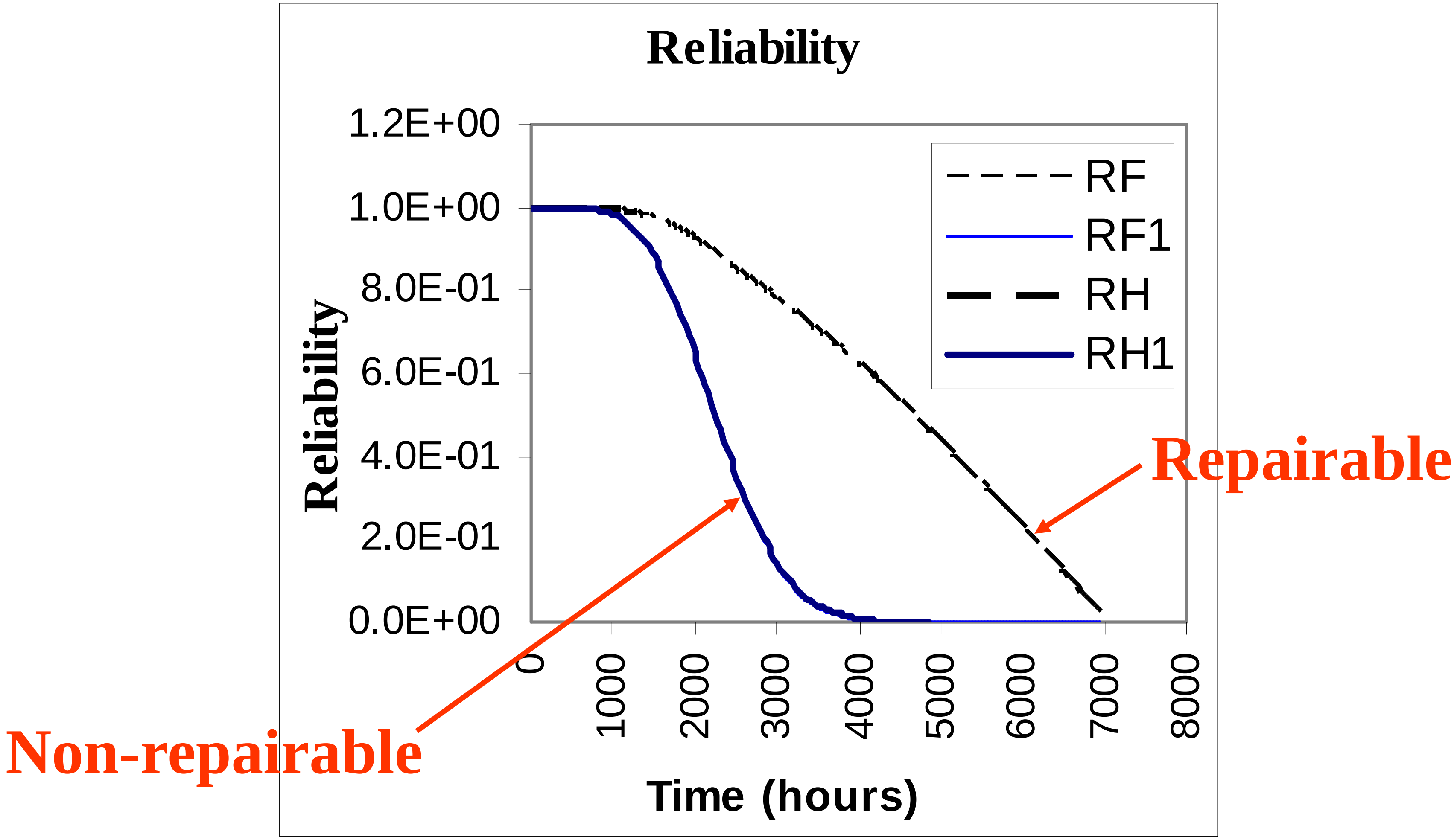
Input Information

Component Number Comp No.	Baseline MTBF in hours ($MTBF_0$)	Coefficient of Variation	B_{factor}	Baseline cost ($Cost_0$)	k
1	4076	0.3	3	$27,500.00	1
2	15000	0.3	3	$7,000.00	1
3	26510	0.3	3	$3,000.00	1
4	40000	0.3	3	$5,000.00	1
5	18000	0.3	3	$5,000.00	1
6	8000	0.3	3	$500.00	1
7	31809	0.3	3	$22,500.00	1
8	9520	0.3	3	$30,000.00	1
9	9713	0.3	3	$12,500.00	1
10	2330	0.3	3	$20,000.00	1
11	40000	0.3	3	$27,500.00	1
12	8614	0.3	3	$1,000.00	1
13	45000	0.3	3	$30,000.00	1
14	20000	0.3	3	$3,000.00	1
15	25000	0.3	3	$15,000.00	1

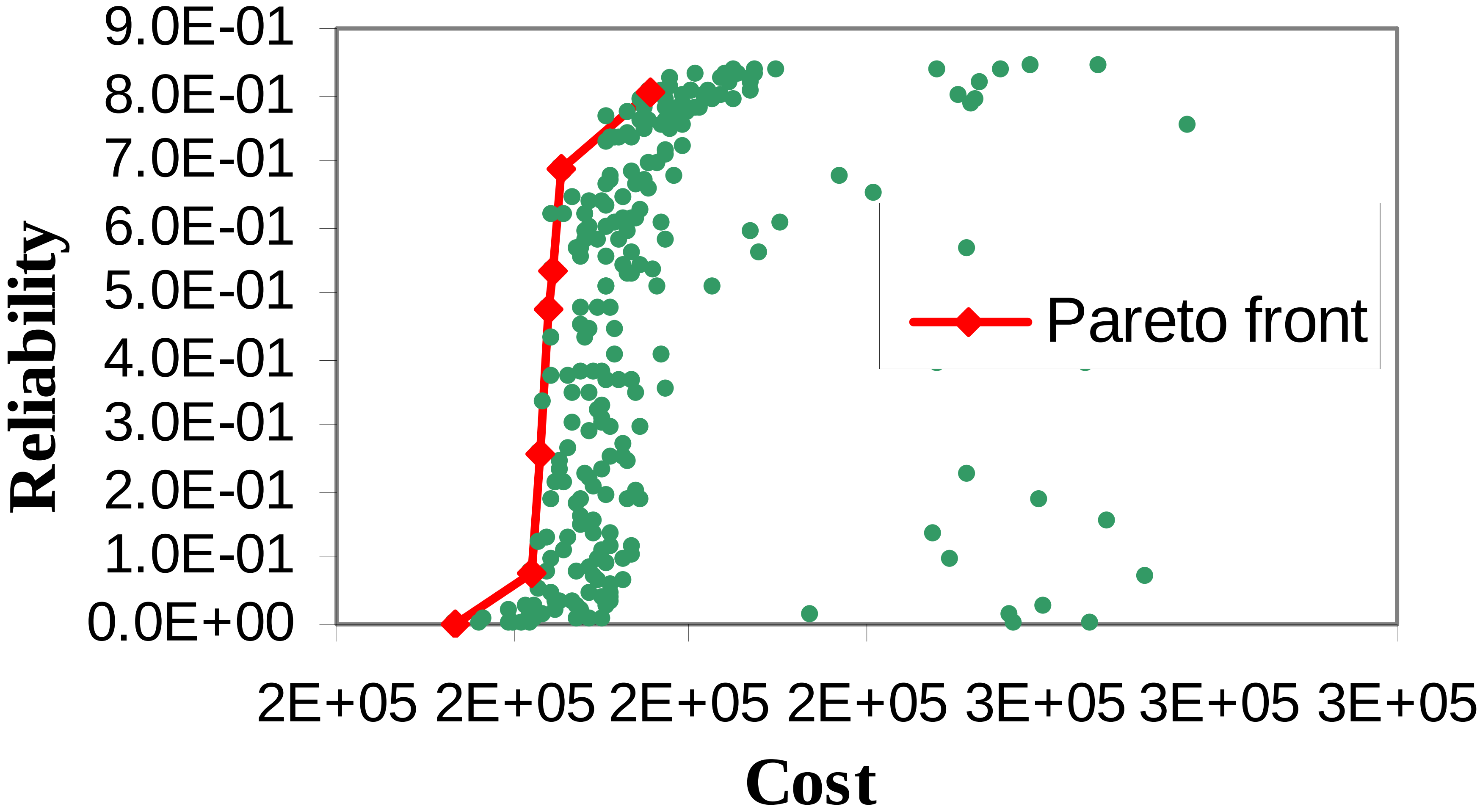
Histogram of System Failures



Reliability Comparison between Repairable and Non-repairable System



System Reliability-Cost Pareto Front



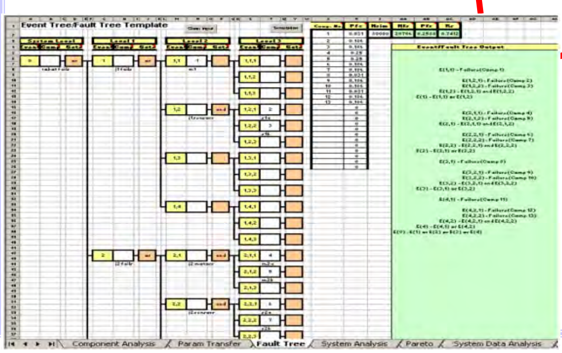
Summary: Methodology

- A methodology was presented to :
  - Calculate system reliability using limited data
  - Perform reliability allocation (determine reliabilities of components) using optimal trade-off between reliability and cost
- The methodology was demonstrated with a fifteen-component vehicle system

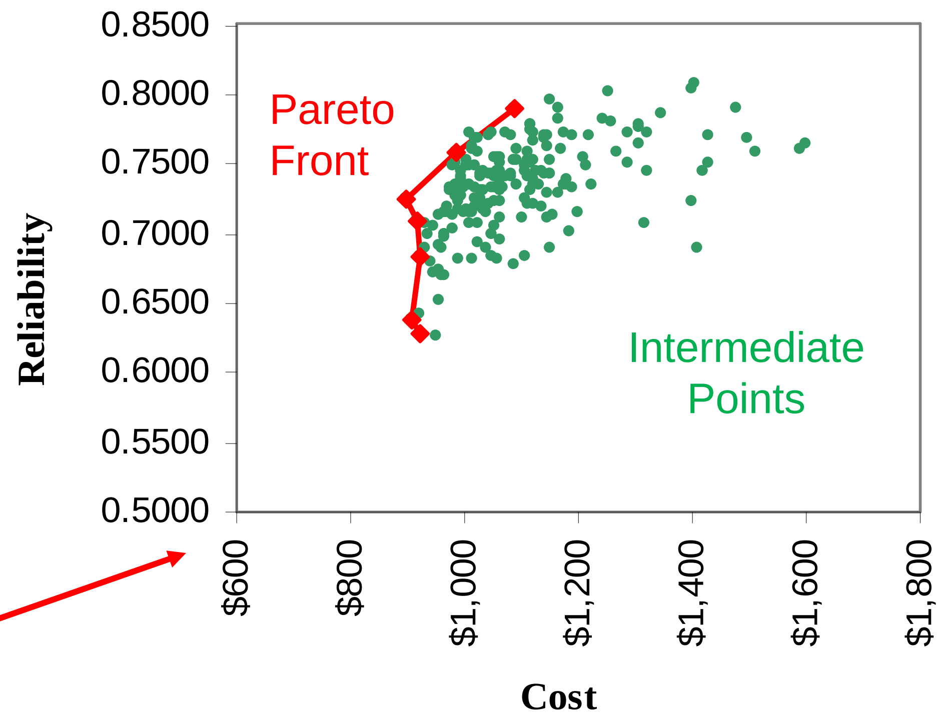
Fleet Maintenance Simulation (FMS) Tool

Simulation and Optimization - FMS Tool

- Developed jointly by TARDEC (CASSI Analytics) and Oakland University
- Predicts vehicle maintenance over lifecycle based on component input data
- Enables reliability-cost trade/sensitivity/optimization studies for vehicle fleets



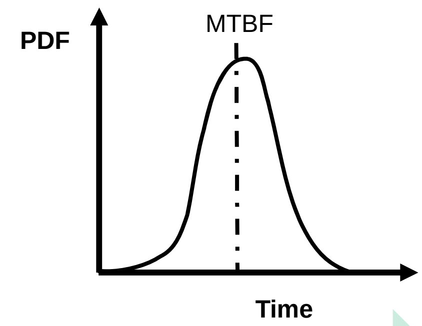
Fault tree in FMS Tool



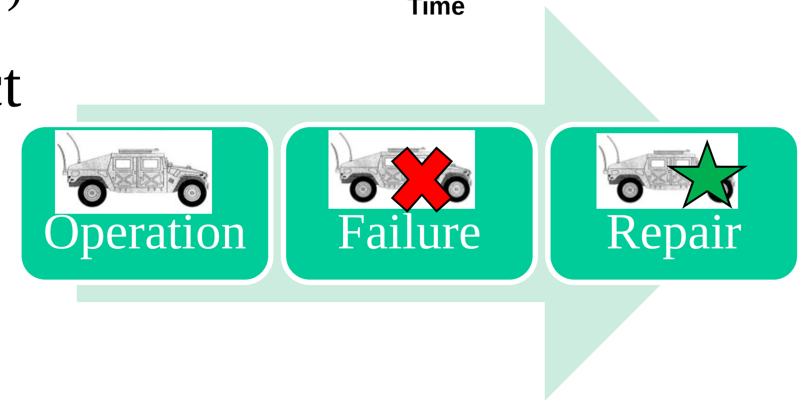
FMS Tool used to perform reliability-cost trade study for adding redundant motors and sensors to an unmanned ground vehicle (UGV) manipulator arm

Analysis Procedure

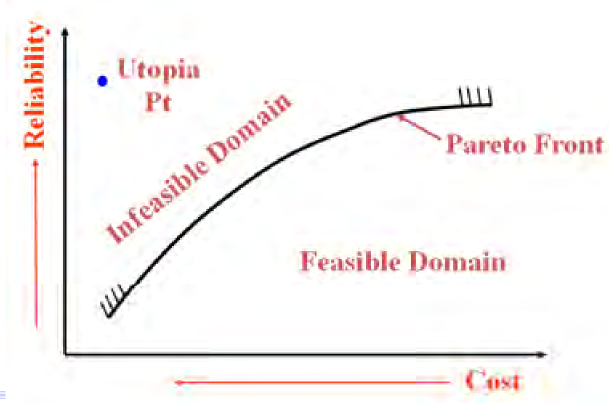
1. Estimate component probability of failure vs time or mileage
   - Focus on cost and repair drivers
   - Minimum data: mean time between failure (MTBF)



2. Run Monte Carlo simulations to predict fleet reliability, availability, cost
   - Vehicle lifetime: user-specified
   - Number of simulated vehicles: user-specified

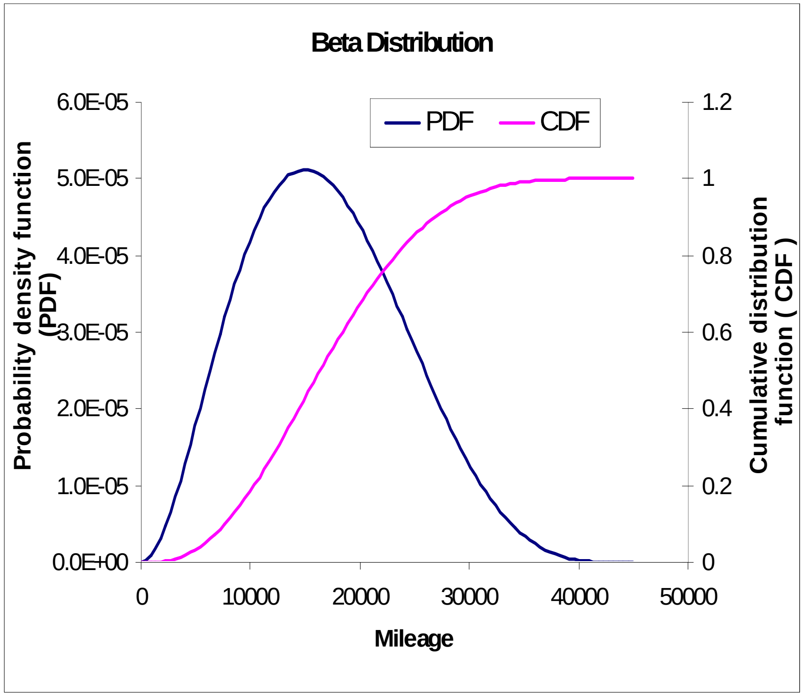


3. Perform trade/sensitivity/optimization studies
   - Tradeoffs among configurations, component changes, maintenance schedules, etc.
   - Sensitivity to data uncertainty, price changes, etc.
   - Optimization of components, schedules, etc.



Estimation of Component Reliability

- Beta distribution family is used to model probability of component failure versus time or mileage
- When maintenance records are available:
  - FMS Tool processes raw data
- For **limited, censored data** FMS Tool has two options to estimate the distribution
  - Censored Maximum Likelihood Estimation (MLE)
  - Bayesian updating approach ("enhances" data with expert opinion)



Example: Unmanned Ground Vehicle (UGV)

- Focus on robotic arm design
- For original design, each joint and the end effector has:
  - 1 motor
  - 1 optical encoder (sensor)
- Perform trade study for adding secondary sensors, motors
- Use reliability @ 1000 hours of operation as input data
  - **Motor: R(1000) = 0.969**
  - **Sensor: R(1000) = 0.814**

Reliability of UGV Arm – Original Design

$$R_s = (0.969 \times 0.814)^4 = 0.387$$

Fault Tree for Original Design

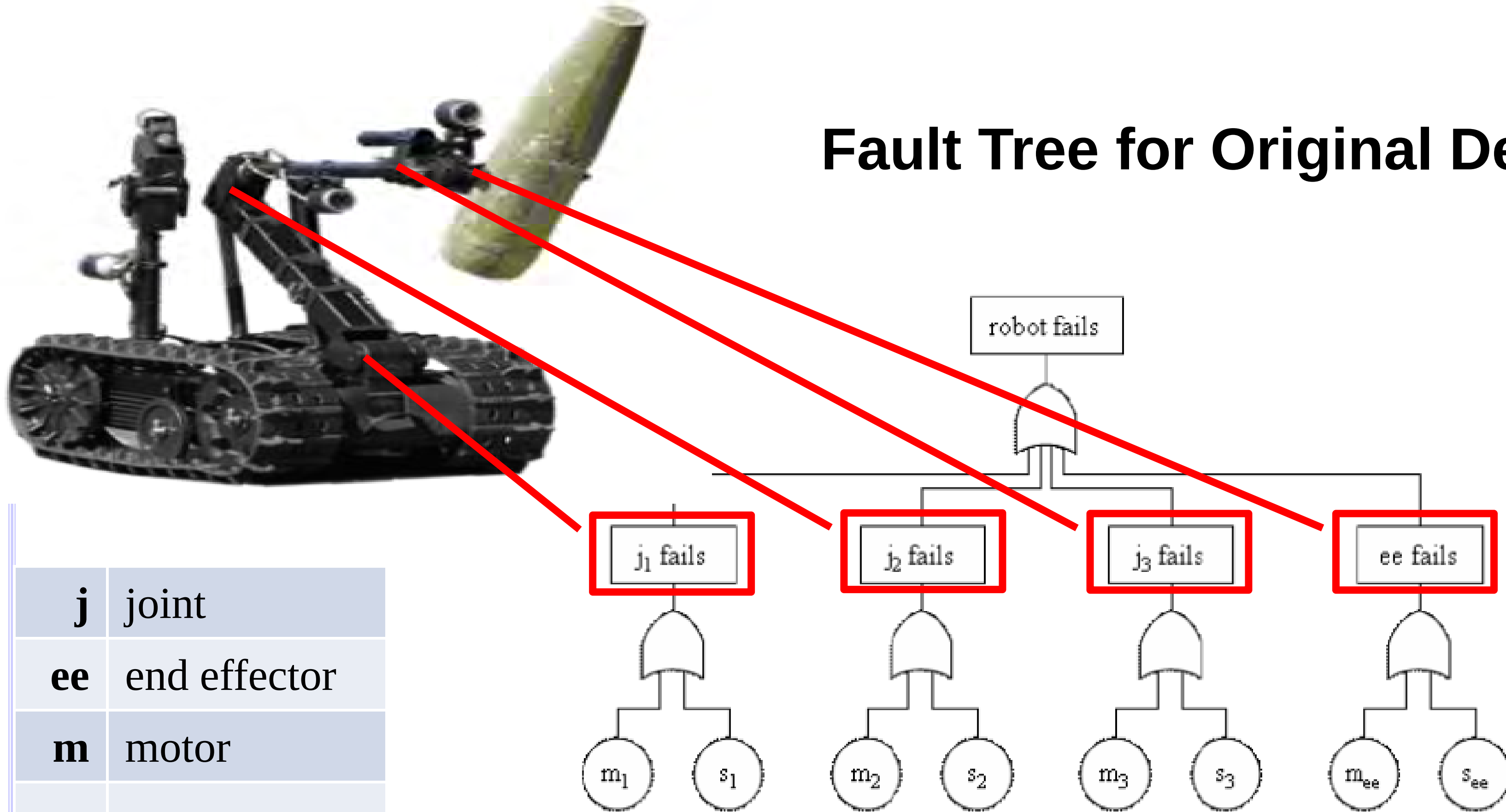


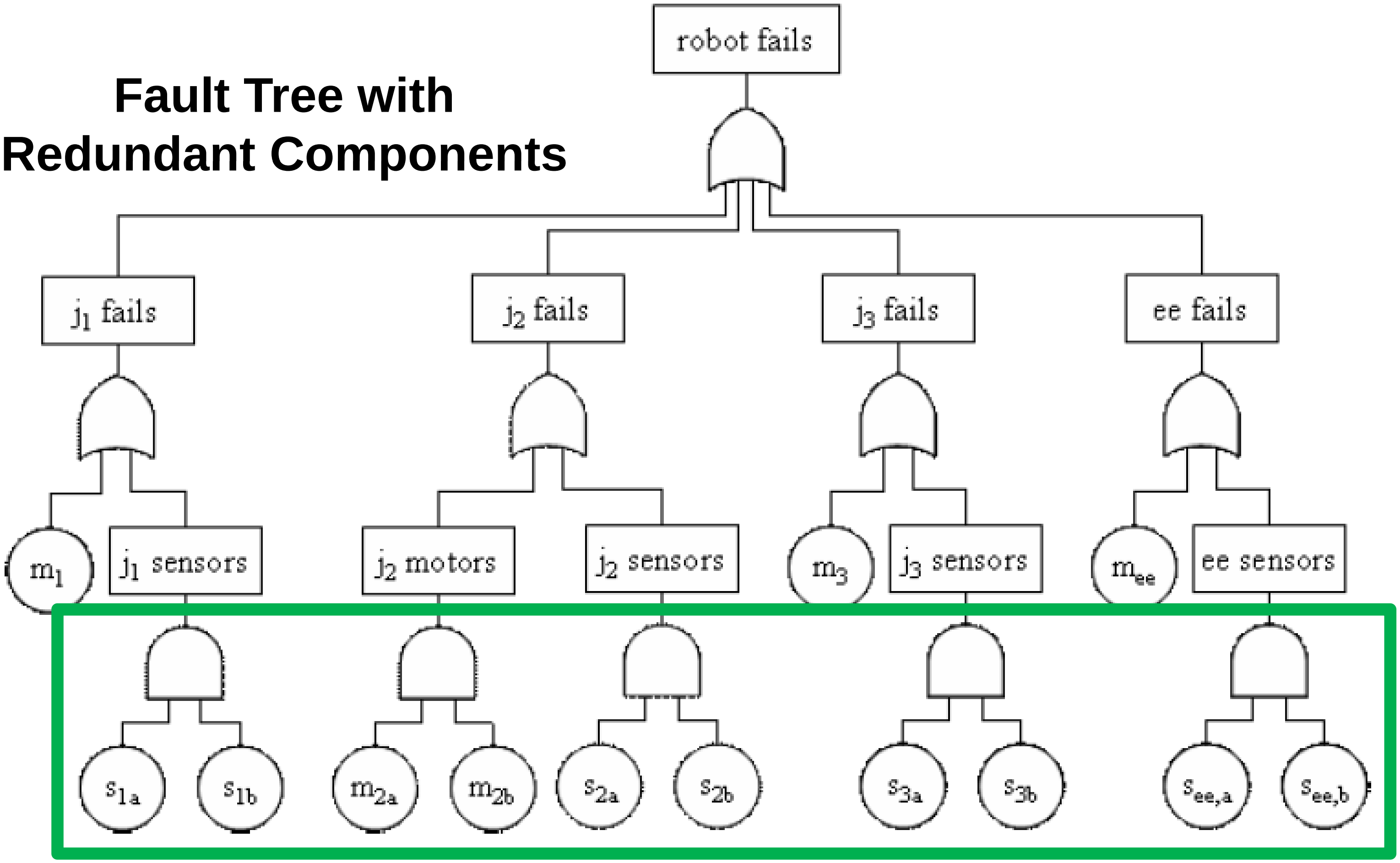
Figure 4. Fault tree for four-joint UGV manipulator with 3DOF and 1DOF servo gripper

j	joint
ee	end effector
m	motor
s	sensor

Reliability for One Design Configuration with Redundant Components

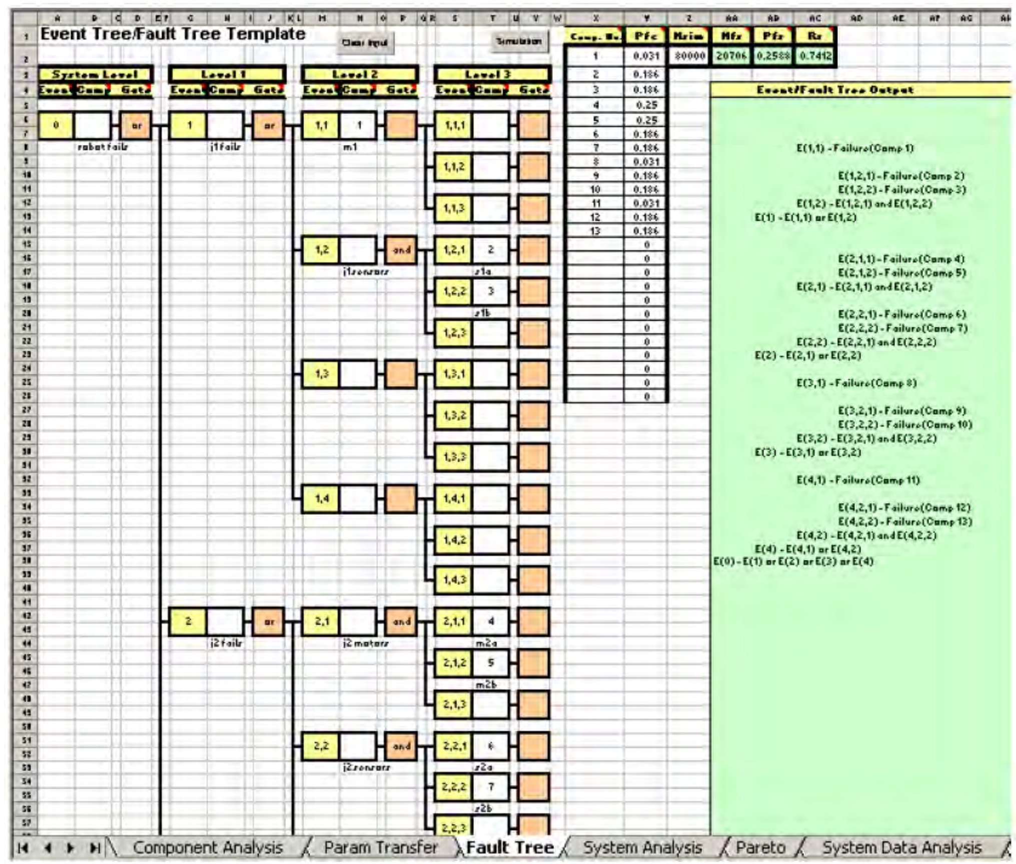
$$R_s = \underbrace{\left\{0.969 \times \left[1-(1-0.814)^2\right]\right\}^3}_{\text{for joints 1, 3, and 4}} \underbrace{\left\{\left[1-(1-0.75)^2\right] \times \left[1-(1-0.814)^2\right]\right\}}_{\text{for joint 2}} = 0.741$$

Fault Tree with Redundant Components



Reliability vs. Cost Trade Study

- Redundant components provide higher system reliability, but...
  - At what cost?
  - Is it worth it?
- Use FMS Tool to
  - Perform trade study
  - Find Pareto frontier



Fault Tree Model in FMS Tool

FMS Tool Results: Original Design

Simulation results yield system reliability R=0.75 @ t=1000 hours

Close to theoretical value of 0.741

Total failure Cnts	$R_{sys\ sim}$	Total Cost
0.262249998	0.75	$995.27
failure Cnts	Unit Cost	Sub Total Cost
0.0272500	$150.00	$154.09
0.0142500	$50.00	$50.71
0.0157500	$50.00	$50.79
0.0220000	$61.62	$62.98
0.0287500	$61.62	$63.39
0.0172500	$50.00	$50.86
0.0162500	$50.00	$50.81
0.0265000	$150.00	$153.98
0.0147500	$50.00	$50.74
0.0180000	$50.00	$50.90
0.0295000	$150.00	$154.43
0.0165000	$50.00	$50.83
0.0155000	$50.00	$50.78

$995

System reliability and cost @ 1000 hours of operation

Component Alternatives

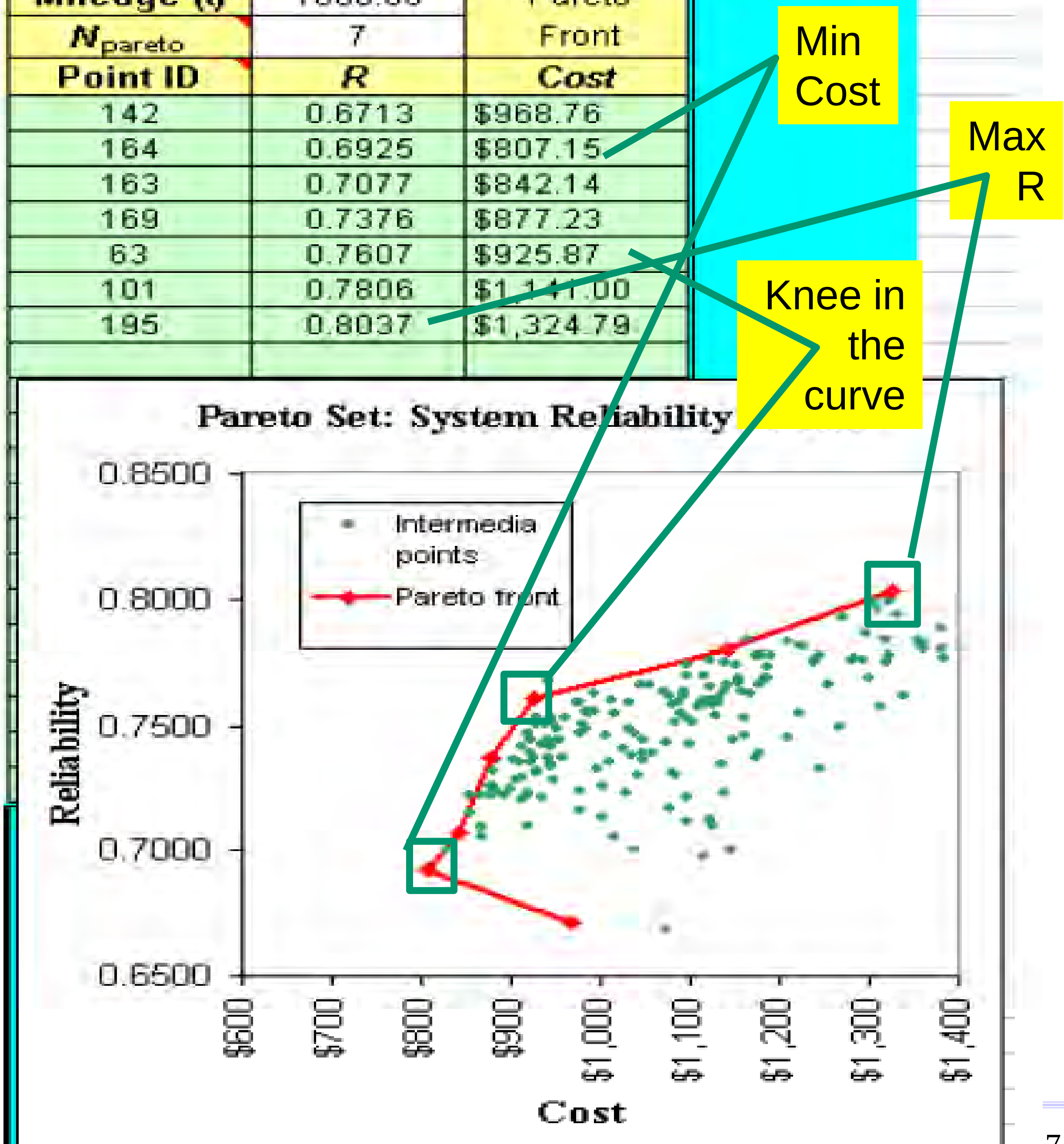
Component Input Data					
Comp. No	$MTBF_0$	Cov	B_{factor}	Unit $Cost_0$	*k*
1	31519	0.98	26.09	$150.00	1
-2	4845	0.77	2.8228	$50.00	1
-3	4845	0.77	2.8228	$50.00	1
4	3476.616	0.98	26.09	$61.62	1
5	3476.616	0.98	26.09	$61.62	1
-6	4845	0.77	2.8228	$50.00	1
-7	4845	0.77	2.8228	$50.00	1
8	31519	0.98	26.09	$150.00	1
-9	4845	0.77	2.8228	$50.00	1
-10	4845	0.77	2.8228	$50.00	1
11	31519	0.98	26.09	$150.00	1
-12	4845	0.77	2.8228	$50.00	1
-13	4845	0.77	2.8228	$50.00	1

Component Input Data

Negative numbers: components that do not have alternatives

FMS Tool Results: Trade Study

Mileage (t)	1000.00	Pareto
N_{pareto}	7	Front
Point ID	*R*	*Cost*
142	0.6713	$968.76
164	0.6925	$807.15
163	0.7077	$842.14
169	0.7376	$877.23
63	0.7607	$925.87
101	0.7806	$1,141.00
195	0.8037	$1,324.79



Reliability-cost Pareto set @ 1000 hours of operation

Recent and Ongoing Work

- **Adding system and fleet attributes**
  - Weight, fuel efficiency/cost
  - Availability
- **Enhancing underlying models**
  - Different types of failure modes, more probability distributions
  - Scheduled maintenance, preventive maintenance
- **Implementing state-of-the-art multi-objective optimizer**
  - Non-dominated sorting genetic algorithm II (NGSA-II)
  - Multiple objectives beyond cost and reliability
- **Converting software framework from Excel to MATLAB**
  - Improve computational performance
  - Leverage MATLAB toolkits
  - Foster collaborative development (TARDEC, OU, SMART Students)

Summary: FMS Tool

- Fleet Maintenance Simulation (FMS) Tool has been developed to perform trade/sensitivity/optimization studies
- FMS Tool applied to example UGV trade study for validation and demonstration purposes
- Software is under active development by TARDEC and OU to enhance capabilities and improve efficiency

Q & A