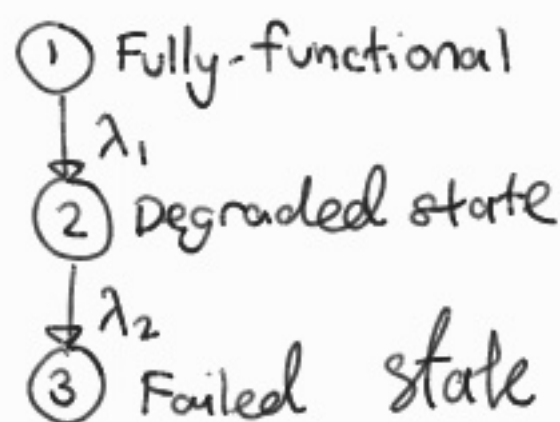## Q1.

$$P_1(t + \Delta t) = P_1(t) - \lambda_1 \Delta t \, P_1(t)$$

$$P_2(t + \Delta t) = P_2(t) + \lambda_1 \Delta t \, P_1(t)$$
$$- \lambda_2 \Delta t \, P_2(t)$$

$$P_3(t + \Delta t) = P_3(t) + \lambda_2 \Delta t \, P_2(t)$$

① Fully-functional
  $\downarrow \lambda_1$
② Degraded state
  $\downarrow \lambda_2$
③ Failed state

$$\frac{d P_1(t)}{dt} = -\lambda_1 P_1(t)$$

$$\frac{d P_2(t)}{dt} = \lambda_1 P_1(t) - \lambda_2 P_2(t)$$

$$\frac{d P_3(t)}{dt} = \lambda_2 P_2(t)$$

$$\ln P_1(t) = -\lambda_1 t, \qquad P_1(t) = e^{-\lambda_1 t}$$

$$\frac{d P_2(t)}{dt} + \lambda_2 P_2(t) = \lambda_1 e^{-\lambda_1 t}, \quad v(x) = \int \lambda_2 \, dt = \lambda_2 t + C$$

$$P_2(t) = e^{-\lambda_2 t} \int e^{-\lambda_2 t} \lambda_1 e^{-\lambda_1 t} \, dt$$

$$= C e^{-\lambda_2 t} - \frac{\lambda_1}{\lambda_1 + \lambda_2} e^{-(\lambda_1 + \lambda_2) t}$$

let $P_2(0) = 1$

$$c = \frac{\lambda_1}{\lambda_1 + \lambda_2}$$

$$P_2(t) = \frac{\lambda_1}{\lambda_1 + \lambda_2} \left[e^{-\lambda_2 t} - e^{-(\lambda_1 + \lambda_2) t} \right]$$

$$P_3(t) = 1 - P_1(t) - P_2(t)$$

$$= 1 - e^{-\lambda_1 t} - \frac{\lambda_1}{\lambda_1 + \lambda_2} \left[e^{-\lambda_2 t} - e^{-(\lambda_1 + \lambda_2)t} \right]$$

$$R_p(t) = P_1(t) + P_2(t)$$

$$= e^{-\lambda_1 t} + \frac{\lambda_1}{\lambda_1 + \lambda_2} \left[e^{-\lambda_2 t} - e^{-(\lambda_1 + \lambda_2)t} \right]$$

$$MTTF = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$$

Q2. $D(t) = \beta_1 t$

 Variance

$$\beta_1 \sim \text{LogNorm}(\mu_1, \sigma_1^2)$$

Failure: $D(t) > D_f$ & $D_f \sim \text{LogNorm}(\mu_2, \sigma_2^2)$

$$P(\beta_1 t \geq D_f) = F_T(t)$$

$$\beta_1 = e^{\mu_1 + \sigma_1 Z}, \quad D_f = e^{\mu_2 + \sigma_2 Z}, \quad \text{where } Z \sim N(0, 1)$$

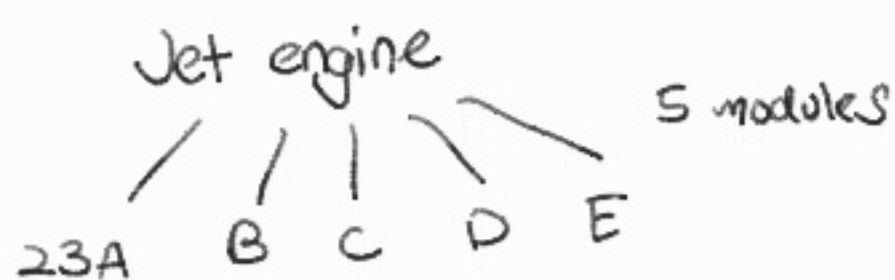$$\beta_1 t \sim \text{LogNorm}(\mu_1 + \ln t, \sigma_1^2)$$

$$P(\beta_1 t \geq D_f) = P(\ln(\beta_1 t) - \ln(D_f) \geq 0)$$

let $Y = \ln(\beta_1 t) - \ln(D_f) \sim N(\mu_1 + \ln t - \mu_2, \sigma_1^2 + \sigma_2^2)$

$$F_T(t) = P(Y \geq 0)$$

$$= 1 - \Phi\left[\frac{\mu_2 - \mu_1 - \ln t}{\sqrt{\sigma_1^2 + \sigma_2^2}}\right]$$

Q3.

Jet engine — 5 modules

/ | | \ \

23A   B   C   D   E

Once daily, average 5 hours

- From among the exponential, Weibull, normal, and lognormal distributions, find a best-fit failure distribution.

From histogram & best fit line plots, the best fit failure distributions:

23A: Weibull ($\beta_A = 2.51787$, $\theta_A = 1332.4332$)

23B: Exponential ($\lambda_B = 1/347.987$)

23C: Weibull ($\beta_C = 2.089338$, $\theta_C = 500.781$)

23D: Exponential ($\lambda_D = 1/1798.82$)

23E: Weibull ($\beta_E = 1.16203$, $\theta_E = 2836.11$)

Repair time: Weibull ($\beta_R = 1.24127$, $\theta_R = 17.0590$)

- Compute performance measurements

  First, calculate system hazard rate, $\lambda(t)$

$$\lambda(t) = \lambda_B + \lambda_D + \sum_{i \in \{A, C, E, R\}} \frac{\beta_i}{\theta_i} \left(\frac{t}{\theta_i}\right)^{\beta - 1}$$

$$R(t) = e^{-\int \lambda(t)\, dt}$$

$$= e^{-\left[\lambda_B t + \lambda_D t + \sum_{i \in \{A, C, E, R\}} \left(\frac{t}{\theta_i}\right)^{\beta_i}\right]}$$

  Now, we can plug the values into this formula in Python to calculate the measurements:

- $R(1^{st} \text{ mission}) = R(5) = 0.982312$

- $R(25^{th} \text{ mission}) = R(125) = 0.598757$

- Median # of missions to failure = 162

- Mean time to repair = $\theta_R \Gamma\left(1 + \frac{1}{\beta_R}\right) = 15.9141$

- 90th percentile of the repair time = t_{90}

$$F_R(t_{90}) = 0.9$$

$$t_{90} = 33.40136$$

- Which subsystem displays the worst reliability?

  Clearly, the 23B module has the worst reliability out of all the modules, based on the MTTF and the distribution/histogram of failure times.

- What should the reliability of that subsystem be to achieve a system reliability of $R(10 \text{ missions}) = 0.9$?

  Current $R(10 \text{ missions}) = 0.827774$

  Need to solve for λ_B^* in the equation below:

  $$0.9 = e^{-\left[\lambda_B^* t + \lambda_D t + \sum_{i \in \{A, C, E, R\}} \left(\frac{t}{\theta_i}\right)^{\beta_i}\right]}$$

  Use the Python solver, we get a $\lambda_B^* = 1/832.92989$

  Reliability of 23B $= R_B(t) = e^{-\frac{t}{832.92989}}$

  $$R_B(10 \text{ missions}) = 0.941737$$

Q4. a. Using TTF info (only):

Solve using MLE on pdf of 15 iid Weibull r.v.s

$$L(\beta, \theta) = \prod_{i \in F} f(t_i) \prod_{i \in C} R(120\,000) \quad,$$

where $F = \{1, 2, 3, 5, 6, 7, 8, 9, 10\}$, (specimens with complete failure data)

$C = \{4, 11, 12, 13, 14, 15\}$, (specimens w/ censored failure data)

$$f(t_i) = \frac{\beta}{\theta}\left(\frac{t_i}{\theta}\right)^{\beta-1} e^{-\left(\frac{t_i}{\theta}\right)^{\beta}}, \quad \theta > 0, \ \beta > 0,$$

$$R(120\,000) = 1 - F(120\,000) = e^{-(120\,000/\theta)^{\beta}}$$

$$\ln\left[L(\beta, \theta)\right] = 6 \ln\left[1 - F(120\,000)\right] + \sum_{i \in F} \ln f(t_i)$$

Using MLE solver on R:

$$\theta = 166420.226$$
$$\beta = 1.07888043$$

$$F(t) = 1 - R(t), \quad R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}}$$

let $F(t) = \alpha$

$$e^{-(t/\theta)^{\beta}} = 1 - \alpha$$

$$(t/\theta)^{\beta} = -\ln(1-\alpha)$$

$$\beta\left(\ln t - \ln \theta\right) = \ln\left(-\ln(1-\alpha)\right)$$

$$t = e^{\frac{\ln(-\ln(1-\alpha))}{\beta} + \ln \theta}$$

$$F(20\,669.94) = 0.1$$

$$F(52442.04) = 0.25$$

$$F(118\,486.6) = 0.5$$

$$F(225263.1) = 0.75$$

$$F(360528) = 0.9$$

b. Assume that the degradation signals follow a linear degradation path:

$$D_f = \beta_1 + \beta_2 t$$

$$\beta_1 \sim \mu_{\beta_1} \quad , \quad \beta_2 \sim N(\mu_{\beta_2}, \sigma_{\beta_2}^2)$$

$$D_f \sim N(\mu_{\beta_1} + \mu_{\beta_2} t, \sigma_{\beta_2}^2 t^2)$$

$$F_T(t) = P(\beta_1 + \beta_2 t \geq D_f)$$

$$P(\beta_2 \leq x) = \Phi\left[\frac{x - \mu_{\beta_2}}{\sigma_{\beta_2}}\right]$$

$$F_T(t) = P\{T \leq t\} \approx \Phi\left[\frac{t - \frac{D_f - \mu_{\beta_1}}{\mu_{\beta_2}}}{\frac{\sigma_{\beta_2} t}{\mu_{\beta_2}}}\right]$$

From numerical estimation using the data,

$$\beta_1 \sim \mu_{\beta_1} = 8.39793572$$

$$\beta_2 \sim N(5.2731428 \times 10^{-5}, (8.9685798 \times 10^{-6})^2)$$

$$\frac{t - \frac{D_f - \mu_{\beta_1}}{\mu_{\beta_2}}}{\frac{\sigma_{\beta_2} t}{\mu_{\beta_2}}} = N_\alpha,$$

$$t - \frac{D_f - \mu_{\beta_1}}{\mu_{\beta_2}} = \frac{N_\alpha \sigma_{\beta_2} t}{\mu_{\beta_2}}$$

$$t = \frac{\frac{D_f - \mu_{\beta_1}}{\mu_{\beta_2}}}{1 - \frac{N_\alpha \sigma_{\beta_2}}{\mu_{\beta_2}}}$$

$$F(102\,795.66) = 0.1$$

$$F(112\,316.98) = 0.25$$

$$F(125\,201.70) = 0.5$$

$$F(141\,425.69) = 0.75$$

$$F(160\,097.66) = 0.9$$

C. Assume the same linear degradation path, use approximate degradation path to estimate pseudo failure times.

$$S_{ij} = D_{ij} + \varepsilon_{ij}$$

Pseudo random failure times = $108\,266.44, \ldots, 146\,556.57$

After estimating the 15 pseudo random failure times, the estimated Weibull distribution has parameters:

$$\theta = 138\,468.62$$

$$\beta = 5.7392593$$

$$F(93\,554.40) = 0.1$$

$$F(111\,448.22) = 0.25$$

$$F(129\,902.36) = 0.5$$

$$F(146\,577.75) = 0.75$$

$$F(160\,126.53) = 0.9$$

d. Bootstrapping:

$\beta_1 \sim$ constant, μ_{β_1}

$\beta_2 \sim N(\mu_{\beta_2}, \sigma_{\beta_2}^2)$

From numerical estimation of the 15 paths

$\beta_1 \sim \mu_{\beta_1} = 8.39793572$

$\beta_2 \sim N(5.2731428 \times 10^{-5}, (8.9685798 \times 10^{-6})^2)$ $\Big\} \hat{\theta}_\beta$

$$F_T(t) = p\{T \leq t\} \approx \Phi\left[\frac{t - \frac{D_f - \mu_{\beta_1}}{\mu_{\beta_2}}}{\frac{\sigma_{\beta_2} t}{\mu_{\beta_2}}} \right]$$

$\hat{F}(102\ 795.66) = 0.1$

$\hat{F}(112\ 316.98) = 0.25$

$\hat{F}(125\ 201.70) = 0.5$

$\hat{F}(141\ 425.69) = 0.75$

$\hat{F}(160\ 097.66) = 0.9$

$S_{ij}^* = D(t_{ij}; \beta_1^*, \beta_2^*) + \varepsilon_{ij}^*$, where for each i, there will
be 35 equally spaced t_{ij} points from 0 to 120 000,
and $\varepsilon_{ij}^* \sim N(0, 0.63382^2)$ which is the standard dev.
of the residual data points.

Set $B = 50,000$

After running algorithm to calculate Bootstrap
Confidence Intervals at $B = 50,000$ & $\alpha = 0.1$,
the confidence intervals are as follows:

$$\hat{F}(102\,795.66) = 0.1$$
$$[\underline{F}(102\,795), \overline{F}(102\,795)] = [7.7561 \times 10^{-5}, 0.27012]$$

$$\hat{F}(112\,316.98) = 0.25$$
$$[\underline{F}(112\,316), \overline{F}(112\,316)] = [0.016758, 0.49062]$$

$$\hat{F}(125\,201.70) = 0.5$$
$$[\underline{F}(125\,201), \overline{F}(125\,201)] = [0.14228, 0.85985]$$

$$\hat{F}(141\,425.69) = 0.75$$
$$[\underline{F}(141\,425), \overline{F}(141\,425)] = [0.49426, 0.98548]$$

$$\hat{F}(160\,097.66) = 0.9$$
$$[\underline{F}(160\,097), \overline{F}(160\,097)] = [0.86178, 0.99901]$$

```python
In [134]:  import numpy as np
           import pandas as pd
           import matplotlib.pyplot as plt
           from scipy.stats import norm
           from sklearn.linear_model import LinearRegression
           from scipy.stats import weibull_min
           import matplotlib.mlab as mlab
           import scipy.stats as ss
           import math
           from scipy.optimize import minimize
           from scipy.optimize import fsolve
           from scipy.special import gamma, factorial
```

```python
In [3]:  df = pd.read_csv("q3.csv",index_col=0)
```

```python
In [11]:  lengths = {'A':80,'B':90,'C':60,'D':126,'E':90}
```

Find best-fit failure distributions

```
In [64]:  for col in df.columns:
              data = df[col].dropna().copy()
              print(col)
              median, mu, sigma = np.median(data),np.mean(data),np.std(data)
              print(median, mu, sigma)

              rX = np.linspace(0,max(data), 100)
              # exponential
              P = ss.expon.fit(data)
              rP = ss.expon.pdf(rX, *P)

              # normal
              normP = ss.norm.fit(data)
              normrP = ss.norm.pdf(rX, *normP)

              # Weibull
              weiP = ss.weibull_min.fit(data, floc=0)
              weirP = ss.weibull_min.pdf(rX, *weiP)

              # Weibull
              logP = ss.lognorm.fit(data)
              logrP = ss.lognorm.pdf(rX, *weiP)

              n,bins,cont = plt.hist(data, density=True, bins=30)   # density=False
          would make counts
              max_ratio = 6
              if max(rP)/max(n) <max_ratio:
                  plt.plot(rX, rP, color ='orange',label='exp')
              if max(normrP)/max(n) <max_ratio:
                  plt.plot(rX, normrP, color ='red',label='normal')
              if max(weirP)/max(n) <max_ratio:
                  plt.plot(rX, weirP, color ='purple',label='weibull')
              if max(logrP)/max(n) <max_ratio:
                  plt.plot(rX, logrP, color ='navy',label='lognorm')
              plt.legend(loc="upper right")
              plt.show()
```
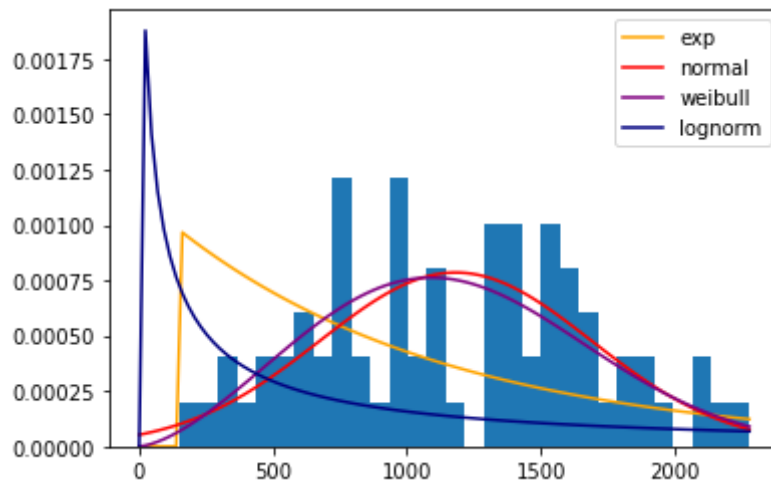
A
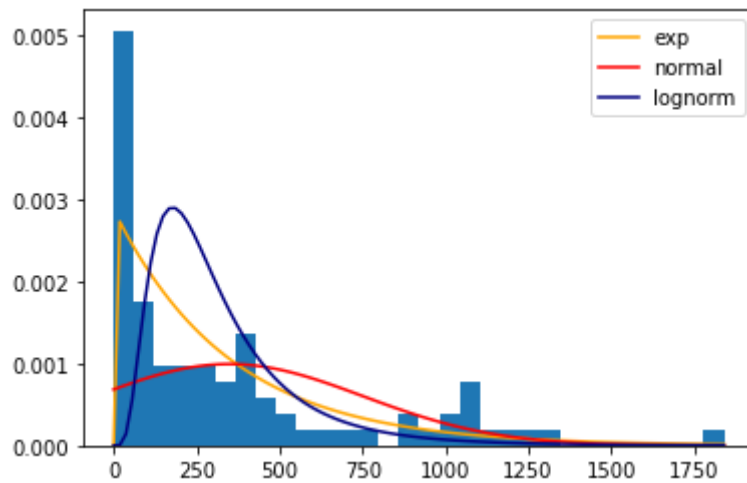
1159.6 1182.347142857143 508.1729322418357

B

232.45 348.08690476190475 402.4948508336006

/Users/hellozhems/opt/anaconda3/lib/python3.8/site-packages/scipy/stats/_continuous_distns.py:2046: RuntimeWarning: divide by zero encountered in power
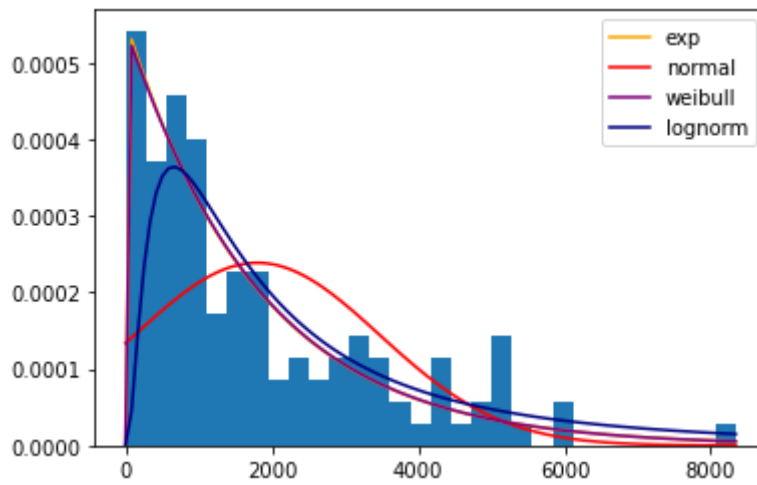 return c*pow(x, c-1)*np.exp(-pow(x, c))

C

447.45 446.7766666666665 217.45955667408344
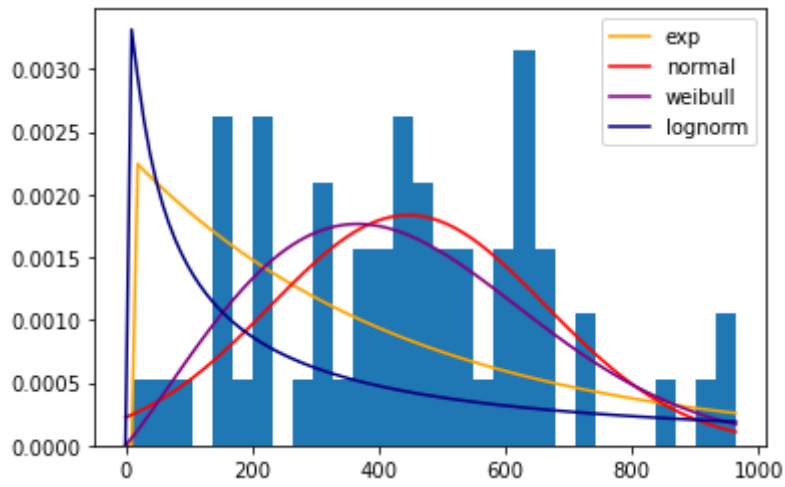
D
1184.7 1800.61746031746 1670.1909587657206

E
2081.2 2697.241772151898 2127.137768868946
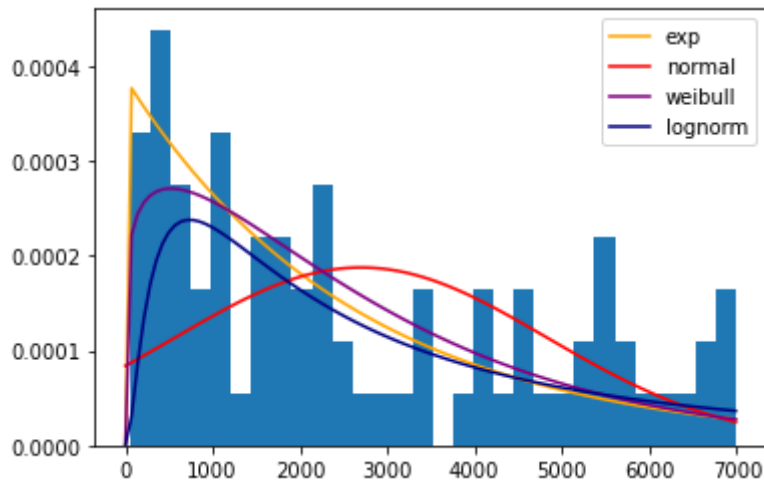
Repair Time
11.8 15.717021276631579 16.701513567073224
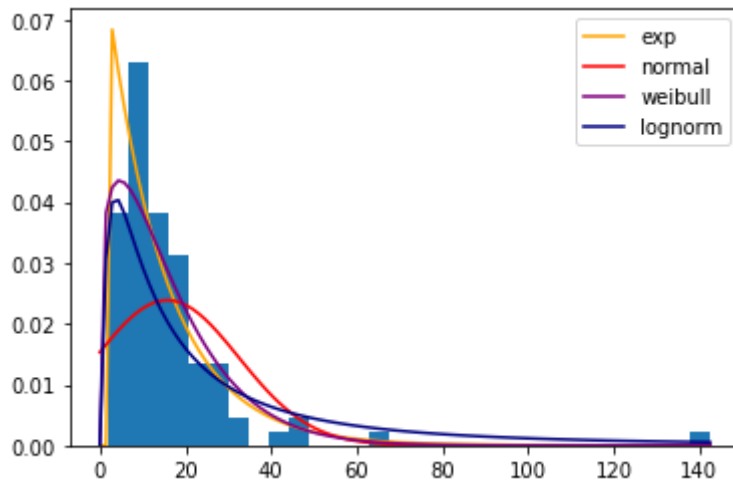
```
In [137]: best_fit = {'A':'w','B':'e','C':'w','D':'e','E':'w','Repair Time':'w'}
          paras = {}
          for i in df.columns:
              data = df[i].dropna().copy()
              print(i)
              if best_fit[i] == 'w':
                  shape,loc,scale = ss.weibull_min.fit(data, floc=0)
                  paras[i] = shape,scale
                  print(shape,scale)
              elif best_fit[i] == 'e':
                  loc, scale = ss.expon.fit(data)
                  paras[i] = 1/scale
                  print(scale)
```

```
A
2.517875275657132 1332.4332341044333
B
347.9869047619048
C
2.089338035932316 500.781212480881
D
1798.81746031746
E
1.1620315113324662 2836.105261943644
Repair Time
1.2412661365976316 17.058960233972957
```

Compute Performance Measurements

β is the first, θ is the second

```
In [138]: paras
```

```
Out[138]: {'A': (2.517875275657132, 1332.4332341044333),
           'B': 0.00287367135462815,
           'C': (2.089338035932316, 500.781212480881),
           'D': 0.0005559207768772254,
           'E': (1.1620315113324662, 2836.105261943644),
           'Repair Time': (1.2412661365976316, 17.058960233972957)}
```

```
In [139]: def R(t):
              return np.exp(-(t*(paras['B']+paras['D'])+sum([(t/paras[i][1])**para
          s[i][0] for i in ['A','C','E']])))
```

```
In [140]: R(5)
```

```
Out[140]: 0.9823124629123697
```

```
In [147]: R(125)
```

```
Out[147]: 0.5987569008055672
```

```
In [142]: def R_(t):
              return np.exp(-(t*(paras['B']+paras['D'])+sum([(t/paras[i][1])**para
          s[i][0] for i in ['A','C','E']])))-0.5
          fsolve(R_, [1])
```

```
Out[142]: array([162.41229796])
```

```
In [143]: R(162.41229796)
```

```
Out[143]: 0.4999999999996832
```

```
In [144]: paras['Repair Time'][1]*gamma(1+1/paras['Repair Time'][0])
```

```
Out[144]: 15.914133241640979
```

```
In [159]: def wb(x):
              return 1-np.exp(-(x/paras['Repair Time'][1])**paras['Repair Time'][0
          ])
          def wb90(x):
              return 1-np.exp(-(x/paras['Repair Time'][1])**paras['Repair Time'][0
          ])-0.9
          fsolve(wb90,[1])
```

```
Out[159]: array([33.40135005])
```

```
In [146]: wb(33.40135005)
```

```
Out[146]: 0.8999999999825136
```

Which subsystem displays the worst reliability?

```
In [148]:  R(50)

Out[148]:  0.827774072533606


In [150]:  def R_imp(t):
               return np.exp(-(t*(paras['D'])+sum([(t/paras[i][1])**paras[i][0] for
           i in ['A','C','E']]))))
           R_imp(50)

Out[150]:  0.9556806657659889


In [162]:  def R_solve(c):
               t = 50
               return np.exp(-(t*(1/c+paras['D'])+sum([(t/paras[i][1])**paras[i][0]
           for i in ['A','C','E']]))))-0.9
           fsolve(R_solve,[1])

Out[162]:  array([832.92988569])


In [163]:  def R_imp(t):
               return np.exp(-(t*(paras['D']+1/832.92988569)+sum([(t/paras[i][1])**
           paras[i][0] for i in ['A','C','E']])))
           R_imp(50)

Out[163]:  0.9000000000000954


In [165]:  np.exp(-50/fsolve(R_solve,[1])[0])

Out[165]:  0.9417371641380229


In [ ]:
```

```python
In [1]: import numpy as np
        import pandas as pd
        import matplotlib.pyplot as plt
        from scipy.stats import norm
        from sklearn.linear_model import LinearRegression
```

```python
In [2]: df = pd.read_csv("4.csv")
```

```python
In [3]: df = df.set_index('(mm)')
        df.head(2)
```

Out[3]:

(mm)	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6	Specimen 7	Specimen 8	S
9.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	
9.2	5529.0	5630.0	8502.0	9063.0	6109.0	6840	6078.0	6366.0	

a

Obtained results for optimal θ and β from an Excel add-in (real-statistics) for censored TTF data for Weibull data (https://www.real-statistics.com/distribution-fitting/distribution-fitting-via-maximum-likelihood/weibull-with-multi-censored-data/ (https://www.real-statistics.com/distribution-fitting/distribution-fitting-via-maximum-likelihood/weibull-with-multi-censored-data/))

```python
In [4]: t = 166420.226
        b = 1.07888043
```

```python
In [5]: alphas = [.1,.25,.5,.75,.9]
        for a in alphas:
            print(a, np.exp(((np.log(-np.log(1-a)))/b)+np.log(t)))

        0.1 20669.93774535842
        0.25 52442.03519397936
        0.5 118486.62598664196
        0.75 225263.0986931237
        0.9 360528.0322513916
```
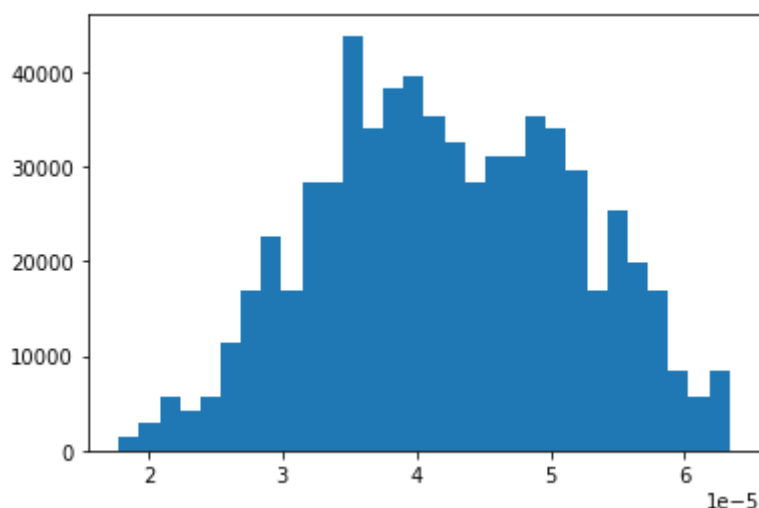
b

```
In [4]: values = []
        for index, row in df.iterrows():
            for col in df.columns:
                if np.isnan(row[col]):
                    continue
                values.append((index-9)/row[col])
```

```
<ipython-input-4-c96cccd5ba18>:6: RuntimeWarning: invalid value encount
ered in double_scalars
  values.append((index-9)/row[col])
```

```
In [5]: plt.hist(values, density=True, bins=30)   # density=False would make coun
        ts
        plt.show()
```



```
In [6]: datasets = []
        for col in df.columns:
            temp = df[col].dropna()
            temp2 = [[i] for i in temp.tolist()]
            datasets.append((np.array(temp2),list(temp.index)))
        paras = []
        for ds in datasets:
            reg = LinearRegression().fit(ds[0], ds[1])
            paras.append((reg.intercept_,reg.coef_[0]))
```

```
In [7]: b0 = [i[0] for i in paras]
        b1 = [i[1] for i in paras]
        mu1 = np.mean(b0)
        mu2,sigma2 = np.mean(b1), np.std(b1)
```

```
In [8]: print(mu1)
        print(mu2,sigma2)
```

```
8.397935719833548
5.273142846989178e-05 8.96857984216601e-06
```

```
In [9]:  alphas = [.1,.25,.5,.75,.9]
         for a in alphas:
             print(a, ((15-mu1)/mu2)/(1-(norm.ppf(a)*sigma2/mu2)))
```

```
0.1 102795.66099119555
0.25 112316.97835407344
0.5 125201.69606131667
0.75 141425.69116837715
0.9 160097.66131363285
```

c

```
In [10]:  datasets = []
          for col in df.columns:
              temp = df[col].dropna()
              temp2 = [[i] for i in temp.tolist()]
              datasets.append((np.array(temp2),list(temp.index)))
```

```
In [11]:  paras = []
          for ds in datasets:
              reg = LinearRegression().fit(ds[0], ds[1])
              paras.append((reg.intercept_,reg.coef_[0]))
```

```
In [12]:  paras
```

```
Out[12]:  [(8.450164920576583, 6.049736997913594e-05),
           (8.393495930149058, 5.8396000329688914e-05),
           (8.326126086470293, 5.2720157664771053e-05),
           (8.581878706294306, 3.948956843744145e-05),
           (8.219714093847719, 5.936038054956756e-05),
           (7.934458348505408, 6.658446055109067e-05),
           (8.516418007102576, 5.566229060232148e-05),
           (8.31240549788686, 6.018848739924009e-05),
           (8.412326337331098, 5.649477009969021e-05),
           (8.206963892180443, 6.345300642150366e-05),
           (8.434316734321353, 4.812507103998807e-05),
           (8.555435717579321, 4.4691167712151454e-05),
           (8.449608113249457, 4.650482330749459e-05),
           (8.514525013632095, 3.555230309979747e-05),
           (8.661198398376644, 4.325156985449416e-05)]
```

```
In [13]:  TTFs = [(15-x0)/x1 for x0,x1 in paras]
          TTFs

Out[13]:  [108266.44334592222,
           113132.81787369522,
           126590.55300946794,
           162527.00517285083,
           114222.41305361166,
           106113.97303539251,
           116480.68957886215,
           111110.85842302749,
           116606.78769104372,
           107056.17418180294,
           136429.58075268276,
           144202.19055203637,
           140854.03235356233,
           182420.6709805208,
           146556.5671476941]

In [14]:  from scipy.stats import weibull_min

In [15]:  shape, loc, scale = weibull_min.fit(TTFs, floc=0)

In [16]:  b,t = shape,scale
          b,t

Out[16]:  (5.739259313272218, 138468.62033053272)

In [17]:  for a in [.1,.25,.5,.75,.9]:
              print(a, np.exp((np.log(-np.log(1-a))/b)+np.log(t)))

          0.1 93554.39936058444
          0.25 111448.2199840619
          0.5 129902.35673642042
          0.75 146577.74924038793
          0.9 160126.5281687117
```

d

```
In [18]:  datasets = []
          for col in df.columns:
              temp = df[col].dropna()
              temp2 = [[i] for i in temp.tolist()]
              datasets.append((np.array(temp2),list(temp.index)))
          paras = []
          for ds in datasets:
              reg = LinearRegression().fit(ds[0], ds[1])
              paras.append((reg.intercept_,reg.coef_[0]))
```

```
In [19]: paras
```

Out[19]: [(8.450164920576583, 6.049736997913594e-05),
         (8.393495930149058, 5.8396000329688914e-05),
         (8.326126086470293, 5.2720157664771053e-05),
         (8.581878706294306, 3.948956843744145e-05),
         (8.219714093847719, 5.936038054956756e-05),
         (7.934458348505408, 6.658446055109067e-05),
         (8.516418007102576, 5.566229060232148e-05),
         (8.31240549788686, 6.018848739924009e-05),
         (8.412326337331098, 5.649477009969021e-05),
         (8.206963892180443, 6.345300642150366e-05),
         (8.434316734321353, 4.812507103998807e-05),
         (8.555435717579321, 4.4691167712151454e-05),
         (8.449608113249457, 4.650482330749459e-05),
         (8.514525013632095, 3.555230309979747e-05),
         (8.66119398376644, 4.325156985449416e-05)]

```
In [20]: b0 = [i[0] for i in paras]
         b1 = [i[1] for i in paras]
```

```
In [21]: mu1 = np.mean(b0)
         mu1
```

Out[21]: 8.397935719833548

```
In [22]: mu1 = np.mean(b0)
         mu2,sigma2 = np.mean(b1), np.std(b1)
         print(mu1)
         mu2,sigma2
```

8.397935719833548

Out[22]: (5.273142846989178e-05, 8.96857984216601e-06)

```
In [23]: df.head(2)
```

Out[23]:

	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Specimen 6	Specimen 7	Specimen 8	S
(mm)									
9.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	
9.2	5529.0	5630.0	8502.0	9063.0	6109.0	6840	6078.0	6366.0	

```
In [24]: res = []
         for index, row in df.iterrows():
             for col in df.columns:
                 if np.isnan(row[col]):
                     continue
                 res.append(index-(mu1+mu2*row[col]))
```

```
In [25]: eps = np.std(res)
         eps
```

Out[25]: 0.6338226825013553

```
In [26]: alphas = [.1,.25,.5,.75,.9]
         ts = [((15-mu1)/mu2)/(1-(norm.ppf(a)*sigma2/mu2)) for a in alphas]
         ts
```

Out[26]: [102795.66099119555,
          112316.97835407344,
          125201.69606131667,
          141425.69116837715,
          160097.66131363285]

```
In [ ]:
```

```
In [ ]:
```

```
In [27]:  B = 50000
          n = 15
          Fs = []
          timepoints = np.arange(0,121000,120000/35)
          for it in range(B):
              if it%100 == 1:
                  print(it)
              df2 = pd.DataFrame(index=timepoints)
              mu2s = np.random.normal(mu2, sigma2, n)
              for i in range(n):
                  df2[str(i+1)] = df2.index*mu2s[i]+mu1+np.random.normal(0,eps,36)

              datasets = []
              for col in df2.columns:
                  temp = df2[col]
                  temp2 = [[i] for i in temp.index]
                  datasets.append((np.array(temp2),list(temp.tolist())))
              paras = []
              for ds in datasets:
                  reg = LinearRegression().fit(ds[0], ds[1])
                  paras.append((reg.intercept_,reg.coef_[0]))
              b0 = [i[0] for i in paras]
              b1 = [i[1] for i in paras]
              mu1_ = np.mean(b0)
              mu2_,sigma2_ = np.mean(b1), np.std(b1)
              Fs.append([(time-(15-mu1_)/mu2_)/(sigma2_*time/mu2_) for time in ts
          ])
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In [28]: mu1_,mu2_,sigma2_

Out[28]: (8.339634638736586, 5.441128552842717e-05, 7.4960437653152e-06)

```
In [29]: Fs
```

```
Out[29]:  [[-1.4191510312291276,
          -0.6550661610866064,
          0.19388760302909375,
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          1.8069262372873158],
         [-1.332602117660454,
          -0.8502674881192323,
          -0.3143586966835458,
          0.2215500947521412,
          0.7038847242933628],
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In [36]: `F = [[norm.cdf(j) for j in i] for i in Fs]`

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```

In [44]: `norm.ppf(.975)`

Out[44]: 1.959963984540054

In [46]: `norm.cdf(1.959963984540054)`

Out[46]: 0.975

```
In [66]: F_array = np.array(newF)
         # B
         alpha = 0.1
         for i,(a,t) in enumerate(zip(alphas,ts)):
             curr_F = F_array[:,i]
             q = sum(curr_F<a)/B
             l = B*norm.cdf(2*norm.ppf(q)+2*norm.ppf(alpha/2))
             u = B*norm.cdf(2*norm.ppf(q)+2*norm.ppf(1-alpha/2))
         #     print(q)
         #     print(norm.ppf(q))
             print(t)
             print(a)
             print(curr_F[round(u)],curr_F[round(l)])
             print(l,u)
```

```
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112316.97835407344
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```

In [51]:

Out[51]: array([3.51532829e-06, 1.61140396e-05, 3.40294152e-04, ...,
                2.14385681e-01, 3.82396012e-02, 3.99804596e-01])

In [ ]: