Fleet Management Considering Inspection Schedule Optimization

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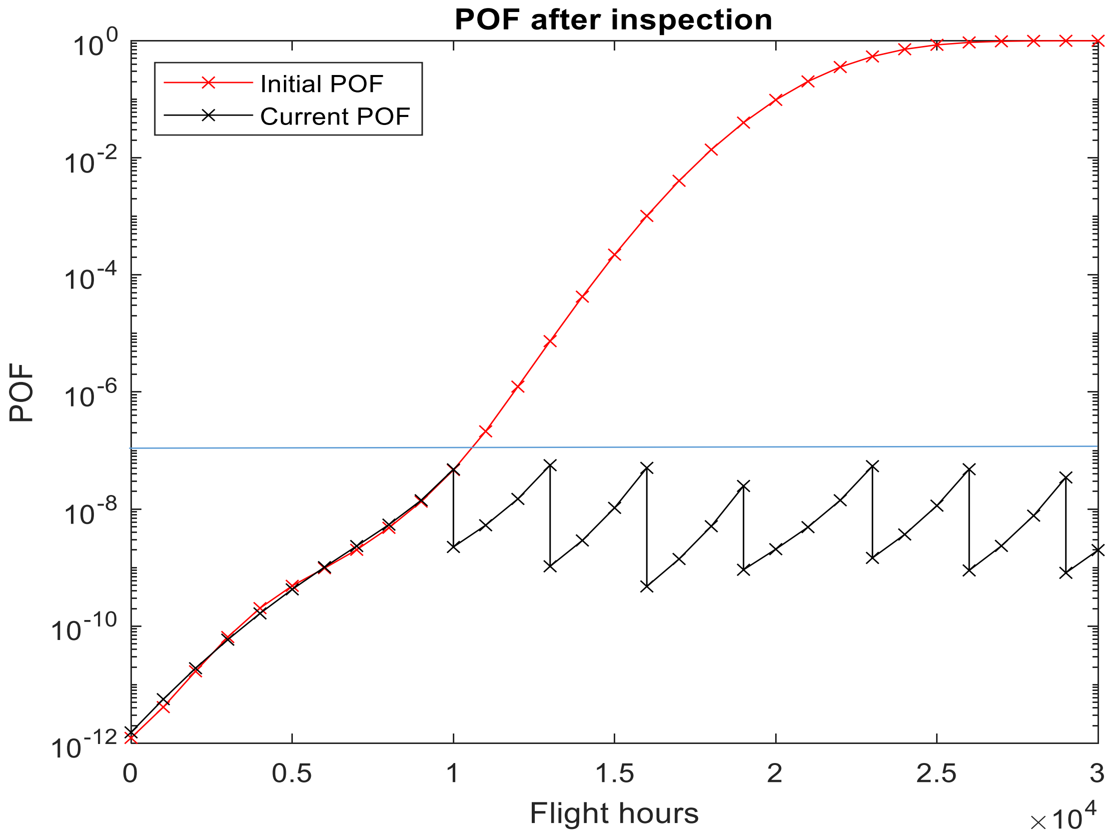
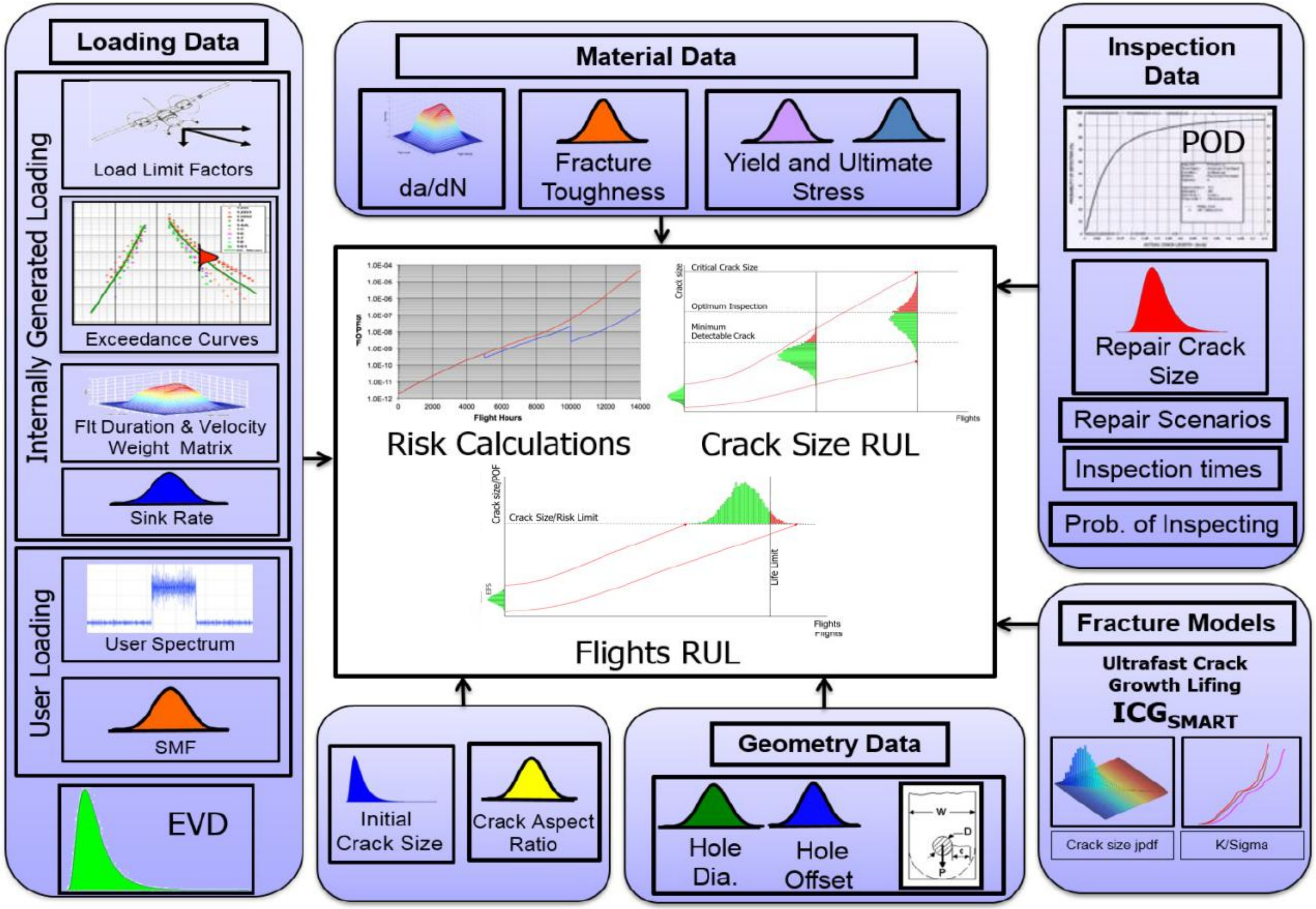
Outline

- ✓ Probabilistic Damage Tolerance Analysis Review
- ✓ Inspections Schedule Optimization
  - ✓ Shortest Path Algorithm
  - ✓ Path trimming
- ✓ Fleet Management
- ✓ Example Problem
  - ✓ Wing Spar
- ✓ Conclusions

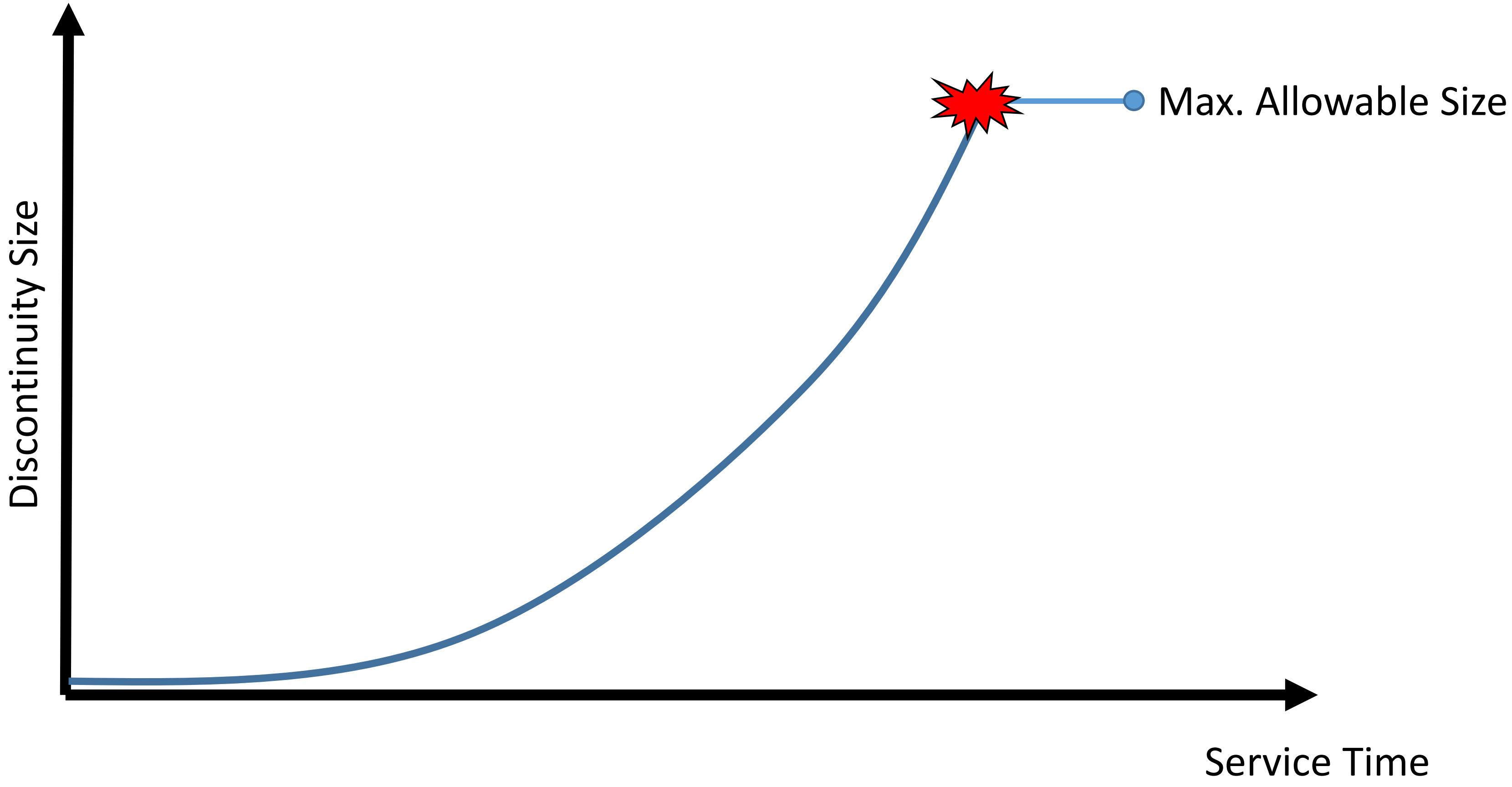


SMART|DT



Loading Data
Internally Generated Loading
Load Limit Factors
Exceedance Curves
Flt Duration & Velocity Weight Matrix
Sink Rate
User Loading
User Spectrum
SMF
EVD
Material Data
da/dN
Fracture Toughness
Yield and Ultimate Stress
Critical Crack Size
Optimum Inspection
Minimum Detectable Crack
Flight Hours
Flights
Risk Calculations
Crack Size RUL
Crack Size/Risk Limit
Life Limit
Flights RUL
Inspection Data
POD
Repair Crack Size
Repair Scenarios
Inspection times
Prob. of Inspecting
Fracture Models
Ultrafast Crack Growth Lifing
ICG SMART
Crack size jpdf
K/Sigma
Initial Crack Size
Crack Aspect Ratio
Geometry Data
Hole Dia.
Hole Offset

Motivation

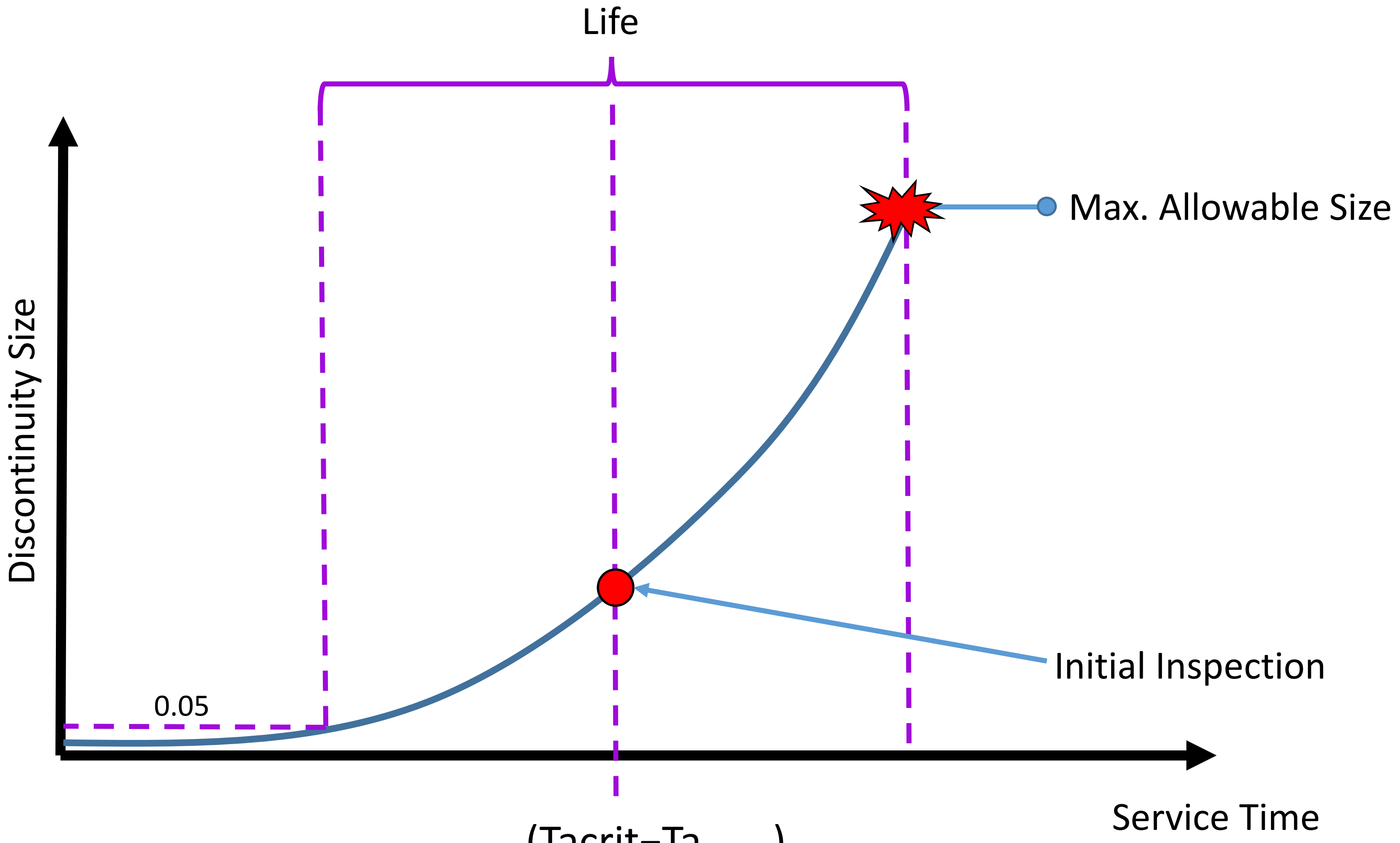


Ref: USAF AFRL-RX-WP-TR-2008-4373, Recommended Processes and Best Practices for NDI of Safety-of-Flight Structures

Motivation

Traditional methods do not:

- account for variation in usage, material, and geometry.
- Have into account past and future usage
- include cost of inspection and repair.



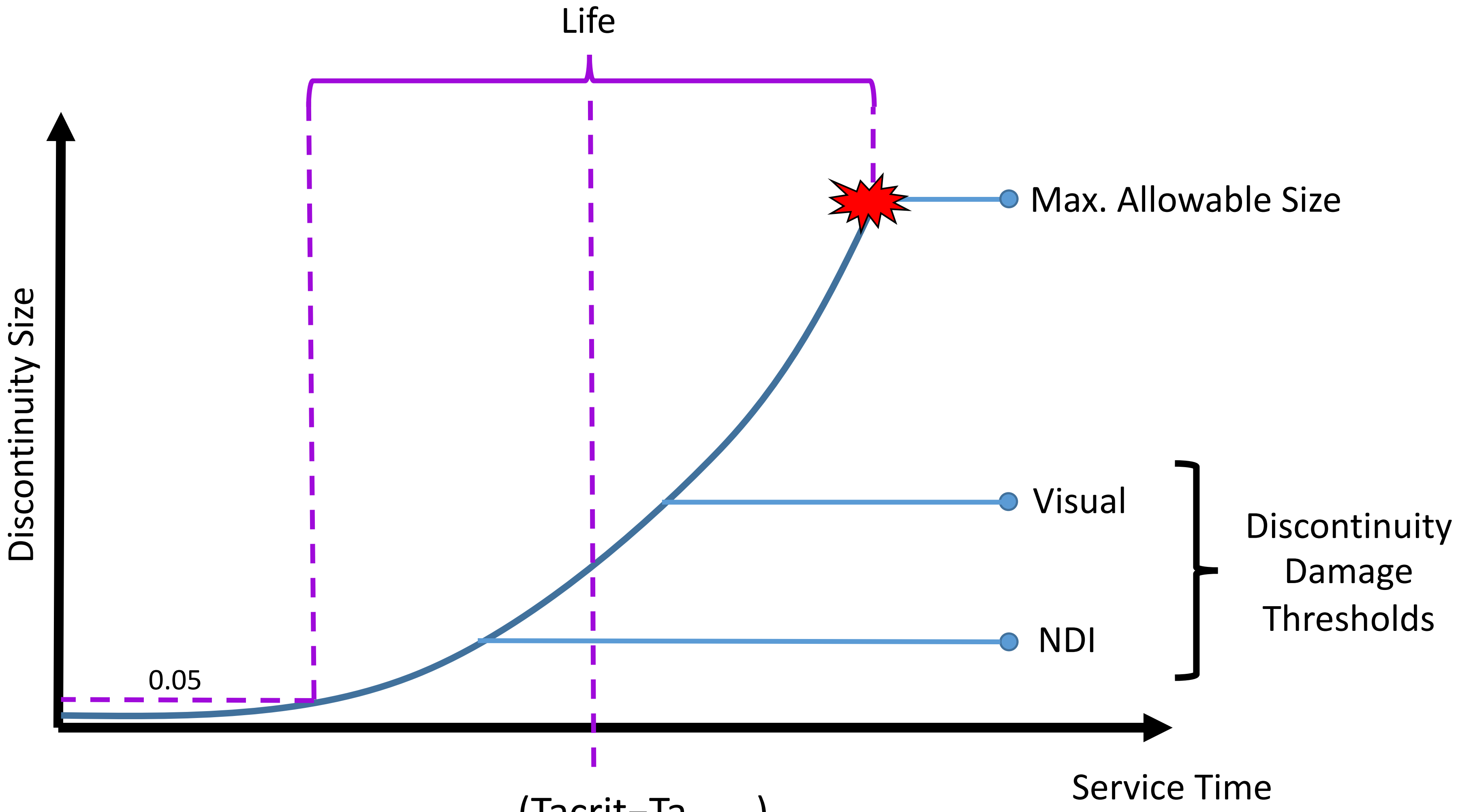
$$T_{insp} = \frac{(Tacrit - Ta_{(0.05)})}{2}$$

Ref: USAF AFRL-RX-WP-TR-2008-4373, Recommended Processes and Best Practices for NDI of Safety-of-Flight Structures

Motivation

Traditional methods:

- Typically set Repeat intervals from detectable to critical divided by 2 or 3
- Assumes 90% POD for a detectable crack size
- Provides two chances to find a crack of detectable size



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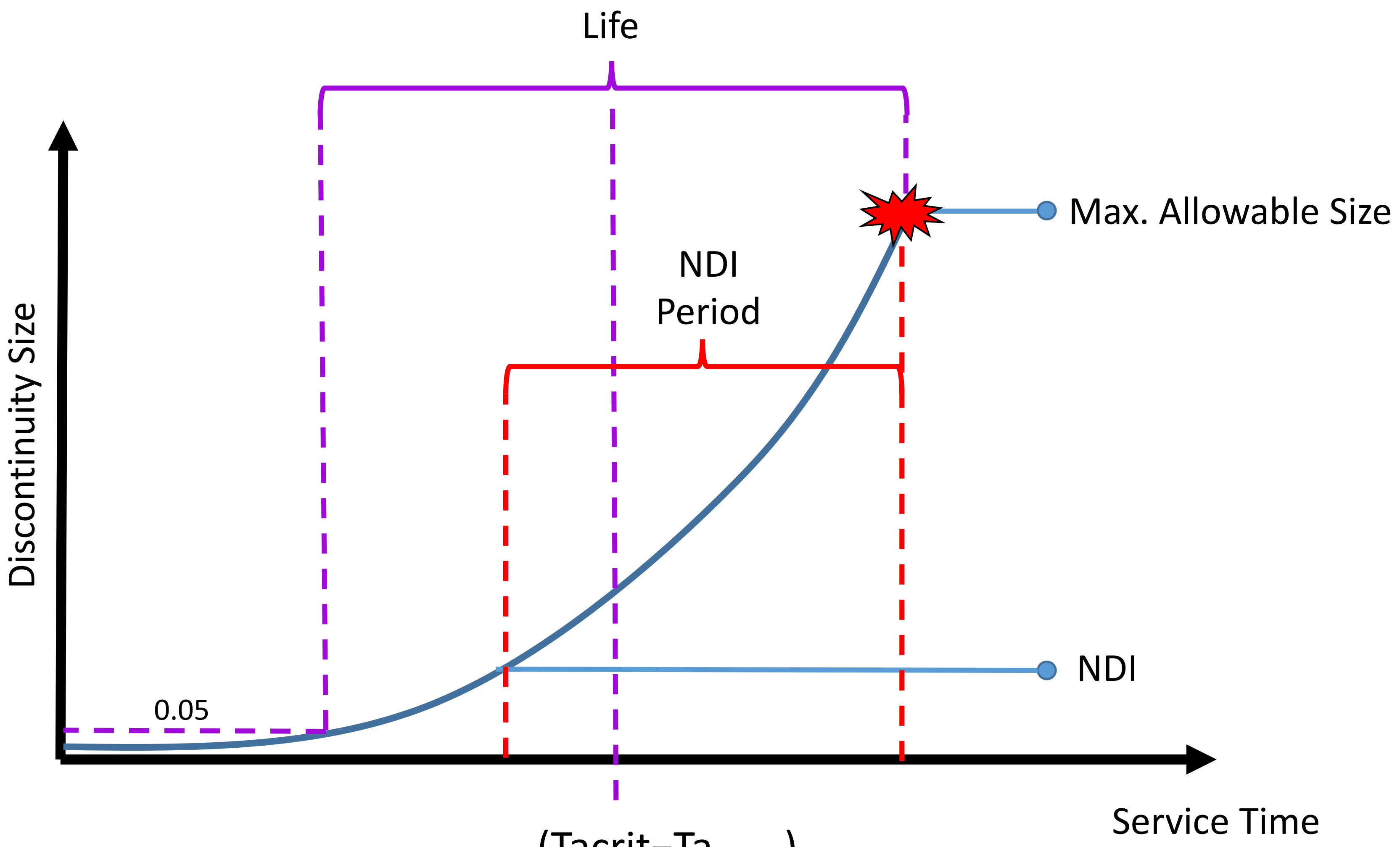

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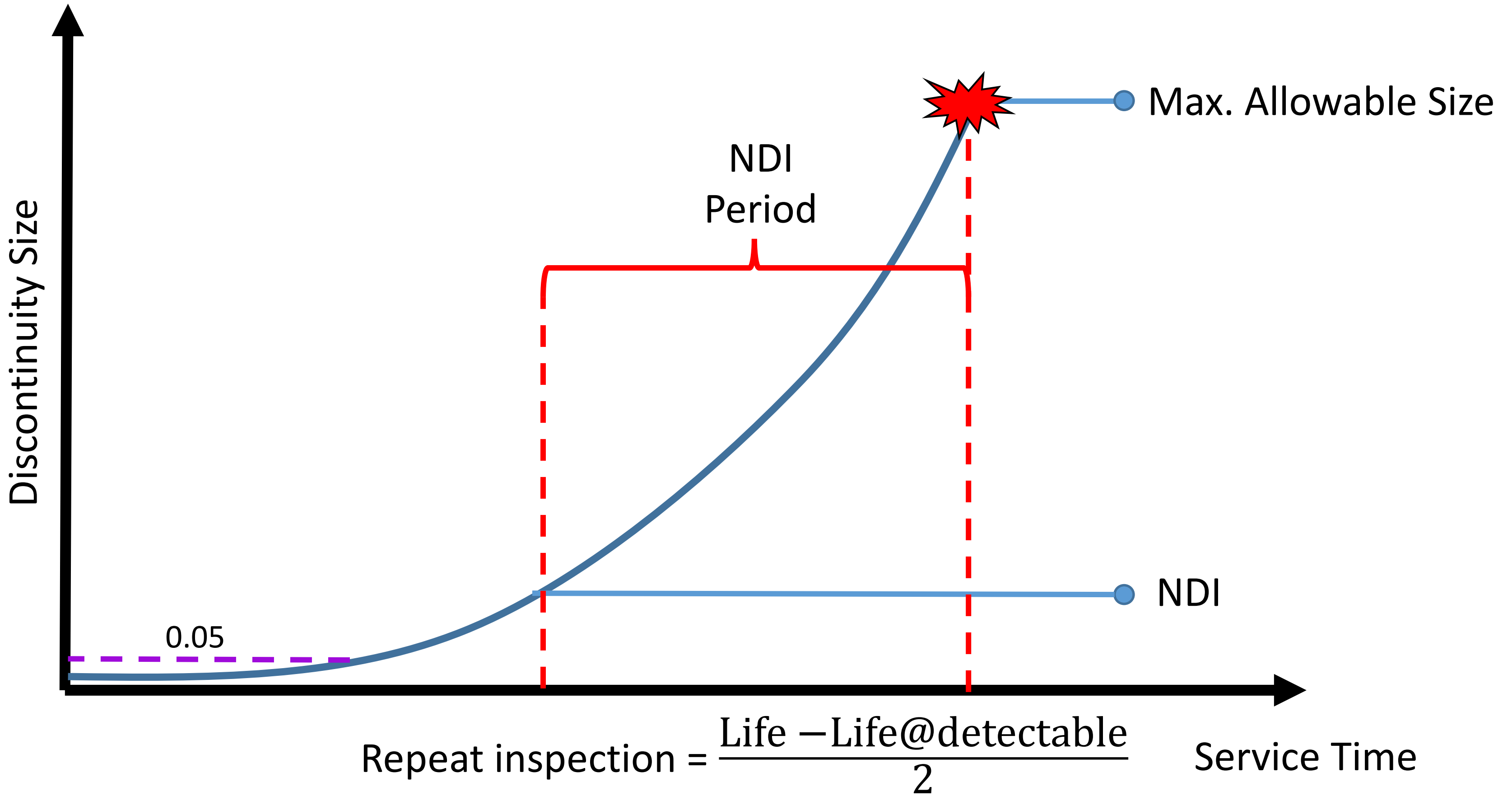

$$\text{Repeat inspection} = \frac{\text{Life} - \text{Life@detectable}}{2}$$

Ref: USAF AFRL-RX-WP-TR-2008-4373, Recommended Processes and Best Practices for NDI of Safety-of-Flight Structures

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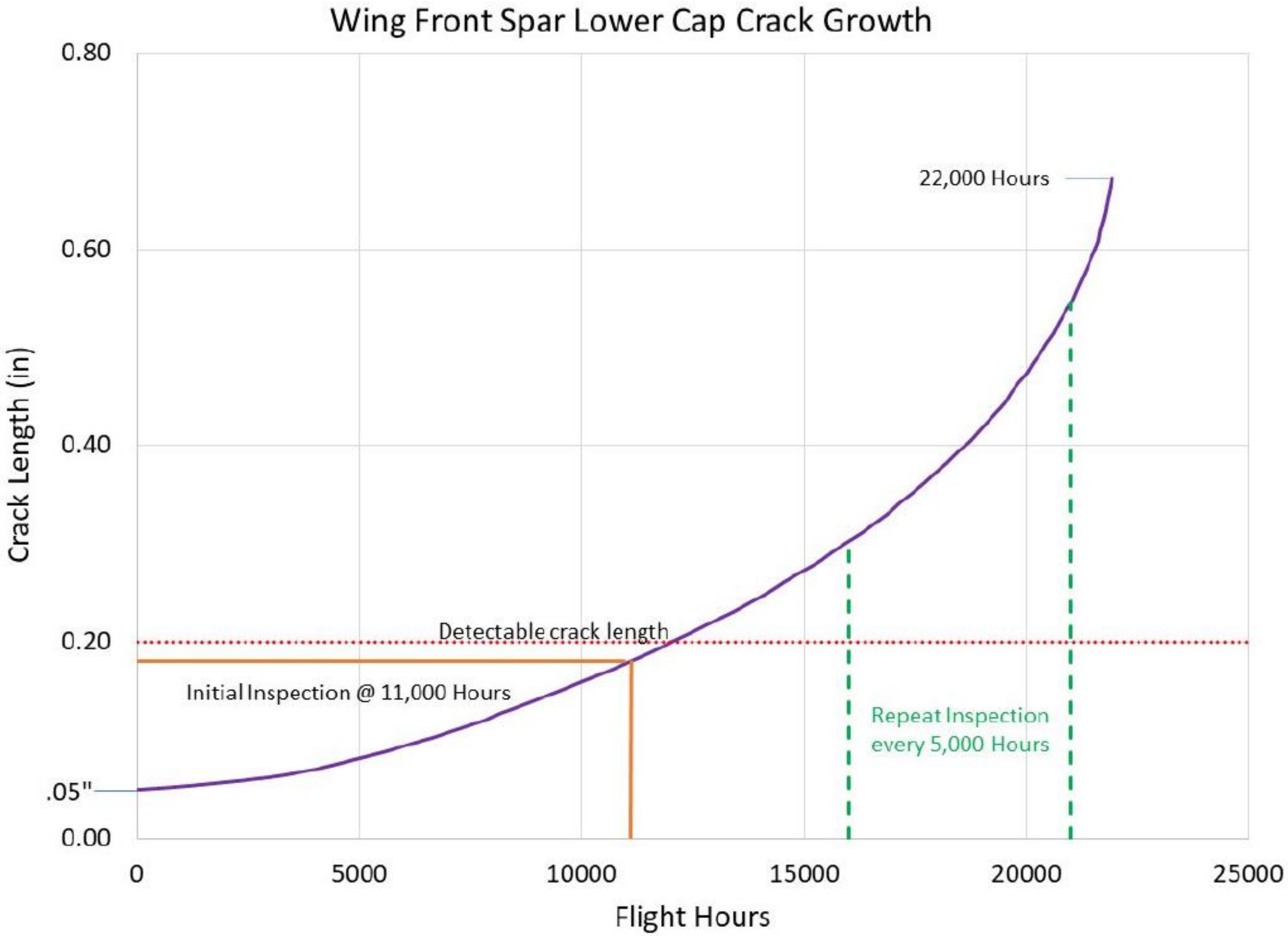

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Inspections Schedule Optimization

Shortest path formulation

The decision tree G(V,A) is described by the set of vertices V and its corresponding set of arcs A.

$$C = \{c_{ij} \ / \ c_{ij} \ is \ the \ cost \ of \ traversing \ the \ link \ between \ i \ and \ j\}$$

$$X = \{x_{ij} \ / \ x_{ij} \ \ is \ 1 \ for \ the \ decision \ of \ travel \ through \ the \ link \ (i,j) \ and \ 0 \ otherwise\}$$

$$V = \{Set \ of \ vertices \ of \ the \ graph\}$$

$$A = \{Set \ of \ arcs \ of \ the \ graph\}$$

Minimize

$$\sum_{(i,j)\in A} C_{ij}X_{ij}$$

subject to

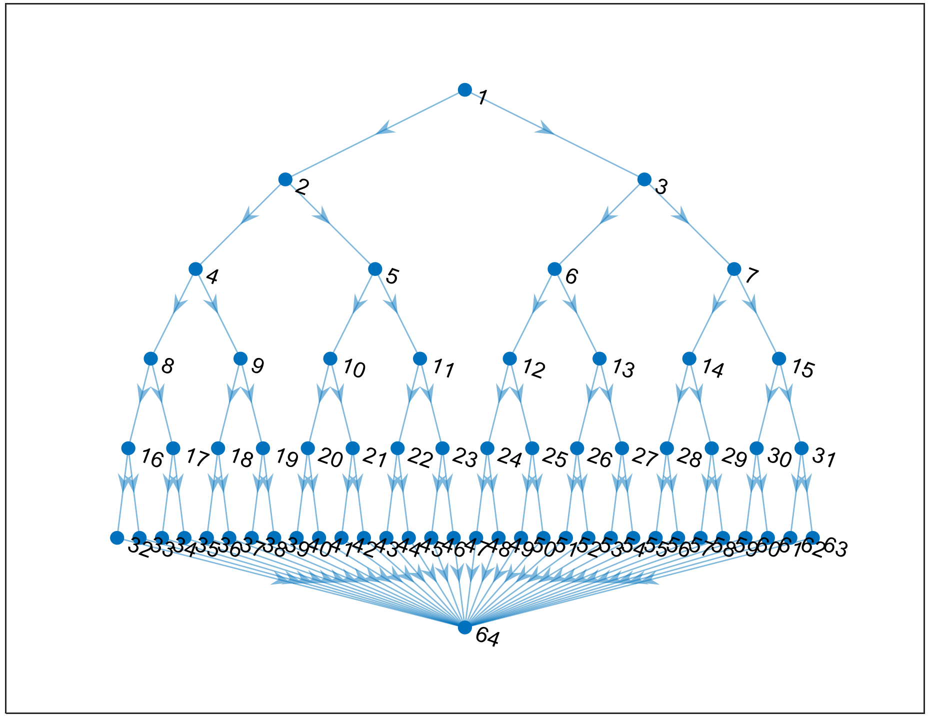
If $\quad F_k > \ threshold$

then $\quad X_{kj} = 0, \ \forall \ j$

$$C_{ij} = M$$

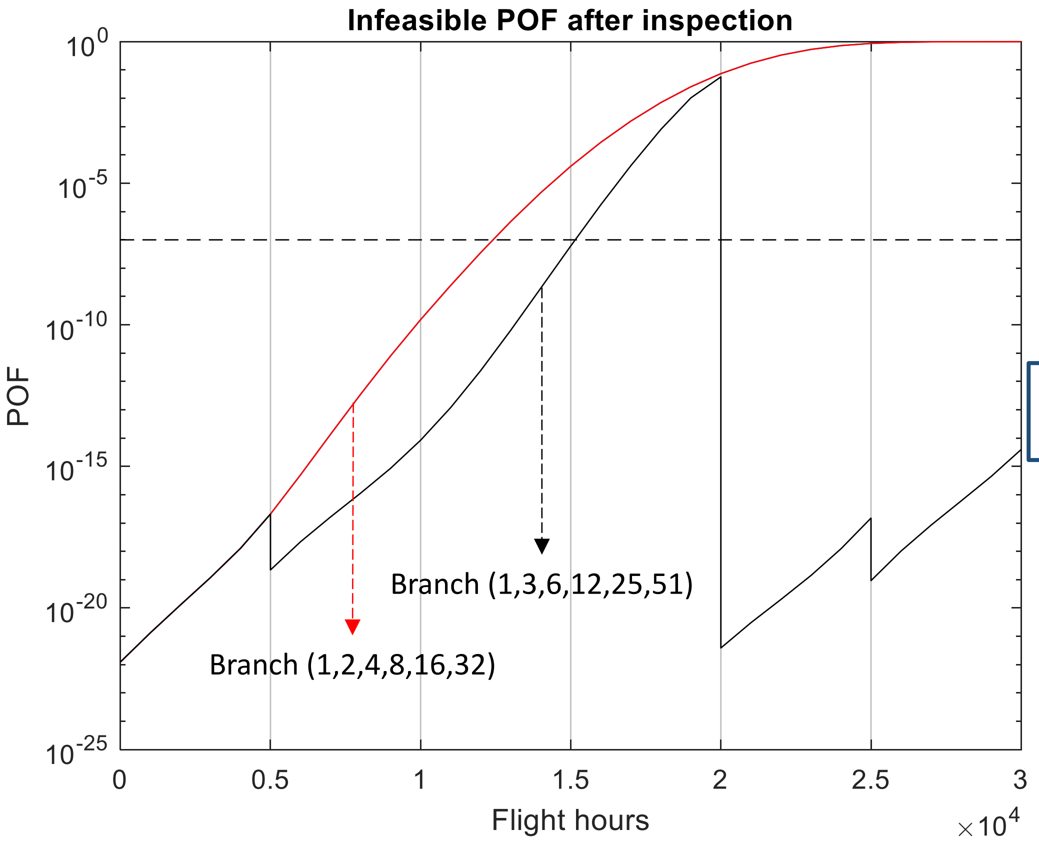
$$X_{ij} \leq F_i, \forall \ j$$

$$x_{ij} \ \in \ \{0,1\}$$

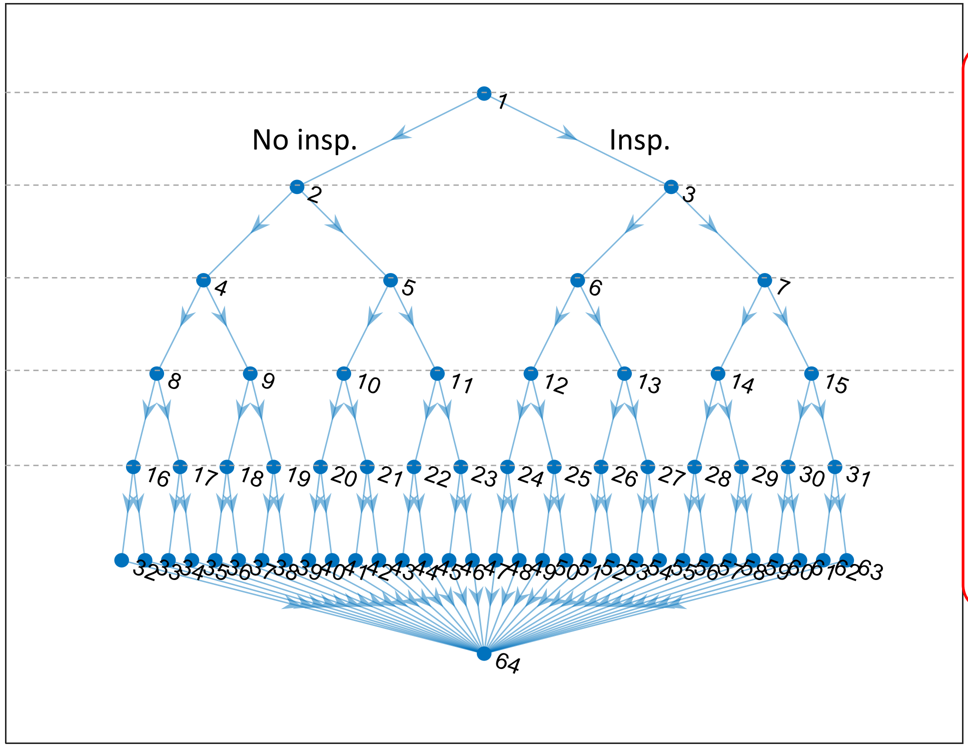


Shortest Path - Single Inspection

User defined inspections at: 5k, 10k, 15k, 20k, and 25k



Visualization example



Insp 1 (5k)
Insp 2 (10k)
Insp 3 (15k)
Insp 4 (20k)
Insp 5 (25k)

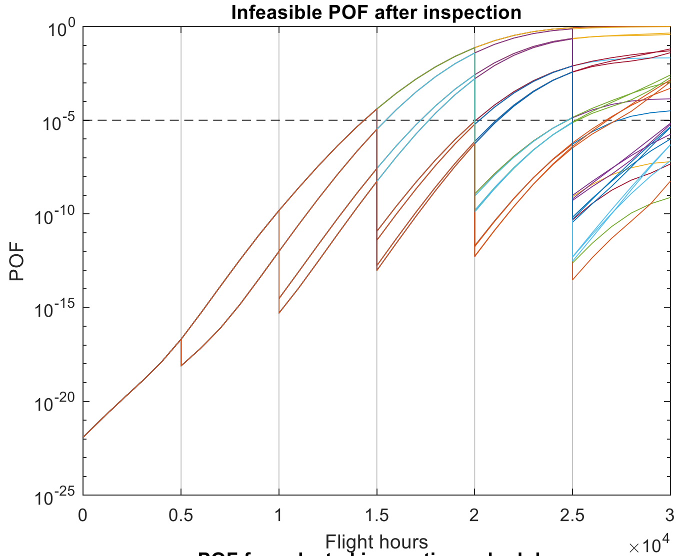
User defined candidate inspection times

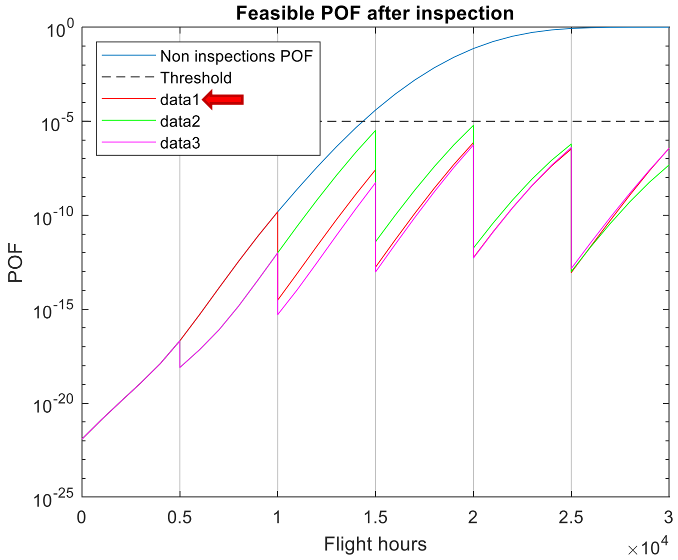
POFs for each branch / inspection schedule

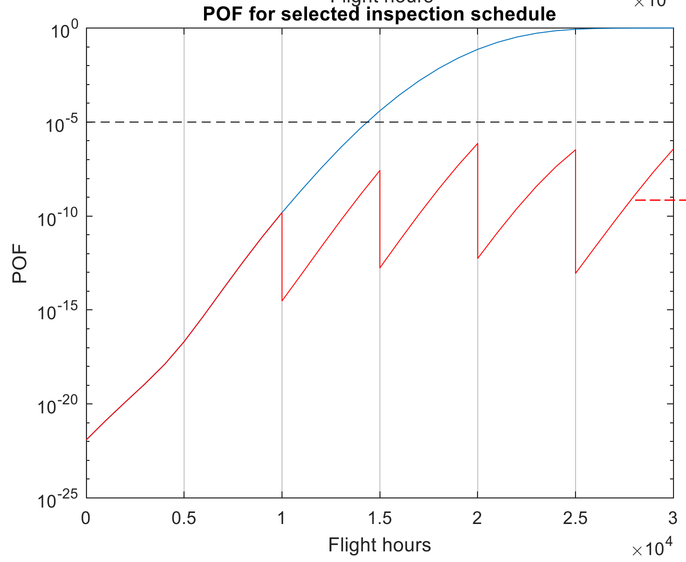
32 SMART Runs

Threshold: 10^{-7}

Shortest Path - Single Inspection



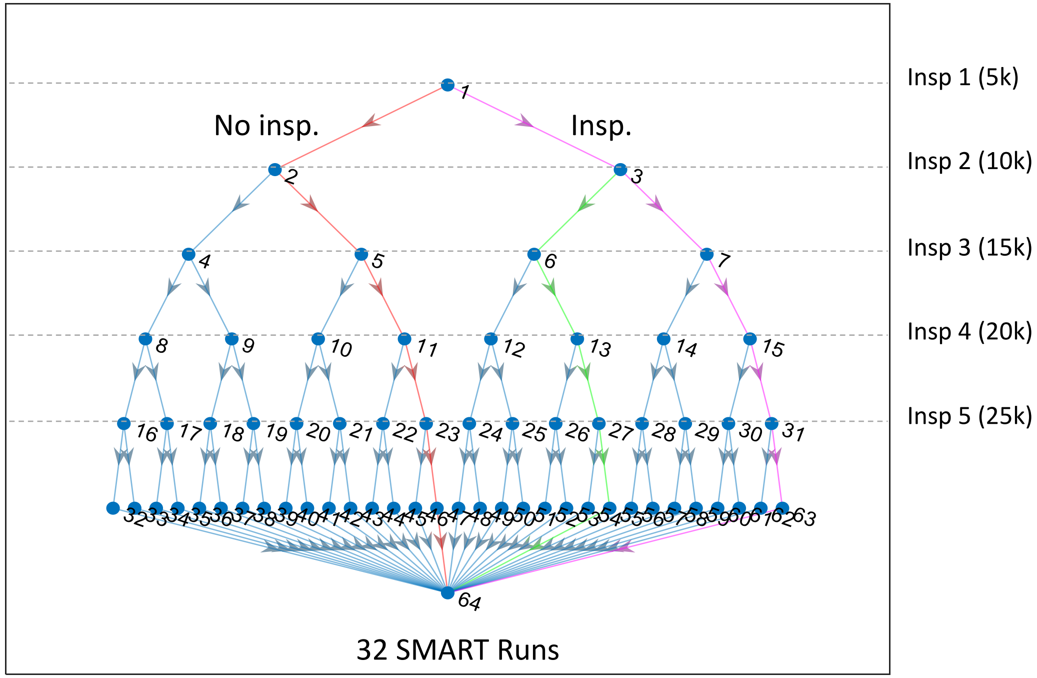




Selected branch
(1,2,5,11,23,47)

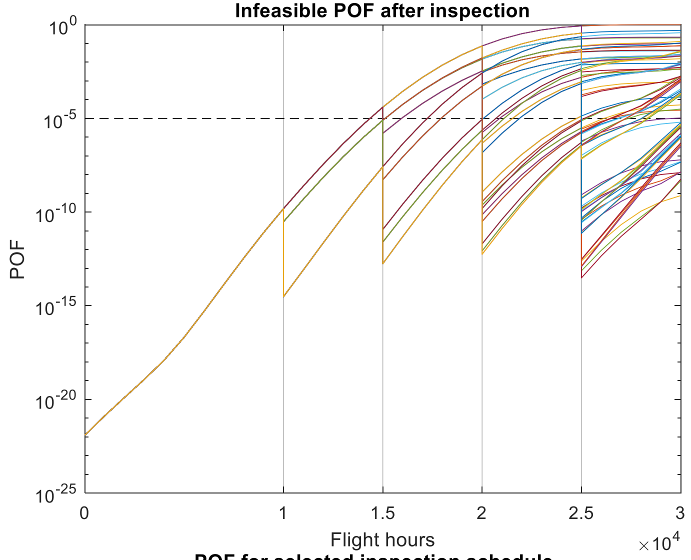
Selected schedule [10000,15000,20000,25000]

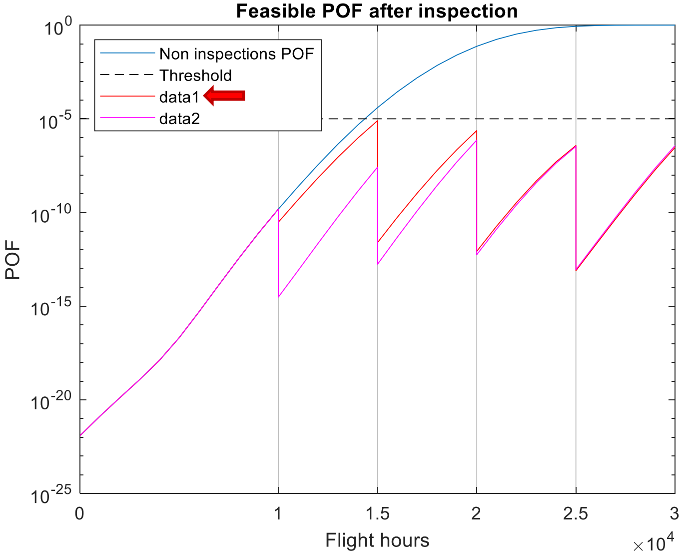
User defined inspections at: 5k, 10k, 15k, 20k, and 25k

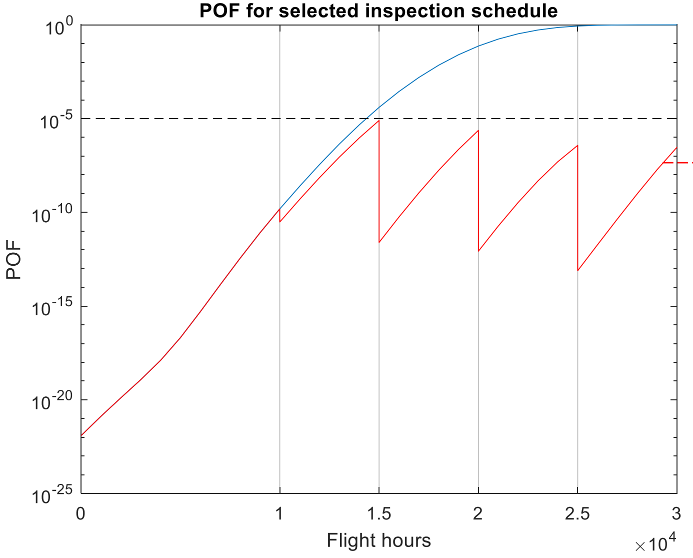


Possible inspection times [5000:5000:25000]

Shortest Path - Single Inspection



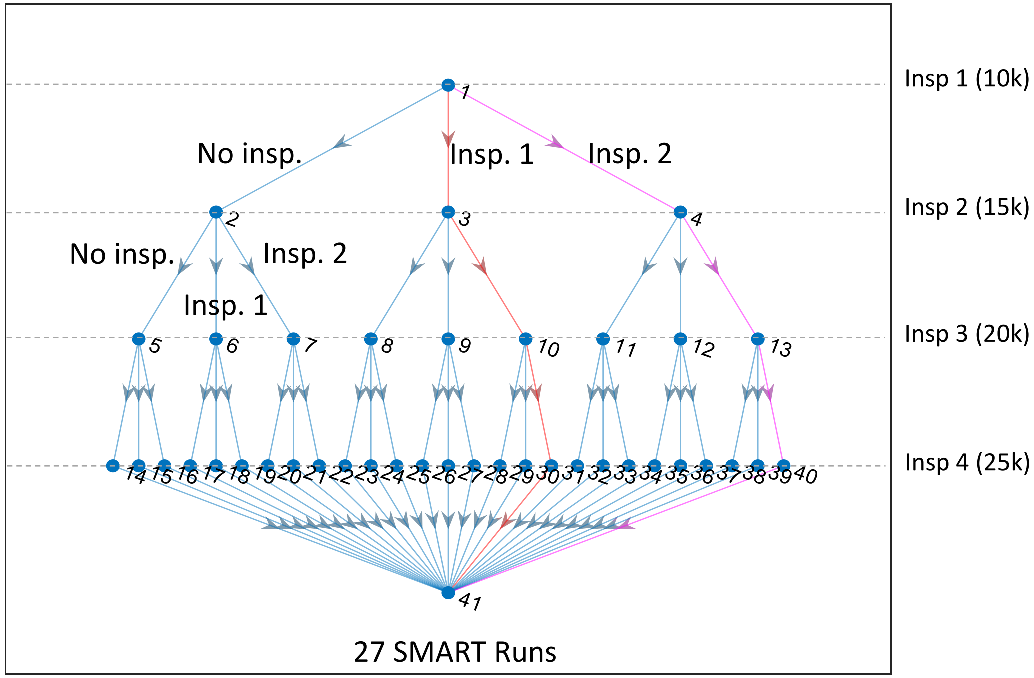




Selected branch (1,3,10,31)

Selected schedule [10000,15000,25000]
Selected inspection type [2,2,2]

User defined inspections at: 10k, 15k, 20k, and 25k



Possible inspection times [10000,15000,20000,25000]

Inspection and repair costs can be variable thru time

$$ Inspection 1 [$0.3 $0.3 $0.3 $0.3]
$$ Inspection 2 [$0.8 $0.8 $0.8 $0.8]

Shortest path with branch skipping algorithm

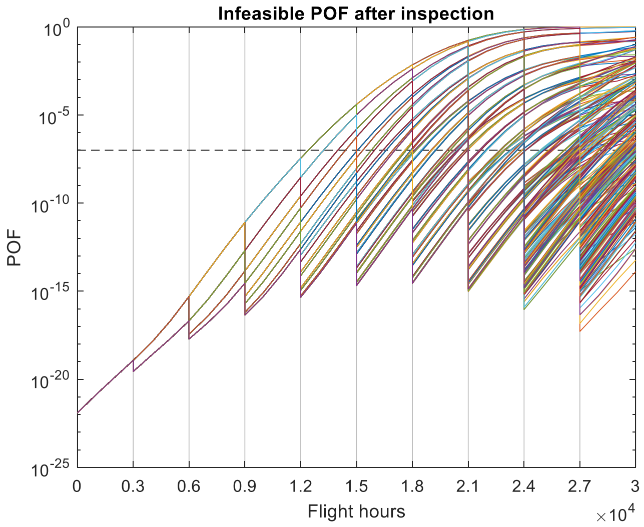
Branches skipping algorithm

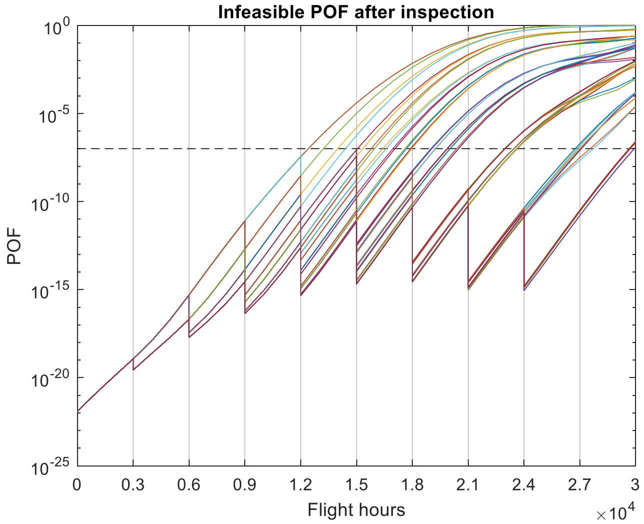
All branches evaluated
512
Without skipping algorithm

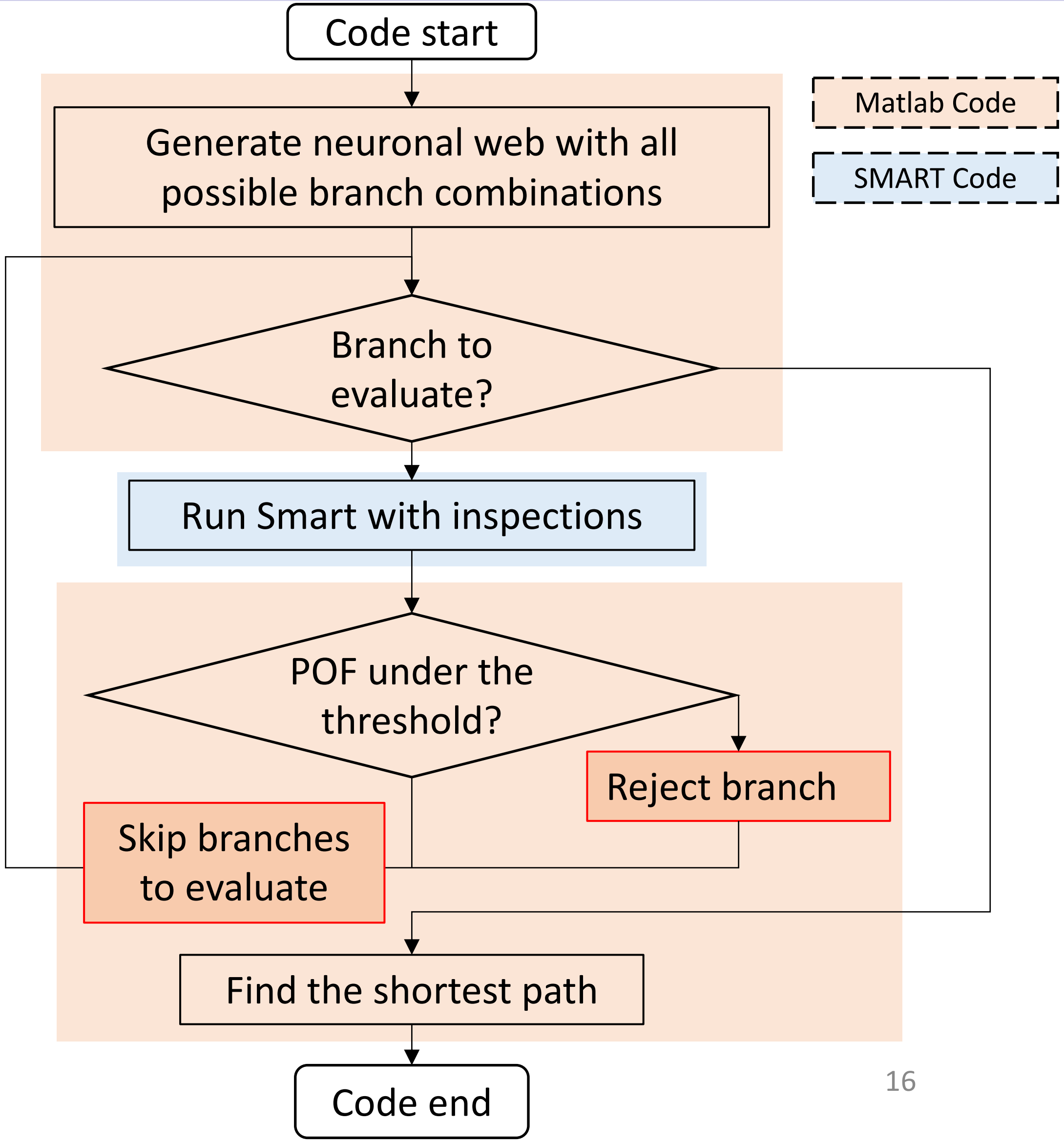
Skipping algorithm filters up all possible scenarios

Necessary branches to evaluate
76
With skipping algorithm

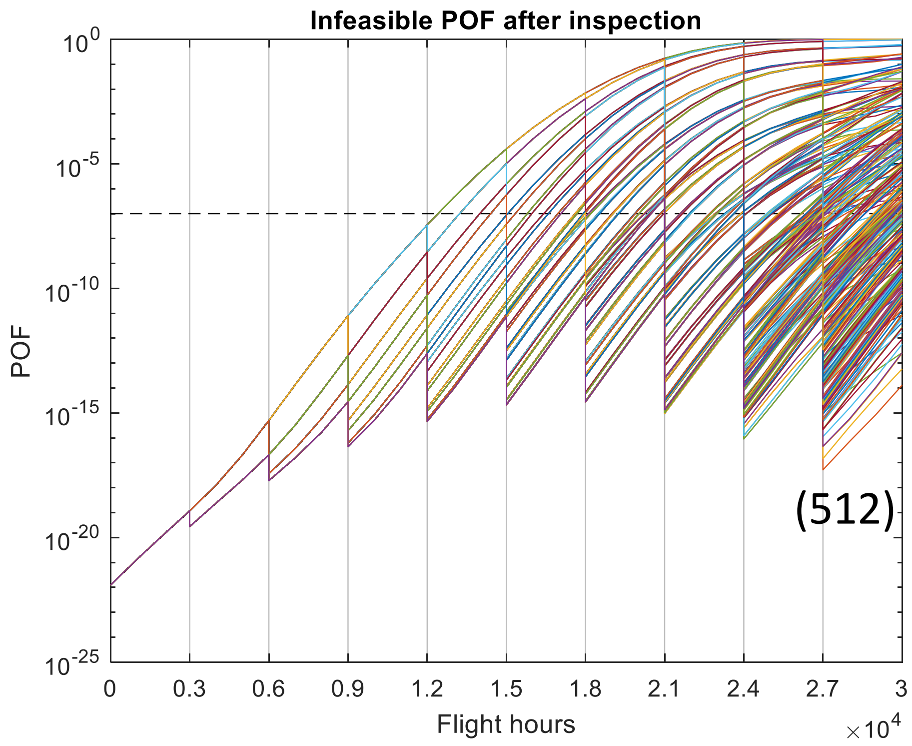
Threshold: 10^{-7}







Inspection Combination Matrix
One Inspection Type



Possible inspection times [3000:3000:27000]

Schedule times (10^3 flight hours)

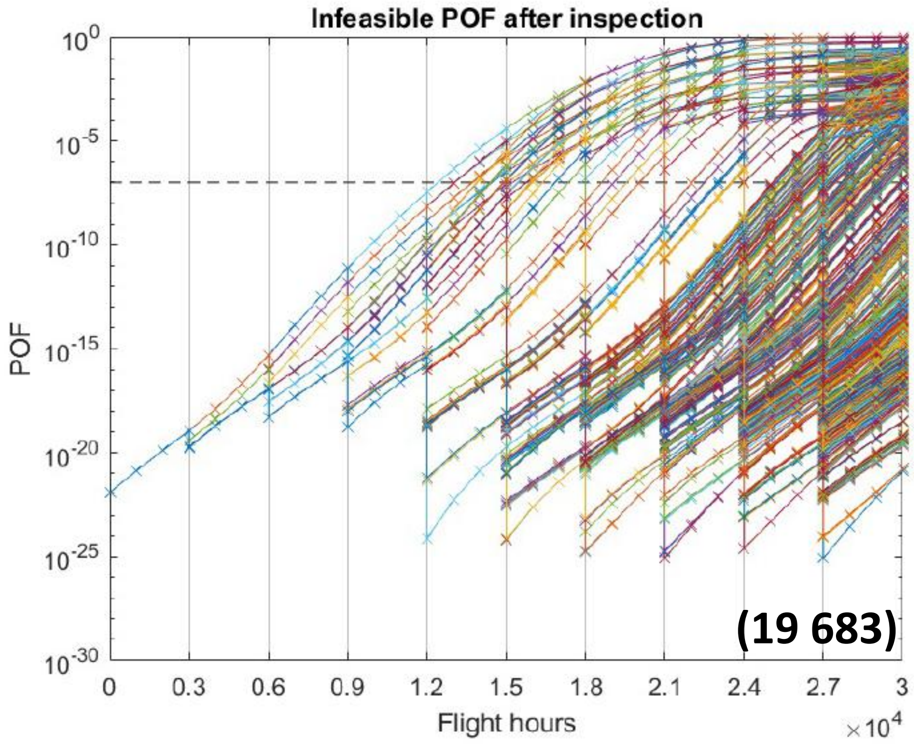
Schedule combinations

	3	6	9	12	15	18	21	24	27
	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
(1)	0	0	0	0	0	0	0	0	0
(2)	0	0	0	0	0	0	0	0	1
(3)	0	0	0	0	0	0	0	1	0
(4)	0	0	0	0	0	0	0	1	1
(5)	0	0	0	0	0	0	1	0	0
	:	:	:	:	:	:	:	:	:
(i)	**Binary(i - 1)**								
	:	:	:	:	:	:	:	:	:
(512)	1	1	1	1	1	1	1	1	1

Number of possible inspections times: number of positions that will be fill with all the numerical combinations in base 2

One inspection type → *"Inspection or no inspection"* → **Base 2** numbers

Inspection Combination matrix
Two Inspections Types



Possible inspection times [3000:3000:27000]

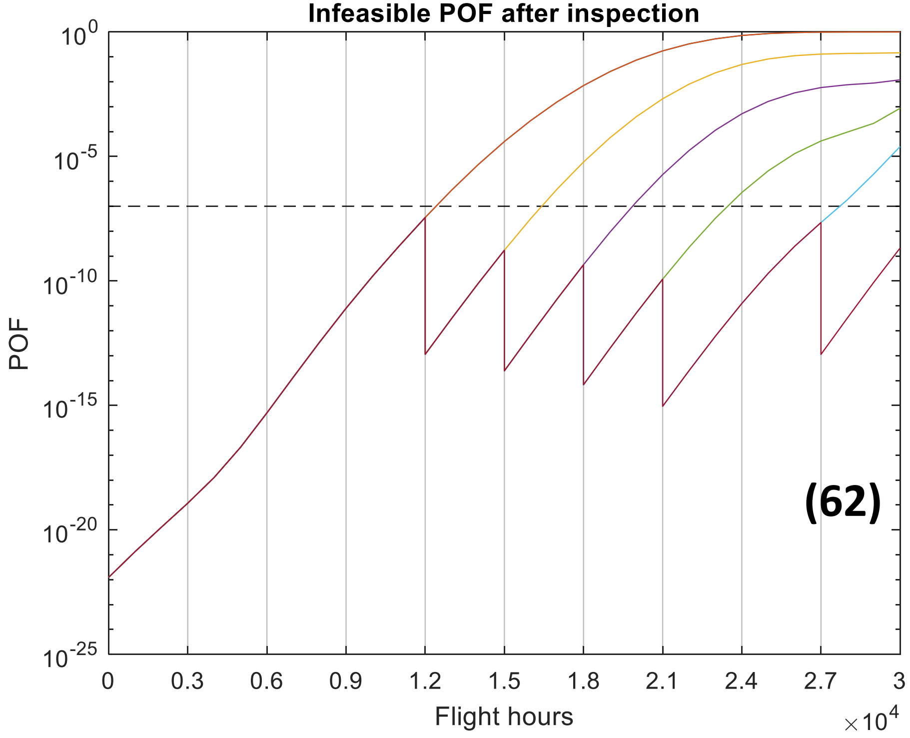
Schedule times (10^3 flight hours)

Schedule combinations	3	6	9	12	15	18	21	24	27
	3^8	3^7	3^6	3^5	3^4	3^3	3^2	3^1	3^0
(1)	0	0	0	0	0	0	0	0	0
(2)	0	0	0	0	0	0	0	0	1
(3)	0	0	0	0	0	0	0	0	2
(4)	0	0	0	0	0	0	0	1	0
(5)	0	0	0	0	0	0	0	1	1
(6)	0	0	0	0	0	0	0	1	2
(7)	0	0	0	0	0	0	0	2	0
	:	:	:	:	:	:	:	:	:
(143)	0	0	0	0	1	2	0	2	1
(i)	**Base3(i - 1)**								
(19 683)	2	2	2	2	2	2	2	2	2

Number of possible inspections times: number of positions that will be fill with all the numerical combinations in base 3

Two inspection types → *"Insp. type 1, insp. type 2 or no insp."* → **Base 3** numbers

Reject and Skip Branches Evaluation One Inspection Type



Possible inspection times [3000:3000:27000]

First, POF without inspections

Schedule times (10^3 flight hours)

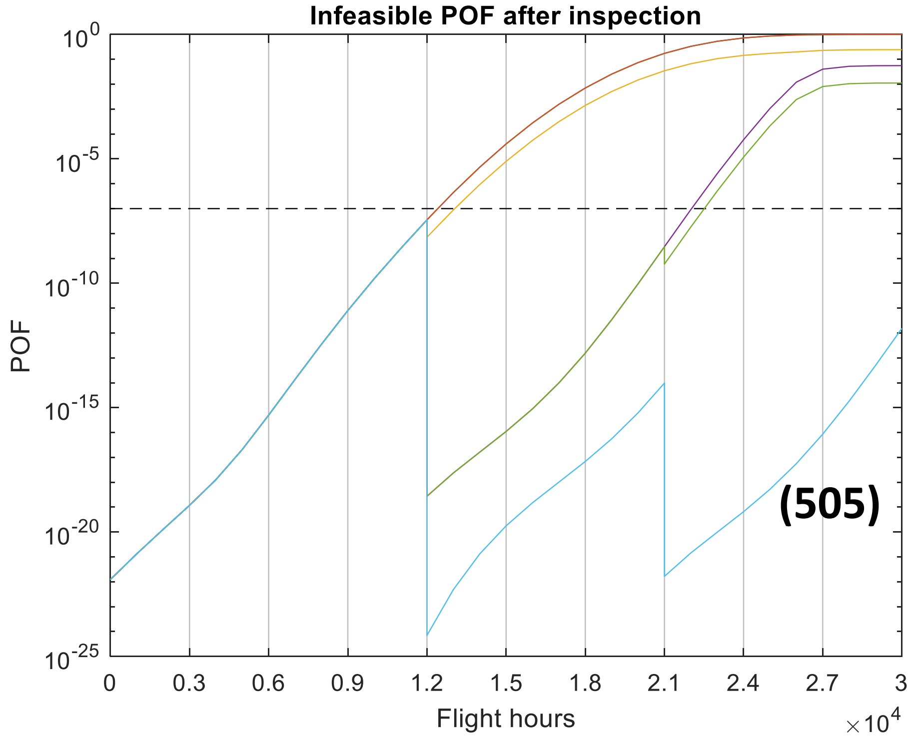
Schedule combinations	3	6	9	12	15	18	21	24	27
(1)	0	0	0	0	0	0	0	0	0
(33)	0	0	0	1	0	0	0	0	0
(49)	0	0	0	1	1	0	0	0	0
(57)	0	0	0	1	1	1	0	0	0
(61)	0	0	0	1	1	1	1	0	0
(62)	0	0	0	1	1	1	1	0	1

+1

Reject all the inspections above risk level on the main branch

The code evaluates each new combination until get a **feasible solution**, which will be **saved**

Reject and Skip Branches Two Inspections Type



Possible inspection times [3000:3000:27000]

Schedule times (10^3 flight hours)

Schedule combinations	3	6	9	12	15	18	21	24	27
(1)	0	0	0	0	0	0	0	0	0
(244)	0	0	0	1	0	0	0	0	0
(487)	0	0	0	2	0	0	0	0	0
(496)	0	0	0	2	0	0	1	0	0
(505)	0	0	0	2	0	0	2	0	0

+1

+1

+1

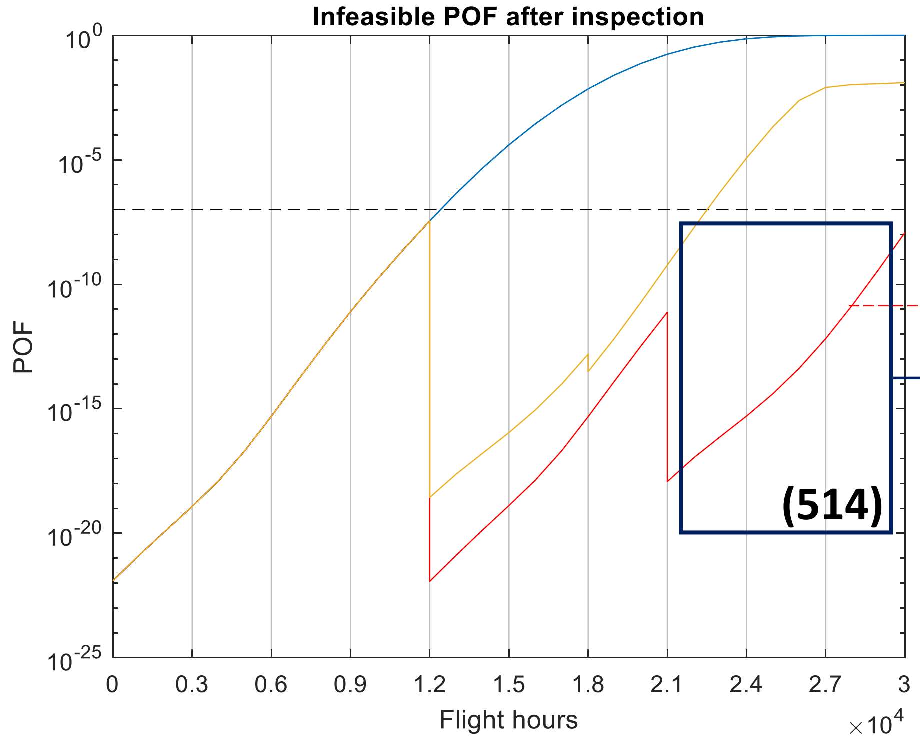
+1

POF without inspections

Reject all the inspections above risk level on the main branch

Feasible solution to be saved

Feasible Branches Evaluation Two Inspection Type



POF curve for a feasible solution

Any inspection added after 21k flight hours will make the branch feasible but more expensive

Schedule times (10^3 flight hours)

Schedule combinations

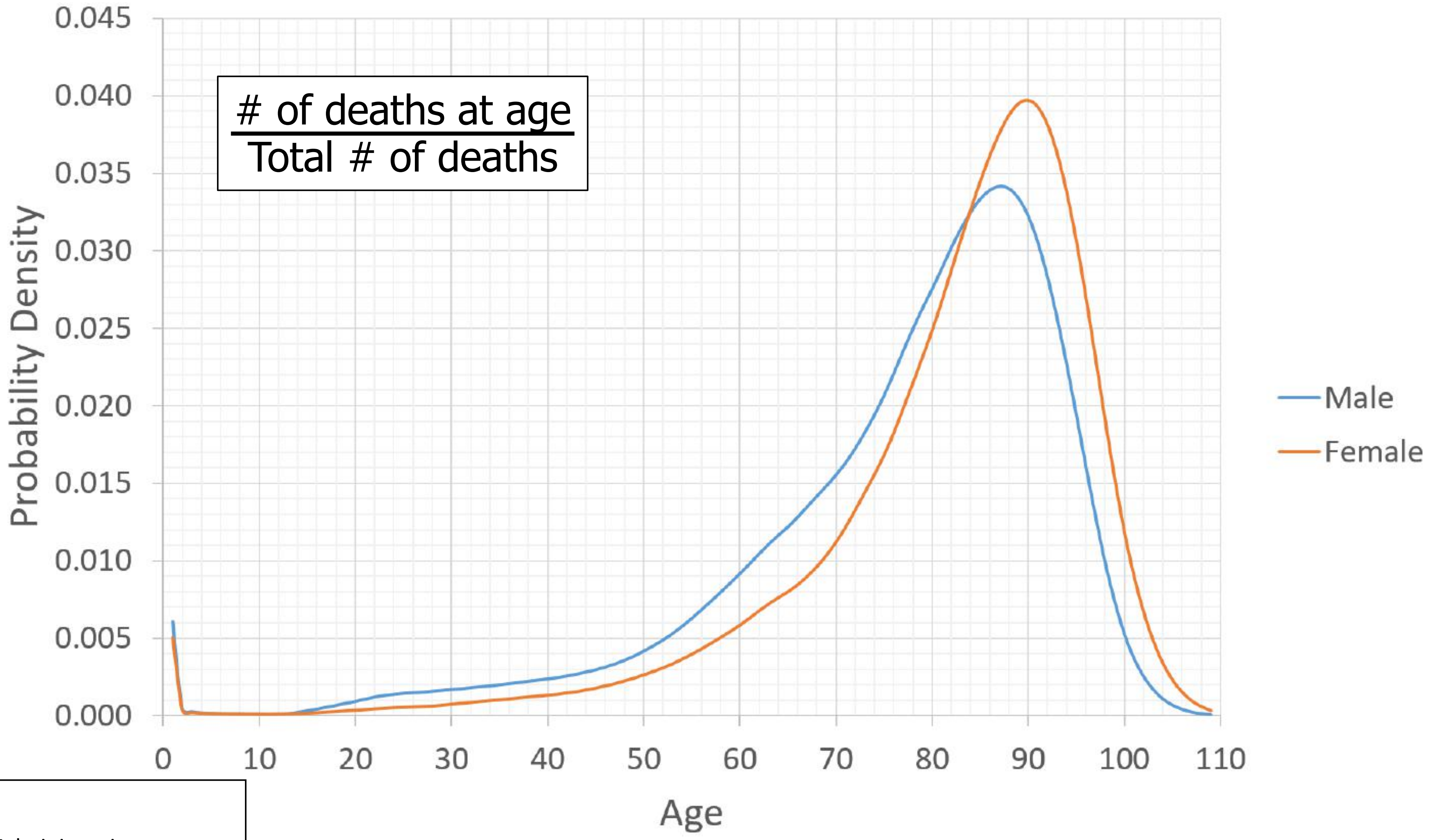
	3	6	9	12	15	18	21	24	27
(1)	0	0	0	0	0	0	0	0	0
(505)	0	0	0	2	0	0	2	0	0
(506)	0	0	0	2	0	0	2	0	1
(507)	0	0	0	2	0	0	2	0	2
(508)	0	0	0	2	0	0	2	1	0
(509)	0	0	0	2	0	0	2	1	1
(510)	0	0	0	2	0	0	2	1	2
(511)	0	0	0	2	0	0	2	2	0
(512)	0	0	0	2	0	0	2	2	1
(513)	0	0	0	2	0	0	2	2	2
(514)	0	0	0	2	0	1	0	0	0

Possible inspection times [3000:3000:27000]

Method will skip POF evaluations from 505 to 514

Risk Management

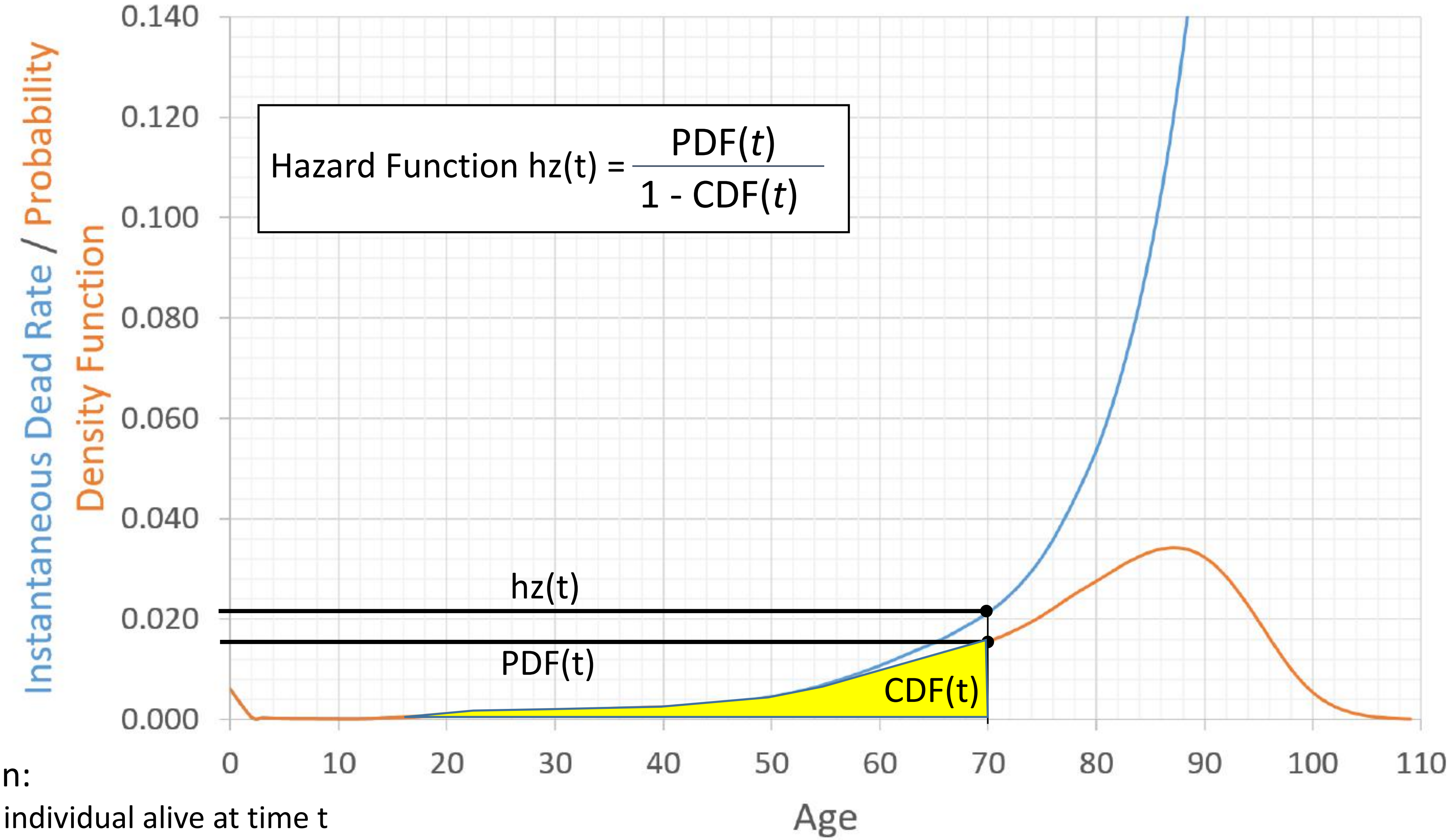
Analogy to Human Mortality



US Mortality, 2019

Source: Social Security Administration

Analogy to Human Mortality

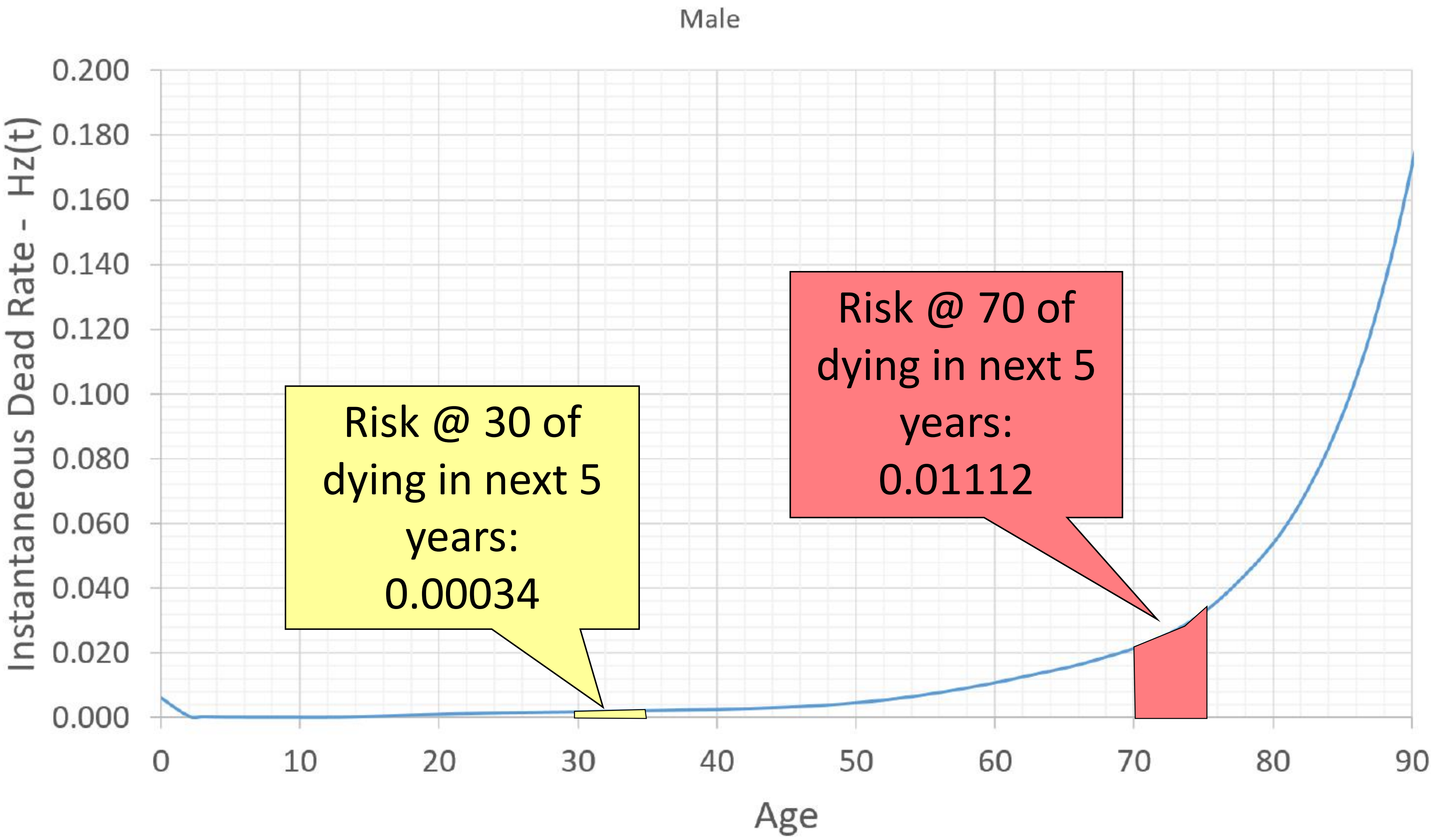


$$\text{Hazard Function } hz(t) = \frac{PDF(t)}{1 - CDF(t)}$$

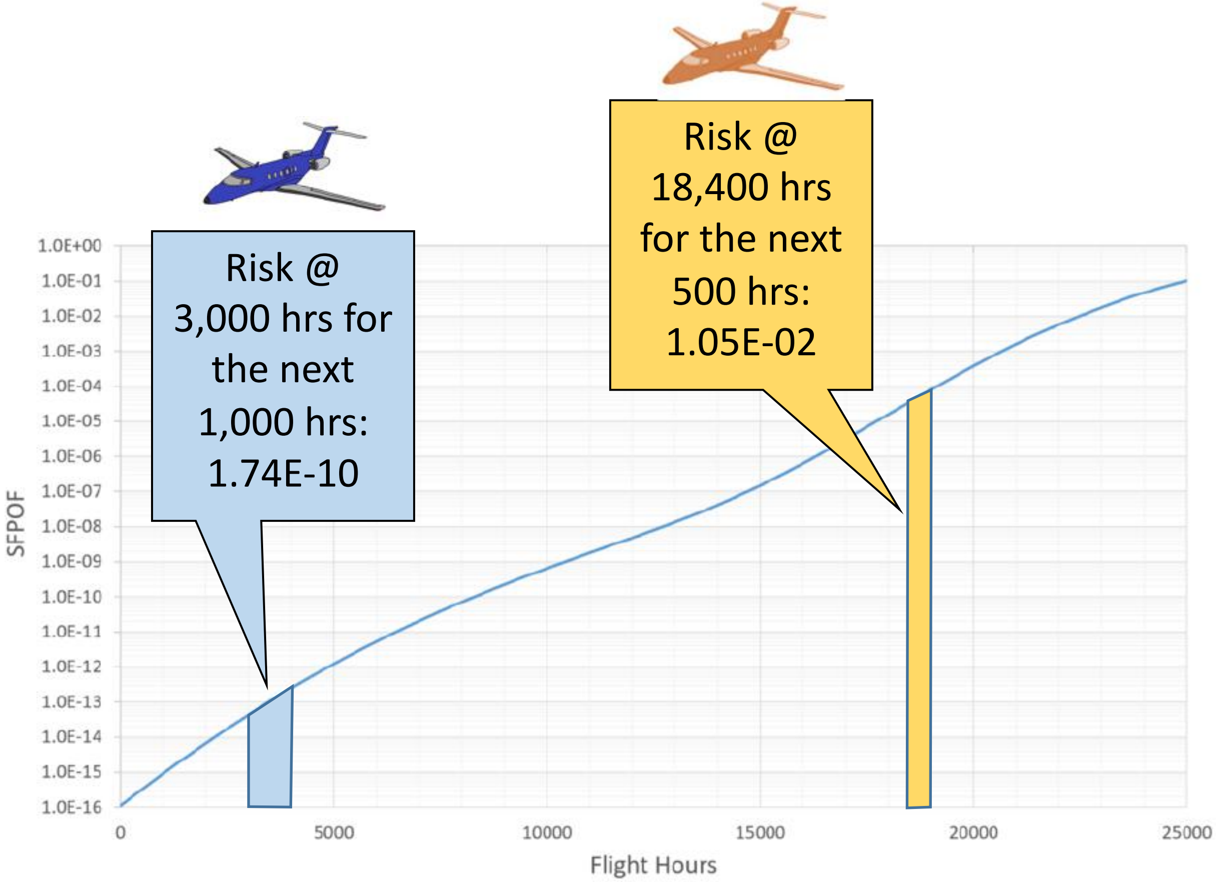
Interpretation:

- Consider an individual alive at time t
- The chances of dying in a small interval [t, t+dt] are then given by: HZ(t) ≅ hz(t)*dt

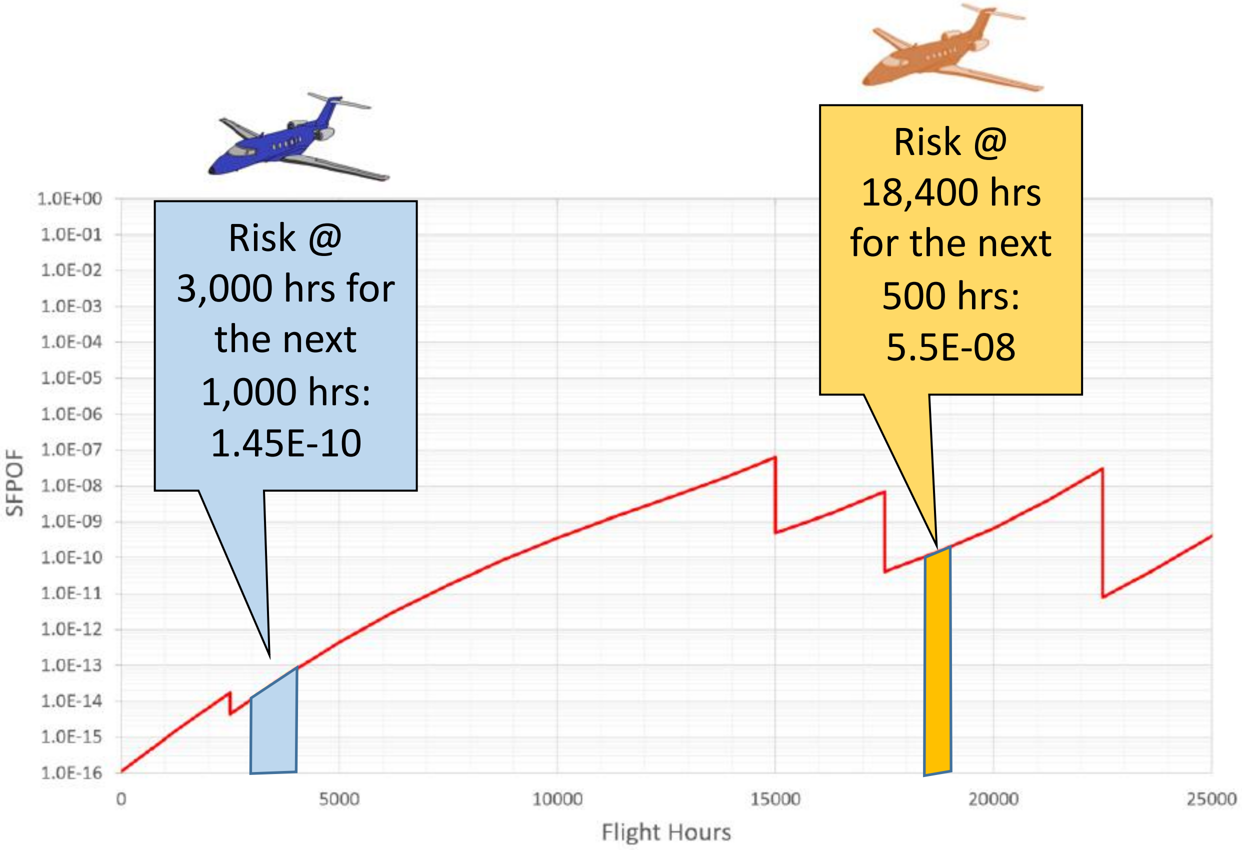
Analogy to Human Mortality



How to use in Fleet Management



Total Fleet Risk = 1.05E-02



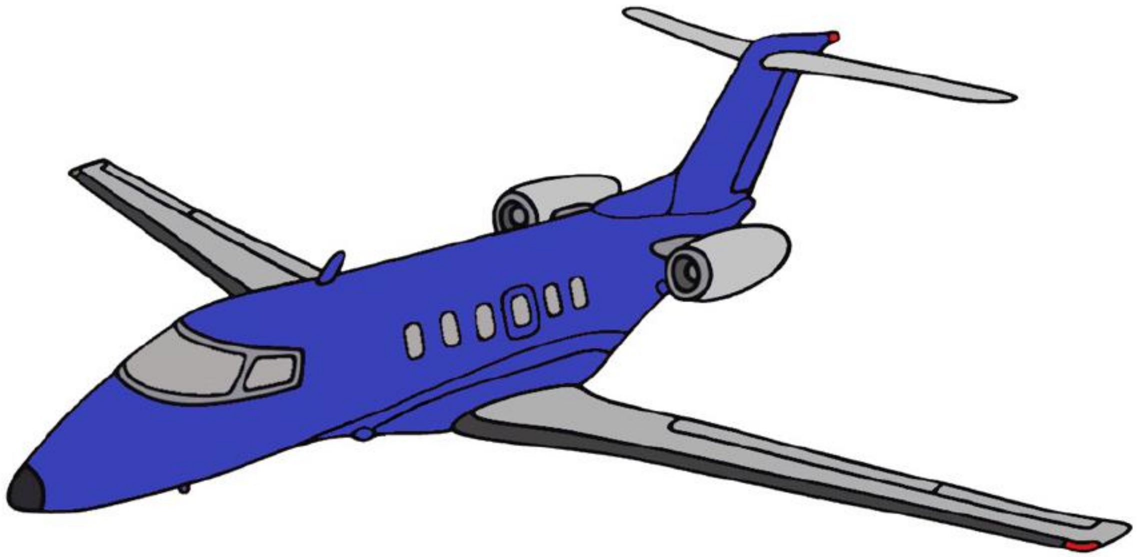
Total Fleet Risk = 5.76E-08

Interpretation:

- Consider an individual aircraft found not cracked at time t
- The chances of having a fatigue crack in a small interval [t, t+dt] are then given by: SFPOF(t) ≅ sfpof(t)*dt

Example

General Aviation Corporate Jet With Wing Forward Spar Cap Cracking



Input Data – Fracture Mechanics

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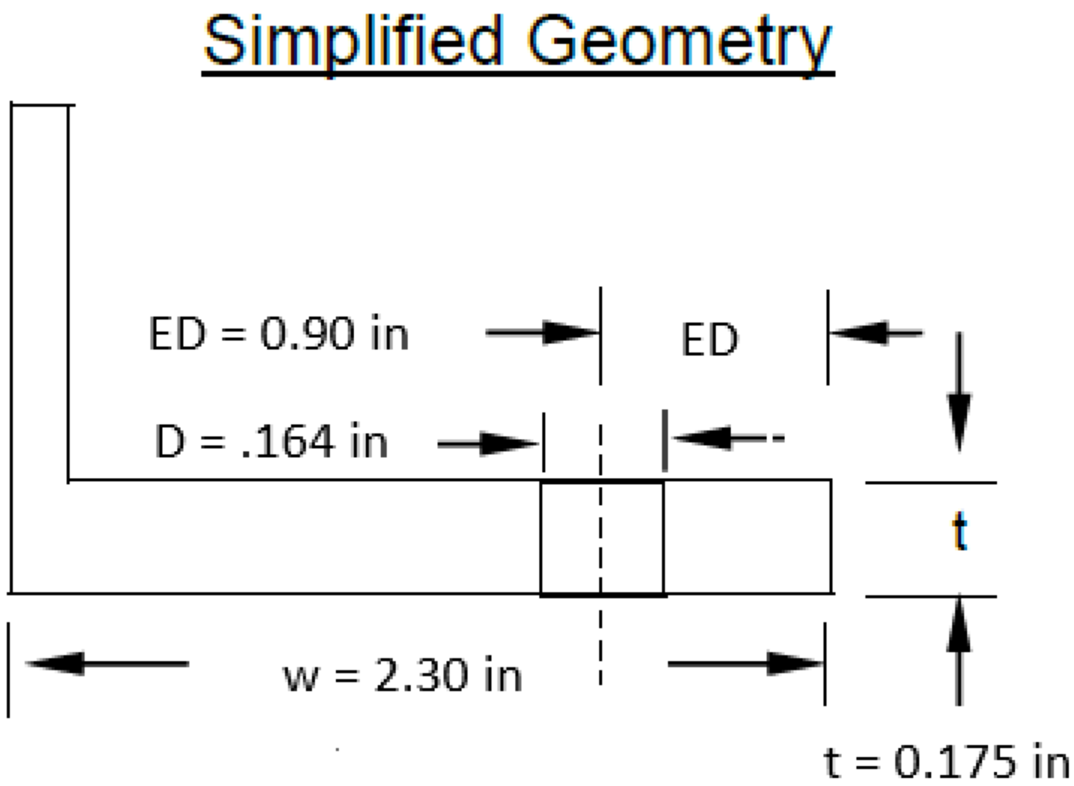
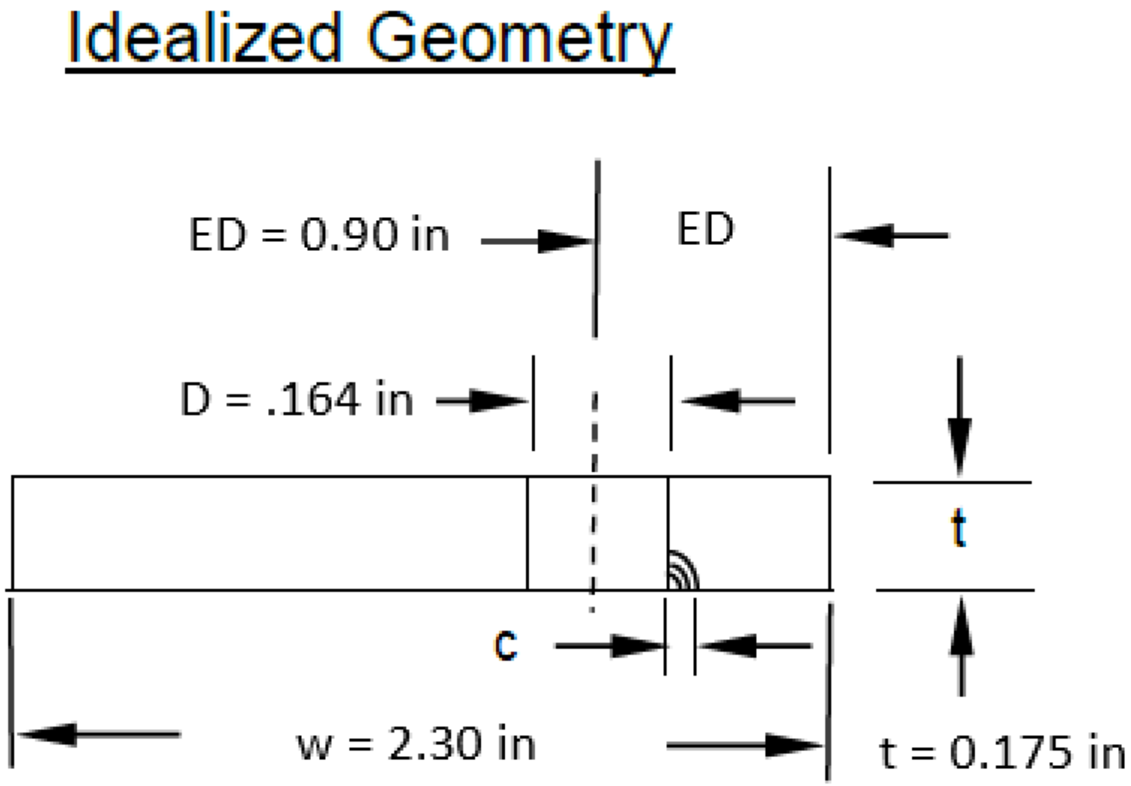




$$\frac{\sigma_{bearing}}{\sigma_{bypass}} = .66$$

Input Data – Fracture Mechanics

Random Variable	Distribution	Parameters
Paris m	Binormal	Mean = 2.586 Standard Deviation = 0.0
Paris c (log)	Binormal	Mean = -7.888 Standard Deviation = 0.04
Correlation	-	0
Walker Exponent	-	0.82
Ultimate Stress	Normal	Mean = 69.0 ksi Standard Deviation = 0.0 ksi
Yield Stress	Normal	Mean = 58.0 ksi Standard Deviation = 0.0 ksi
Hole Offset	Normal	Mean = 0.9000 in Standard Deviation = 0.0 in

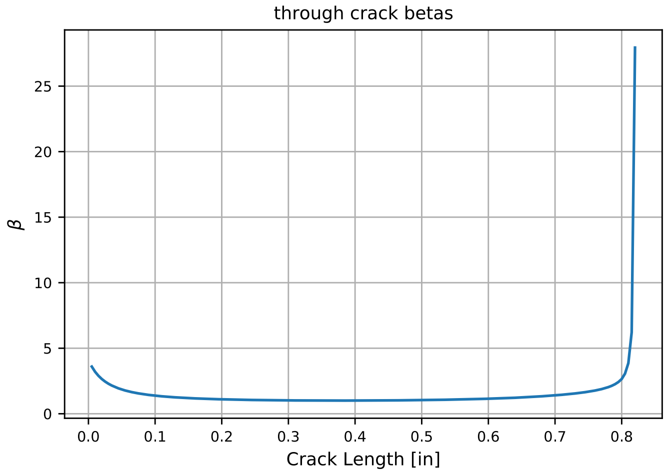
Input Data – Fracture Mechanics

! Afgrow Model 1030 / 2030 - 0.6619 Bearing Load transfer
! Width = 2.30 in
! Thk = 0.175 in
! H Dia = 0.164 in
! H Ofs = 0.90 in
!

Thru crack Betas

!	c	beta
	0.0050	3.59907
	0.0100	3.20130
	0.0150	2.89657
	⋮	⋮
	0.8100	3.86109
	0.8150	6.21646
	0.8200	27.93956

!



Part-thru crack Betas

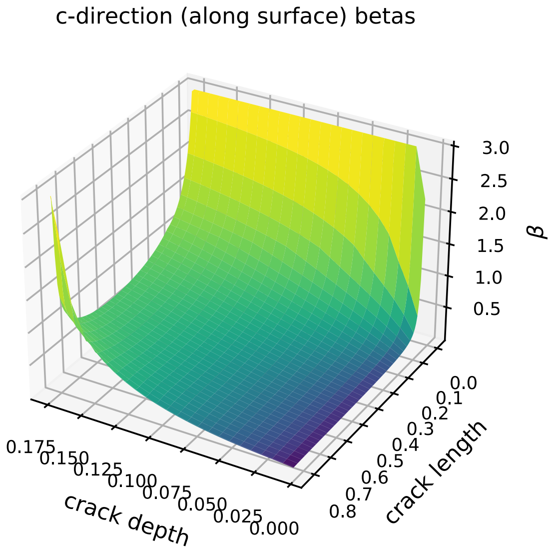
!beta c Crack Direction

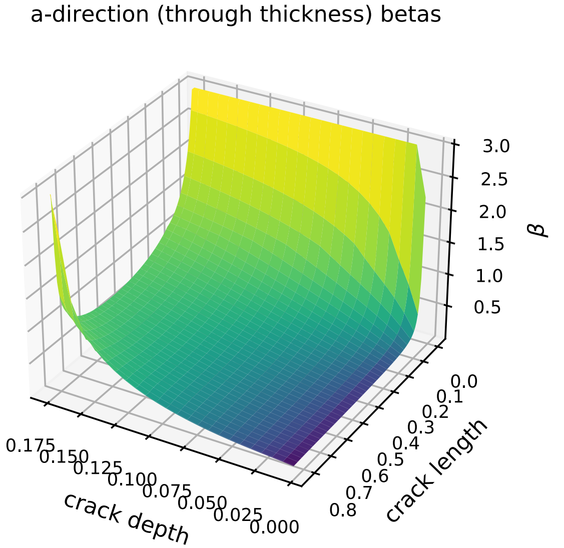
	0.0050	0.0125	0.0200	0.0275	0.0350	⋯	0.1475	0.1550	0.1625	0.1700	0.1750
0.0050	2.24485	3.19804	3.48930	3.62330	3.70123	⋯	3.99493	4.00368	4.01206	4.02010	4.02529
0.0125	1.00838	1.97282	2.45652	2.72711	2.89341	⋯	3.40218	3.41236	3.42193	3.43095	3.43671
0.0200	0.65282	1.21655	1.77304	2.07547	2.28183	⋯	2.97105	2.98348	2.99503	3.00581	3.01263
⋮	⋮	⋮	⋮	⋮	⋮	⋯	⋮	⋮	⋮	⋮	⋮
0.8000	0.02662	0.04209	0.05456	0.06696	0.08040	⋯	0.77079	0.90930	1.09491	1.36974	1.65756
0.8075	0.02630	0.04161	0.05398	0.06629	0.07965	⋯	0.80831	0.97114	1.20536	1.60190	2.12351
0.8150	0.02620	0.04147	0.05383	0.06615	0.07955	⋯	0.86325	1.06395	1.38532	2.08510	3.90826
0.8180	0.02616	0.04141	0.05377	0.06610	0.07952	⋯	0.88947	1.11091	1.48752	2.47098	2.17E+07

!

!beta a Crack Direction

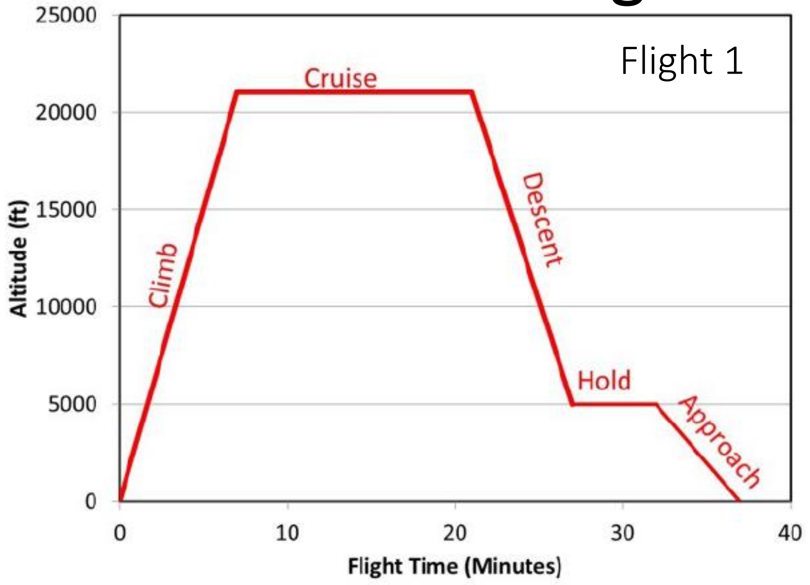
	0.0050	0.0125	0.0200	0.0275	0.0350	⋯	0.1475	0.1550	0.1625	0.1700	0.1750
0.0050	2.38094	1.40933	1.01682	0.81909	0.70182	⋯	0.32664	0.31896	0.31184	0.30520	0.30101
0.0125	2.85559	2.26857	1.78653	1.46485	1.24436	⋯	0.49365	0.48046	0.46834	0.45714	0.45014
0.0200	3.07986	2.35492	2.15685	1.84767	1.60820	⋯	0.61072	0.59219	0.57526	0.55972	0.55005
⋮	⋮	⋮	⋮	⋮	⋮	⋯	⋮	⋮	⋮	⋮	⋮
0.8075	1.15054	1.14212	1.15544	1.18763	1.23595	⋯	3.66367	4.14637	4.85539	6.09787	7.79295
0.8150	1.14916	1.14142	1.15570	1.18912	1.23898	⋯	3.94530	4.58217	5.63174	8.01747	14.50856
0.8180	1.14861	1.14116	1.15584	1.18977	1.24025	⋯	4.07878	4.80130	6.07016	9.54257	8.14E+07





Loading Parameters

Pressurized usage



Parameter	Value
Design Load Limit Factors	Man (-1.50 3.60) Gust (-3.00 5.00)
Ground Stress	-100 psi
One-g Stress	3800 psi
Average Velocity	300 knots

Segment	Weight	KEAS	% Duration
CLIMB	14511	246	0.19
CRUISE	13709	221	0.55
DESCENT	13100	300	0.14
HOLD	12932	250	0.06
APPROACH	12803	150	0.06

V_C = 300 KEAS

MTOW = 17200 lb

Sort matrix in ascending order for speed & weight

Flight Time (hrs)	% of Flights	Average Speed During Flight, % Max Takeoff Weight				
		0.500	0.826	0.833	0.957	1.00
0.62	1.0	0.14	0.19	0.13	0.38	0.16

Flight Time (hrs)	% of Flights	Average Speed During Flight, % Design Velocity				
		0.803	0.810	0.816	0.834	0.855
0.62	1.0	0.14	0.13	0.16	0.38	0.19

Input Data – Fracture Mechanics

Variable	Dist. Type	Mean	St. Dev.	Notes
Initial Crack Size	Lognormal	0.00248 in	0.00129	Reamed Fastener Hole
Repair Crack Size	Lognormal	0.00248 in	0.00129	Assuming Repair is Replacement of Part
Fracture Toughness	Normal	26.0 ksi	2.0	7050-T651 Plate
EVD	Gumbel	14.5 ksi	0.8	

Inspection Data

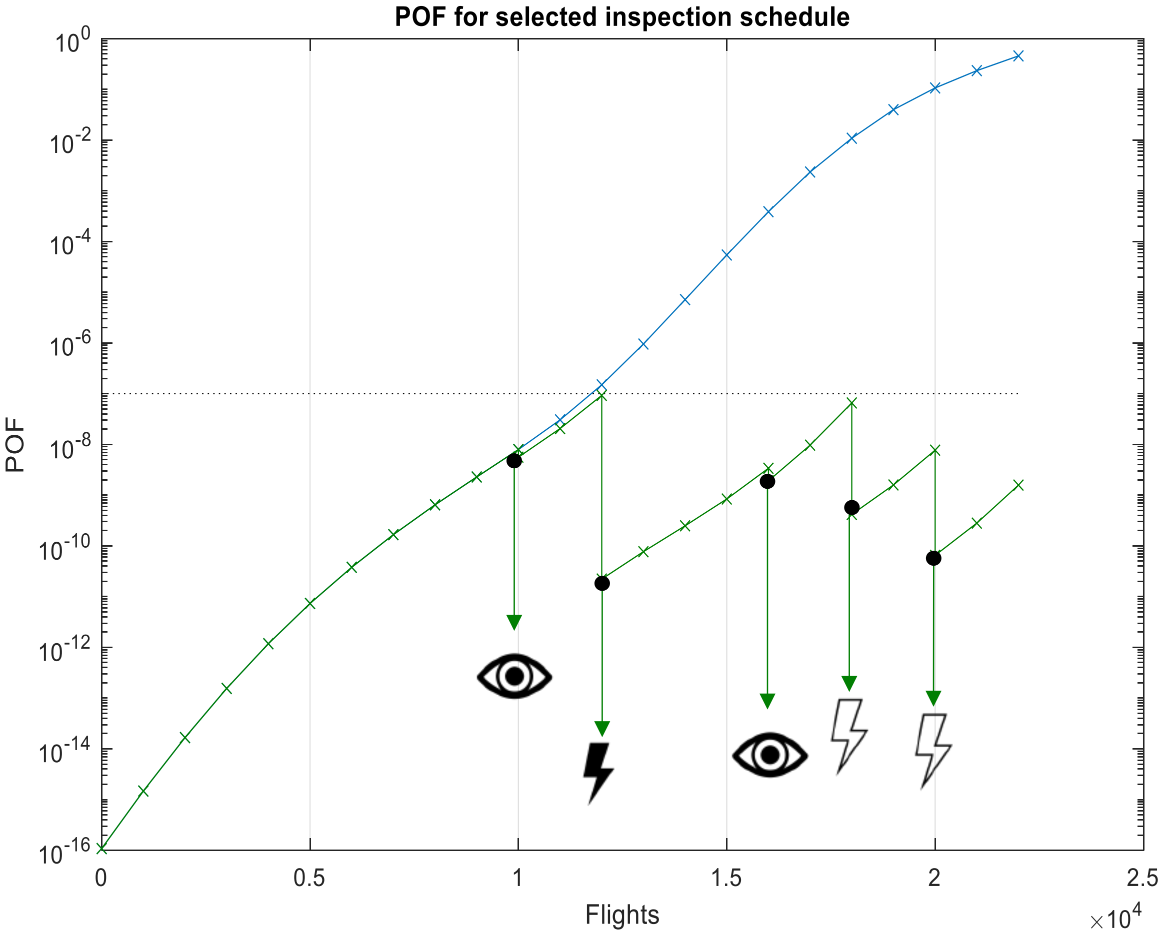
Inspections	Inspection Type	Material	Crack Type	Dist. Type	Mean [in]	St. Dev. [in]	Source	Cost
⚡ POD 1	Automated bolt hole eddy current	Aluminum	T	Lognormal	0.0180	0.0109	Aeronautical Applications of Non-destructive	50x
ϟ POD 2	Eddy current sliding probe	Aluminum	Overall	Lognormal	0.0788 +0.0625	0.0302	NDE Capabilities Book	10x
👁 POD 3	Visual	Aluminum		Lognormal	0.99714 +0.0625	3.66907	NDE Capabilities Book	1x

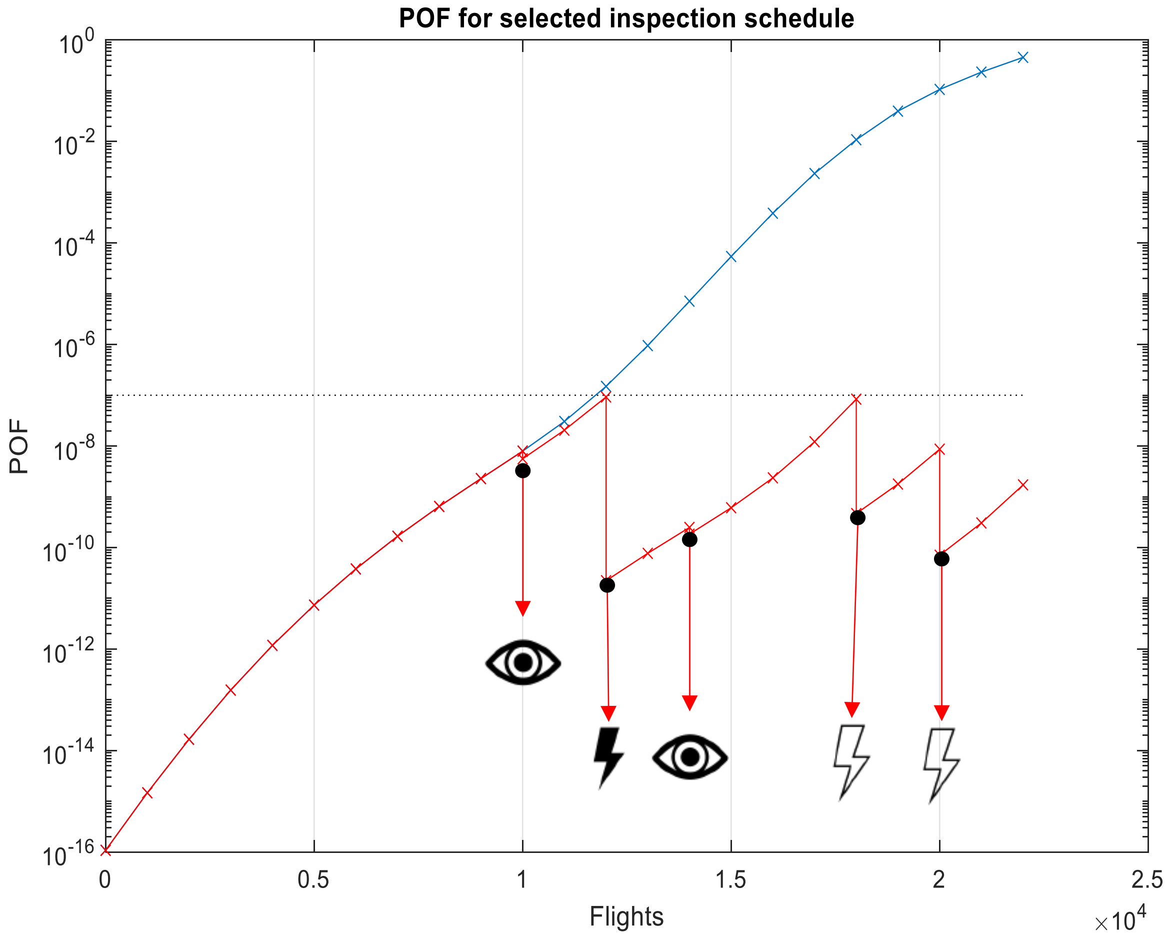
Risk
10^{-7}

Possible inspection times									
2,000	4,000	6,000	8,000	10,000	12,000	14,000	16,000	18,000	20,000
👁	👁	👁 ⚡ ϟ	👁	👁	👁 ⚡ ϟ	👁	👁	👁 ⚡ ϟ	👁 ⚡ ϟ

Results

Possible inspection times = [2000, 4000, 6000, 8000, 10000, 12000, 14000, 16000, 18000, 20000]



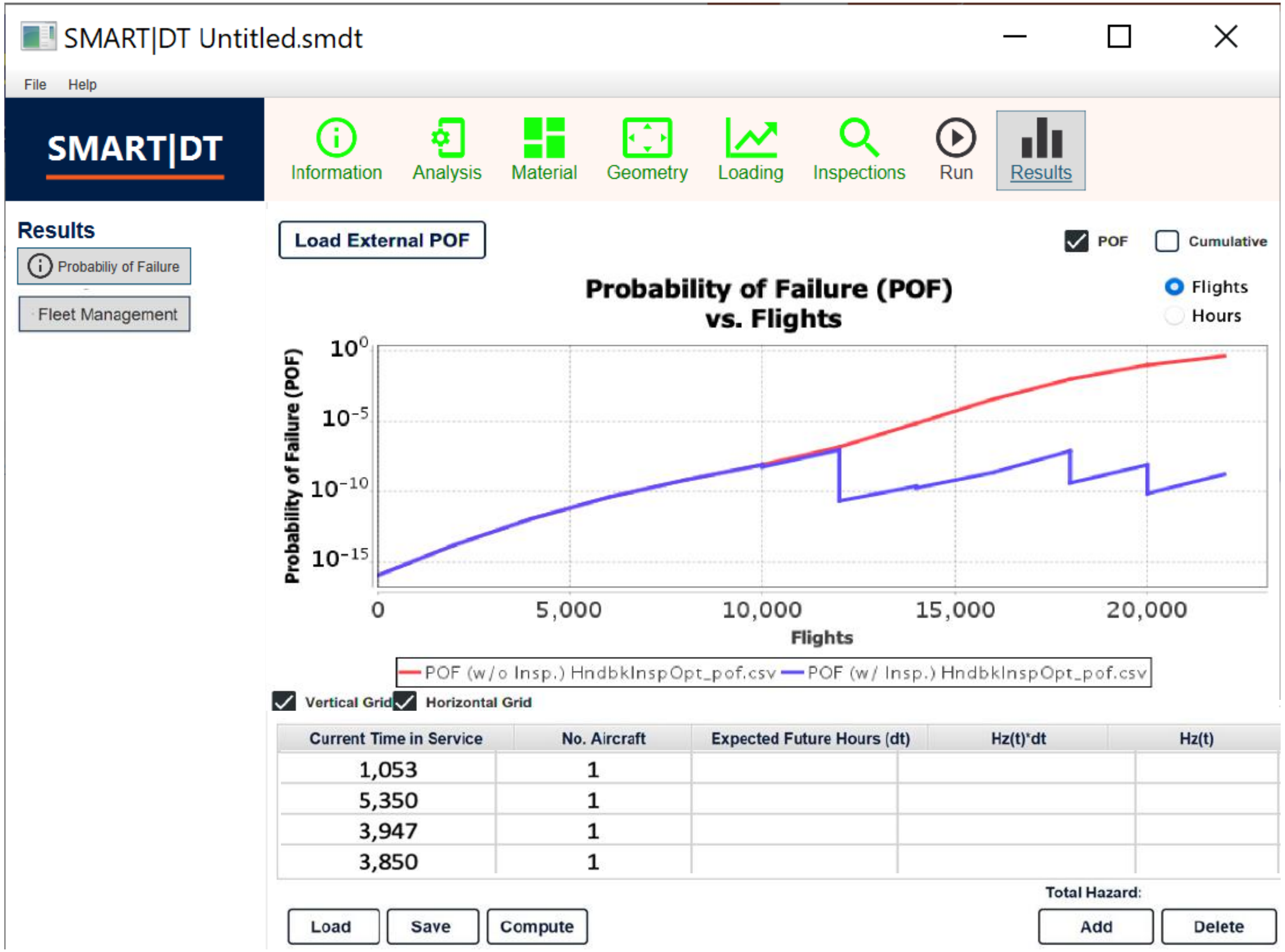


Operations = 1,048,576

SMART-DT runs= 1,287

Fleet Management

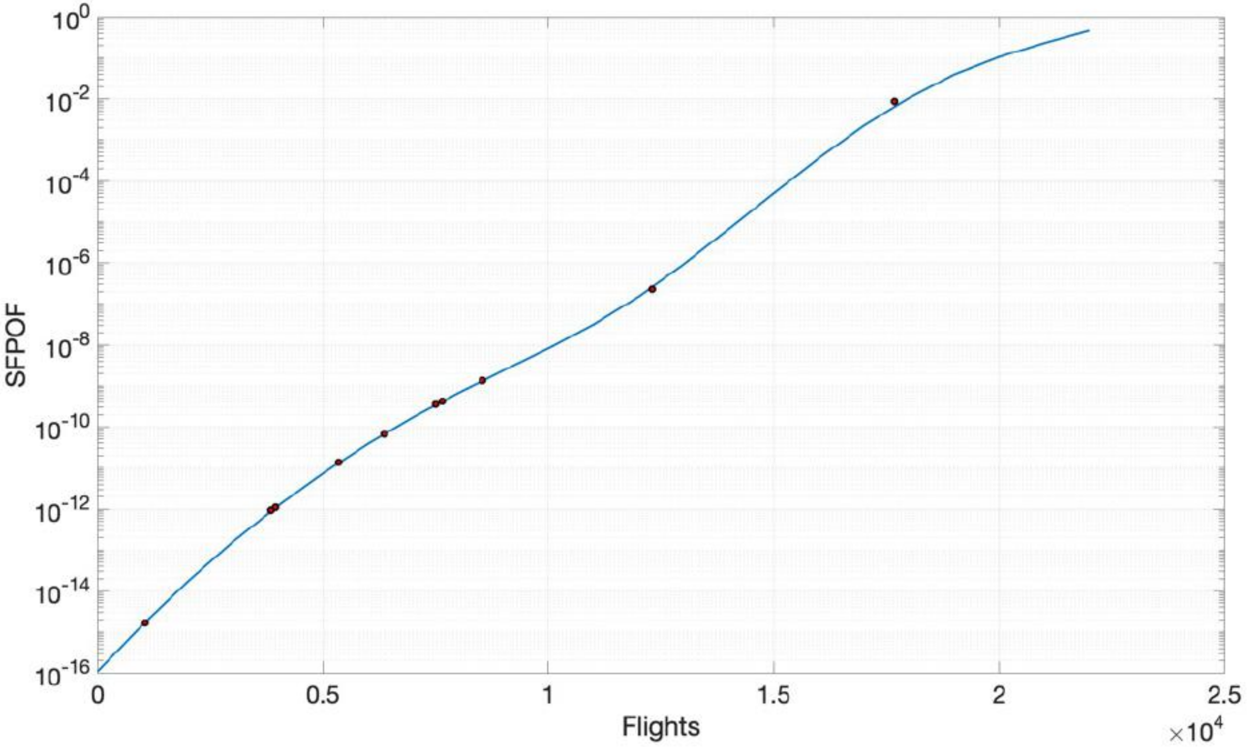
Airplane number	Time in service
1	1,053
2	5,350
3	3,947
4	3,850
5	7,500
6	12,300
7	17,683
8	6,356
9	8,540
10	7,640



Fleet Management

- Scenario 1 – without inspections

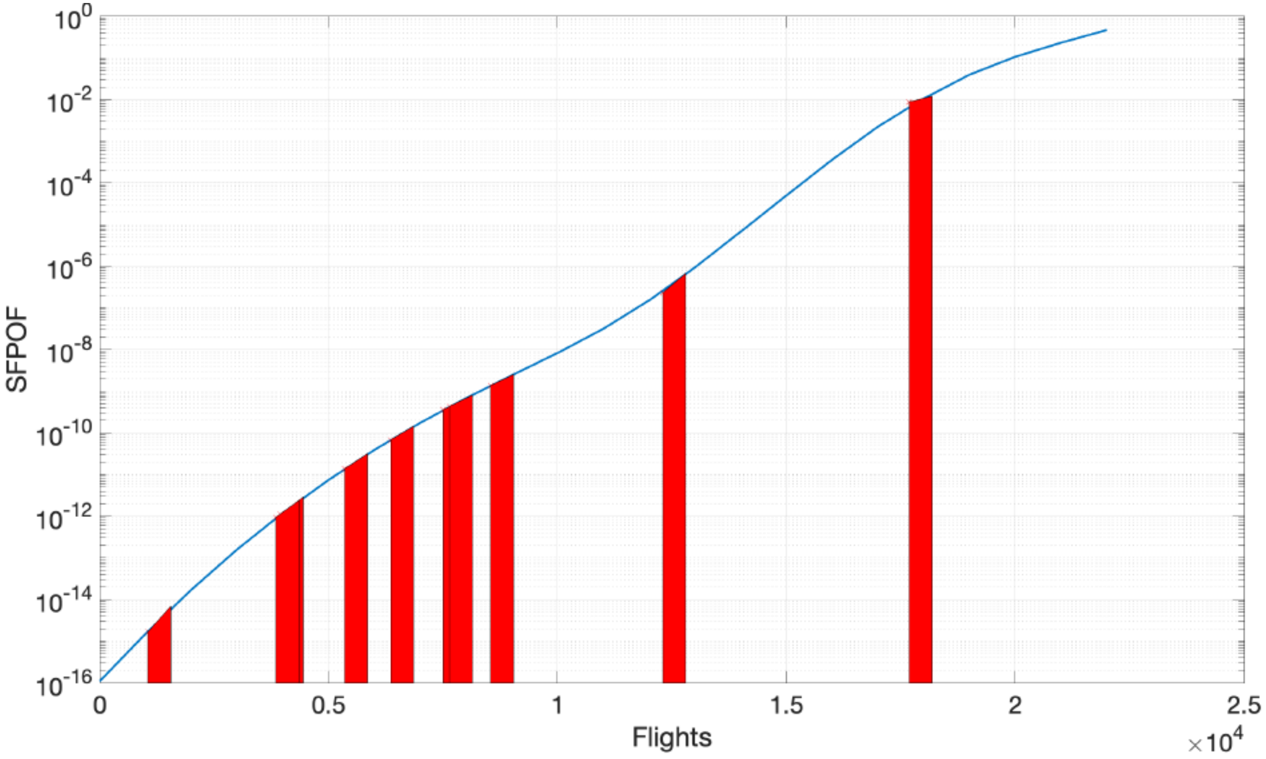
Airplane number	Time in service	Hazard Rate	Probability of Failure For Expected Future Hours		
			100	500	1,000
1	1,053	2.32E-15	3.10E-13	3.10E-12	1.02E-11
2	5,350	1.84E-11	2.00E-09	1.31E-08	4.04E-08
3	3,947	1.14E-12	1.24E-10	1.21E-09	3.98E-09
4	3,850	1.04E-12	1.09E-10	9.64E-10	3.43E-09
5	7,500	4.24E-10	4.49E-08	2.74E-07	8.25E-07
6	12,300	3.79E-07	4.18E-05	2.87E-04	9.94E-04
7	17,683	7.88E-03	8.29E-01	5.29E+00	1.67E+01
8	6,356	8.66E-11	9.33E-09	6.01E-08	1.77E-07
9	8,540	1.60E-09	1.68E-07	1.01E-06	3.05E-06
10	7,640	4.94E-10	5.19E-08	3.21E-07	9.91E-07
Total Hazard			8.29E-01	5.29E+00	1.67E+01



Fleet Management

- Scenario 1 – without inspections

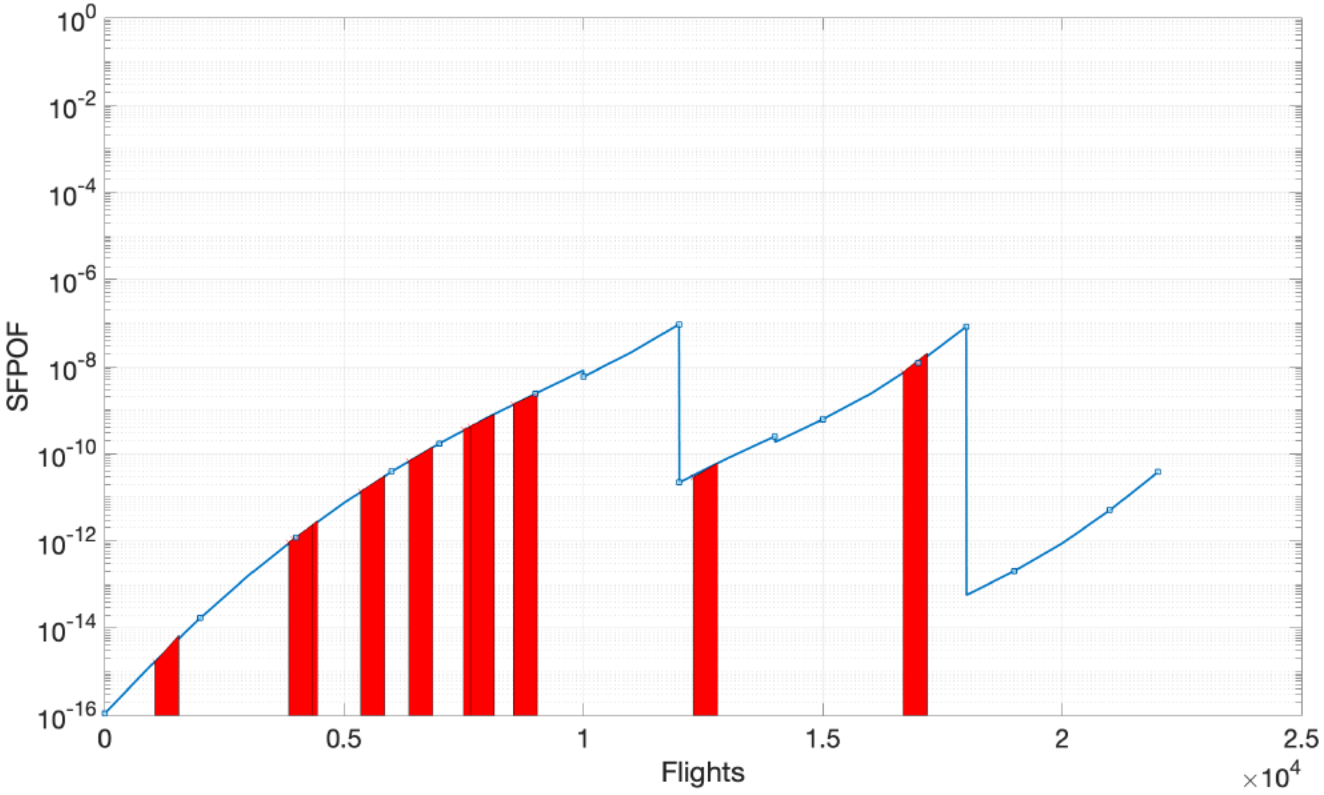
Airplane number	Time in service	Hazard Rate	Probability of Failure For Expected Future Hours		
			100	500	1,000
1	1,053	2.32E-15	3.10E-13	3.10E-12	1.02E-11
2	5,350	1.84E-11	2.00E-09	1.31E-08	4.04E-08
3	3,947	1.14E-12	1.24E-10	1.21E-09	3.98E-09
4	3,850	1.04E-12	1.09E-10	9.64E-10	3.43E-09
5	7,500	4.24E-10	4.49E-08	2.74E-07	8.25E-07
6	12,300	3.79E-07	4.18E-05	2.87E-04	9.94E-04
7	17,683	7.88E-03	8.29E-01	5.29E+00	1.67E+01
8	6,356	8.66E-11	9.33E-09	6.01E-08	1.77E-07
9	8,540	1.60E-09	1.68E-07	1.01E-06	3.05E-06
10	7,640	4.94E-10	5.19E-08	3.21E-07	9.91E-07
Total Hazard			8.29E-01	5.29E+00	1.67E+01



Fleet Management

- Scenario 2 - With inspections

Airplane number	Time in service	Hazard Rate	Probability of Failure For Expected Future Hours		
			100	500	1,000
1	1,053	1.67E-15	3.10E-13	3.10E-12	1.02E-11
2	5,350	1.37E-11	2.00E-09	1.31E-08	4.04E-08
3	3,947	1.10E-12	1.24E-10	1.21E-09	3.98E-09
4	3,850	9.40E-13	1.09E-10	9.64E-10	3.43E-09
5	7,500	3.53E-10	4.49E-08	2.74E-07	8.25E-07
6	12,300	2.85E-11	4.11E-09	2.61E-08	7.14E-08
7	17,683	7.46E-09	9.50E-07	6.73E-06	2.80E-05
8	6,356	6.79E-11	9.33E-09	6.01E-08	1.77E-07
9	8,540	1.36E-09	1.68E-07	1.01E-06	3.05E-06
10	7,640	4.29E-10	5.19E-08	3.21E-07	9.91E-07
Total Hazard			1.23E-06	8.45E-06	3.31E-05



Summary

- Inspection schedule optimization finds ”the best” inspection schedule to manage the risk and minimize the cost.
- The hazard rate computed from a PDTA combined with the fleet demographics (fleet size, individual aircraft time in service, etc.) can be used to determine the probability of an event occurring within a fleet in a given flight time interval.
- Hazard rate and fleet demographics help to assess, manage, and mitigate the fleet safety risk.

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Questions