Reliability analysis of SISs against CAFs during prolonged demands

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Background

- Safety instrumented system (SIS)
- Equipment under control (EUC)
- Demands
- Cascading failures (CAF)

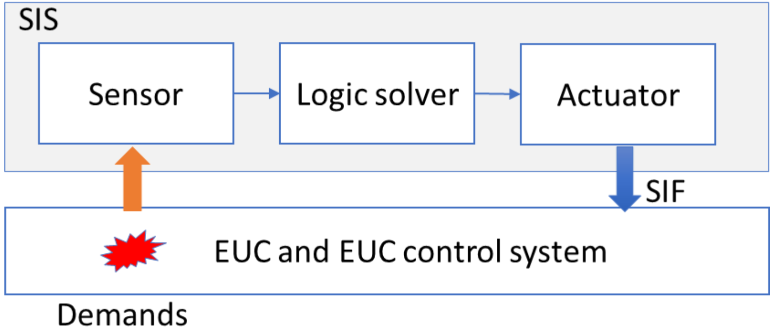

Fig. 1 Illustration of SISs and EUC

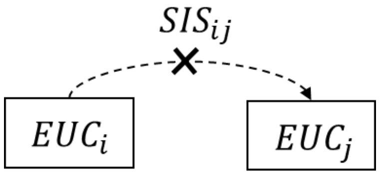

Fig. 2 CAFs within EUCs and SIS

Background

- **Prolonged** demands
  - A deterministic or stochastic period
- **Stress** during demands
  - High failure rates
  - Degradation

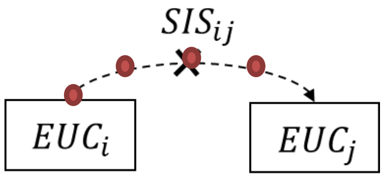

Fig. 2 CAFs within EUCs and SIS

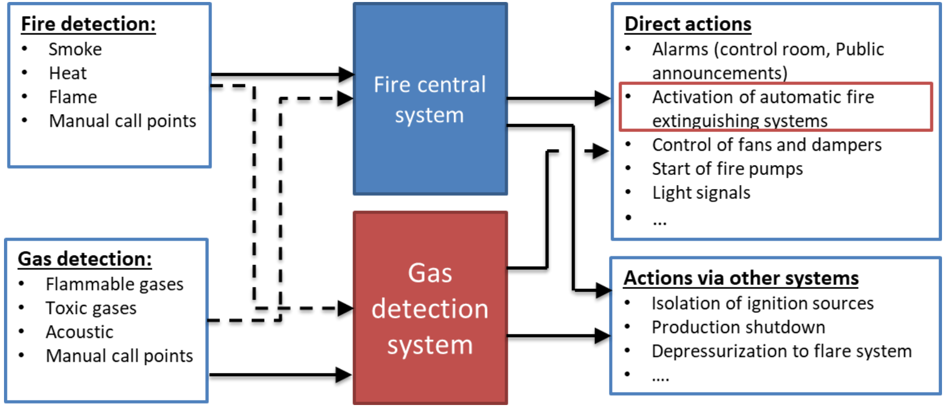

Fig. 3 an example of SIS with prolonged demands

Problems

- Q1:

  SIS performance → SIS ?

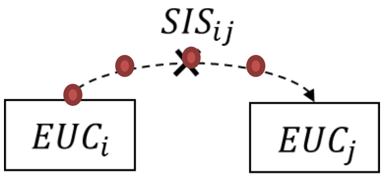

Fig. 2 CAFs within EUCs and SIS

- Q2:

  The failures on activation → PFDavg ?

  The failures during demands → ?

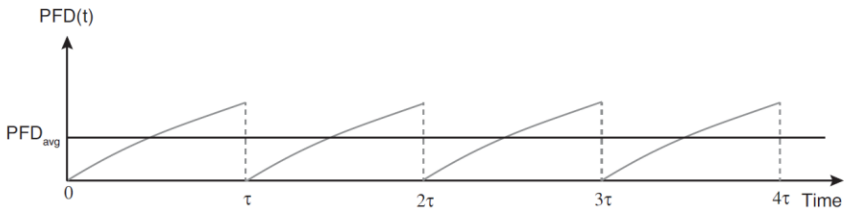

Fig. 4 PFDavg for Low demand SISs

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Objectives

- Propose a new method for modeling SISs to prevent CAFs during prolonged demands
  - SIS performance assessment from system perspective (EUC systems)
  - Consider the failures on demand(FODs) and the failures during demands (FDDs)

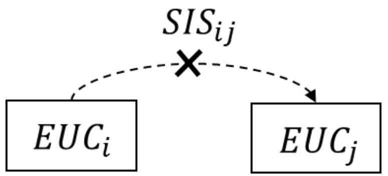


Fig. 2 CAFs within EUCs and SIS

Assumptions

- For any EUC components and SISs, only two states are considered: functioning or failed.
- The time to failure within EUC components and SISs follows known distributions.
- CAFs are concerned for EUC systems.
- Multiple CAFs can simultaneously occur, and the propagation time is negligible.
- Repairs after any failures are not considered.

Modeling CAFs

- Cascading probability [1]:
  - a measure of the easiness of this failure propagation

$$\gamma_i = \Pr(\text{propagation from } EUC_i \,|EUC_i \text{ failed })$$

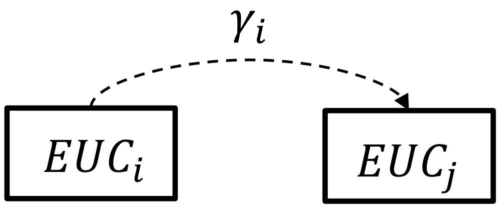
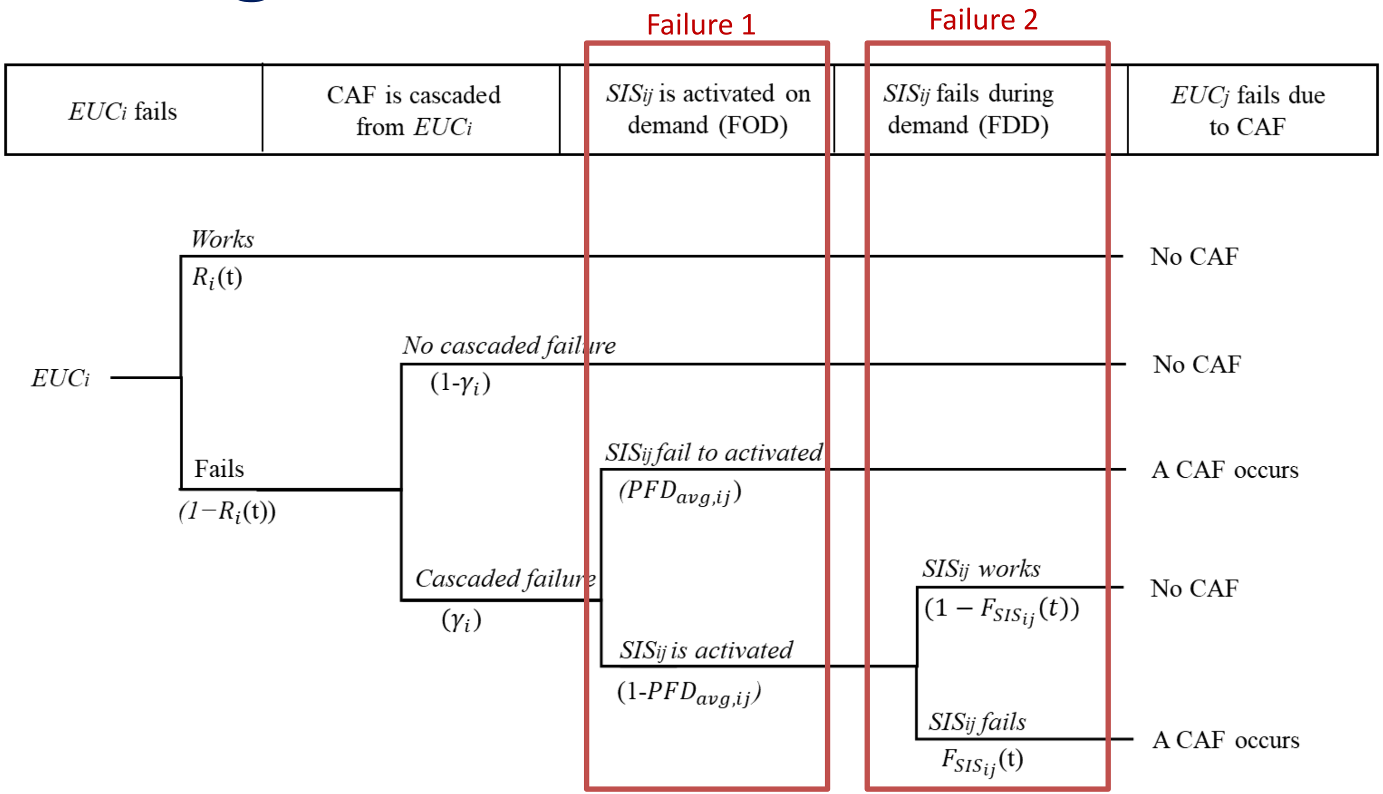


Fig. 5 CAFs within EUCs

[1] Levitin G et al. Reliability of series-parallel systems with random failure propagation time

Modeling SISs



Modeling SISs

$P_{ij}(t) = P_r(SIS_{ij} \text{ fails by time } t)$

$= PFD_{avg,ij} + (1 - PFD_{avg,ij})P(T_{SIS} \leq (t - t_i))$

Failure 1 Failure 2

$\bar{P}_{ij}(t) = P_r(SIS_{ij} \text{ works by time } t)$

$= (1 - PFD_{avg,ij})P(T_{SIS} \geq (t - t_i))$

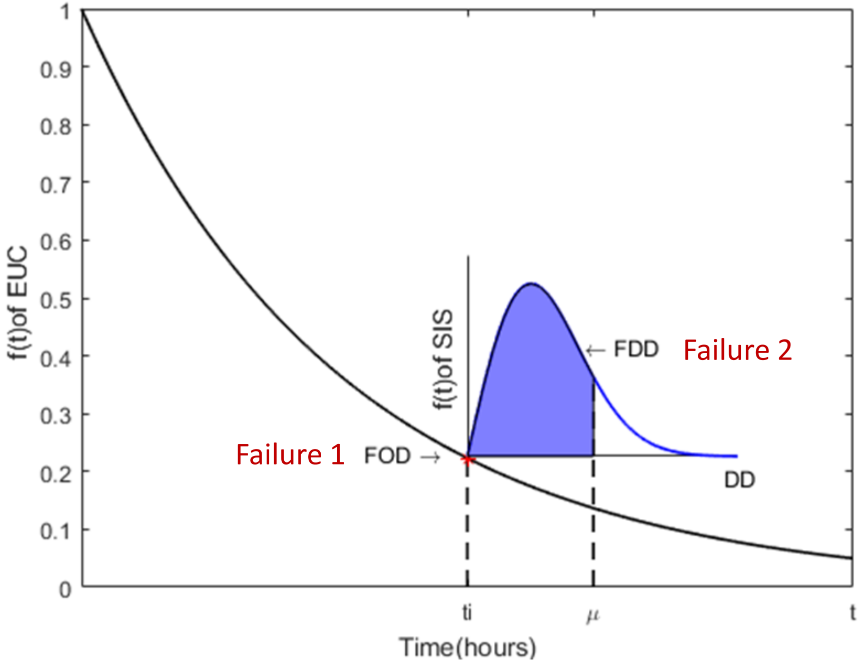


Fig. 6 failures within EUC and SISs

Conditional reliability

- Conditional reliability

$$\tilde{R}_i(t) = \frac{R_i(t)}{1-\gamma_i \bar{R}_i(t)} \qquad \frac{①}{① + ②}$$

- Conditional system reliability

$$\tilde{R}_{\Omega,\mathrm{S}}(t) = \underline{\tilde{R}_i(t)} R_j(t)$$

$$\tilde{R}_{\Omega,\mathrm{P}}(t) = 1 - \left(1 - \underline{\tilde{R}_i(t)}\right)\left(1 - R_j(t)\right)$$

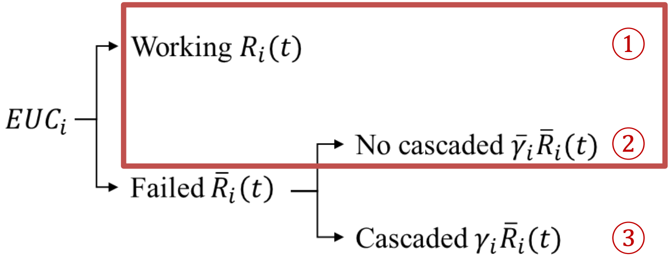


Fig. 7 three scenarios within EUC

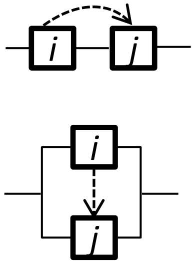


Fig. 8 series and parallel of EUC

Reliability of EUC systems

- Consider one CAF

$$R_S(\mathrm{t}) = \underline{P_r(No\ CAF\ )}\widetilde{\mathrm{R}}_{\Omega_n}(t) + \underline{P_r(CAF\ event\ occurs\ )}\left[\underbrace{P_{ij}(t)\widetilde{\mathrm{R}}_{\Omega_{n-(i,j)}}(t)}_{\text{SIS fails}} + \underbrace{\bar{P}_{ij}(t)\widetilde{\mathrm{R}}_{\Omega_{n-i}}(t)}_{\text{SIS works}}\right]$$

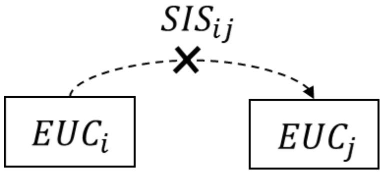


Fig. 2 CAFs within EUCs and SIS

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Reliability of EUC systems

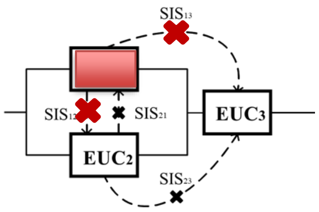

Fig. 10 illustrative example

- Consider multiple CAFs

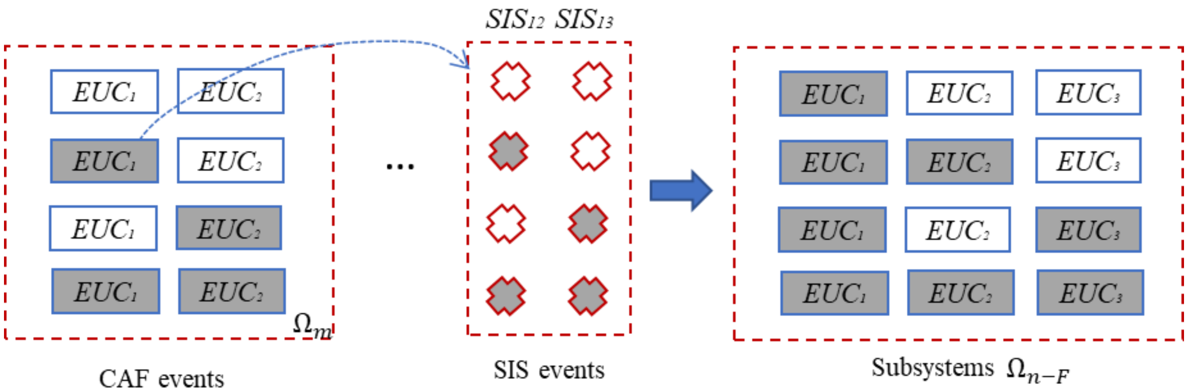

Fig. 9 CAFs events and SIS events

Reliability of EUC systems

- Consider multiple CAFs
  - CAF event probability: $\theta_a(t) = \prod_{i=1}^{m} [\gamma_i \bar{R}_i(t)]^{mod\left(\left\lfloor \frac{a-1}{2^{i-1}} \right\rfloor, 2\right)} [1 - \gamma_i \bar{R}_i(t)]^{\left(1 - mod\left(\left\lfloor \frac{a-1}{2^{i-1}} \right\rfloor, 2\right)\right)}$
  - SIS event probability: $\delta_{h,g}(t) = \frac{\int_0^t f_h(t_h) \prod_{j=1}^{l} [P_{h,j}(t)]^{mod\left(\left\lfloor \frac{g-1}{2^{j-1}} \right\rfloor, 2\right)} [\bar{P}_{h,j}(t)]^{\left(1 - mod\left(\left\lfloor \frac{g-1}{2^{j-1}} \right\rfloor, 2\right)\right)} dt_h}{\int_0^t f_h(t) dt}$
  - Conditional reliability: $\tilde{R}_{\Omega_{n-F}}(t)$
- System reliability:

$$R_S(\mathrm{t}) = \sum_{a \in \forall(1,2 \ldots 2^m)} \prod_{h \in \forall \Omega_a} \sum_{g=1}^{2^l} \delta_{h,g}(t)\, \tilde{R}_{\Omega_{n-F}}(t)\, Q_a(t)$$

= CAF event · SIS event · Conditional R

Illustrative example

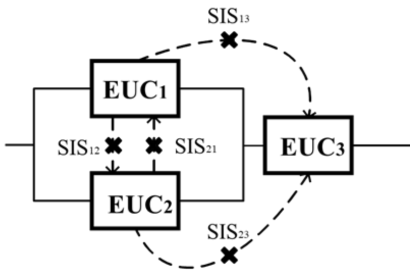

Fig. 10 illustrative example

- Step 1: Conditional reliabilities

$$\tilde{R}_1(t) = \frac{R_1(t)}{1-\gamma_1\bar{R}_1(t)} \qquad \tilde{R}_2(t) = \frac{R_2(t)}{1-\gamma_2\bar{R}_2(t)}$$

- Step 2: CAF events probabilities:

$$\theta_1(t) = [1-\gamma_1\bar{R}_1(t)]\cdot[1-\gamma_2\bar{R}_2(t)] \quad \theta_2(t) = [\gamma_1\bar{R}_1(t)]\cdot[1-\gamma_2\bar{R}_2(t)] \quad \theta_3(t) = [1-\gamma_1\bar{R}_1(t)]\cdot[\gamma_2\bar{R}_2(t)]$$

- Step 3: SIS events probabilities:

$$\delta_{2,1}(t)=\frac{\int_0^t f_1(t_1)\left[(1-PFD_{avg,12})(1-\int_{t_1}^t f_{SIS\,12}(\mu-t_1)d\mu)\right]\left[(1-PFD_{avg,13})(1-\int_{t_1}^t f_{SIS\,13}(\mu-t_1)d\mu)\right]dt_1}{\int_0^t f_1(t)dt} \quad \ldots$$

- Step 4: Conditional reliability:

$$\tilde{R}_{\Omega_{n-1}}(t) = \tilde{R}_2(t)\tilde{R}_3(t) \quad \ldots$$

- Step 5: System reliability:

$$R_S(\mathrm{t}) = \theta_1(t)\,\tilde{R}_{\Omega_n}(t) + \theta_2(t)\delta_{2,1}(t)\tilde{R}_{\Omega_{n-1}}(t) + \theta_3(t)\delta_{3,1}(t)\tilde{R}_{\Omega_{n-2}}(t)$$

Verification

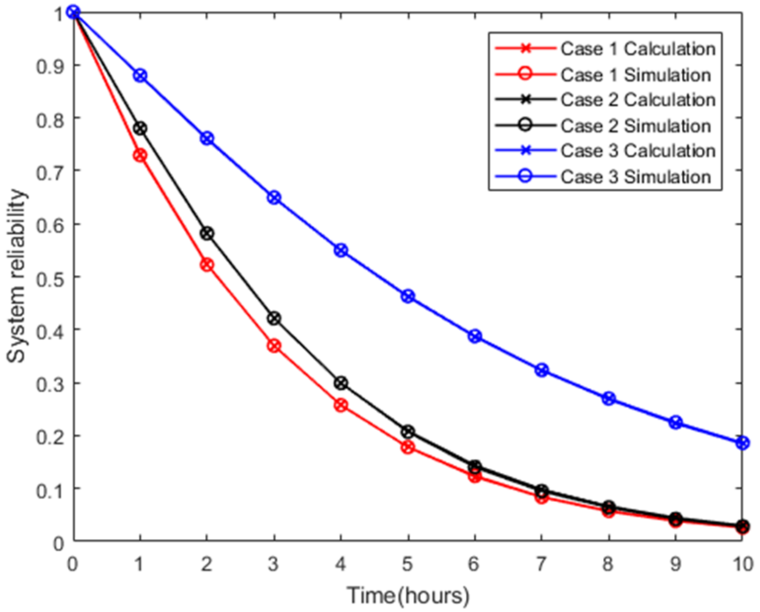

Fig. 11 system reliability using analytical method and simulations

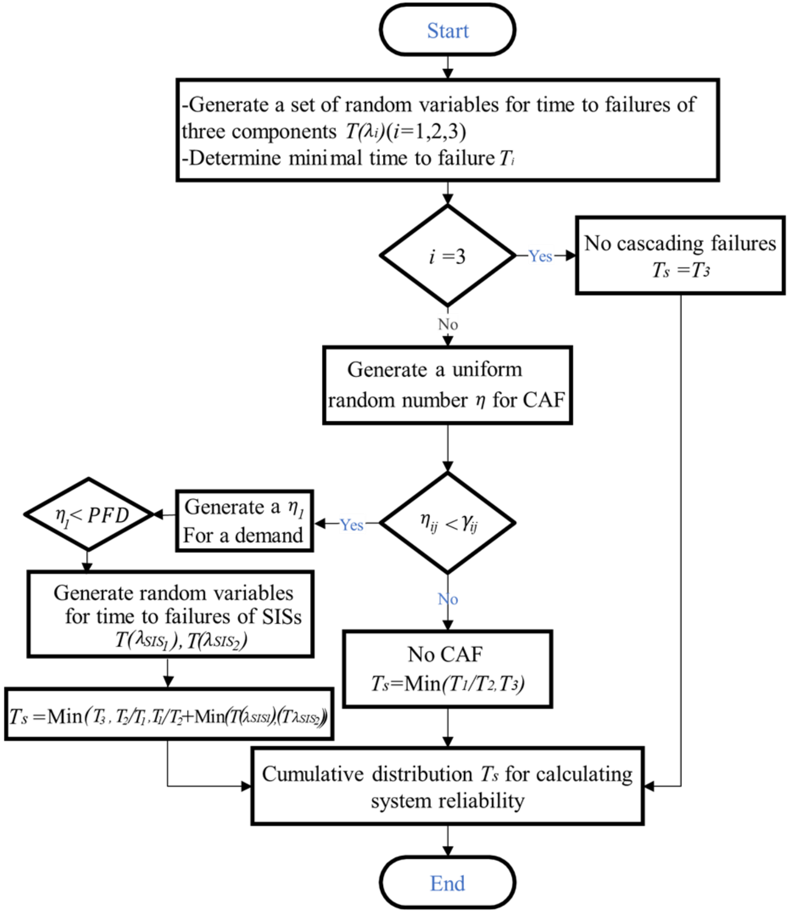

Fig. 12 flowchart of MCSs for failure propagations

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Case study

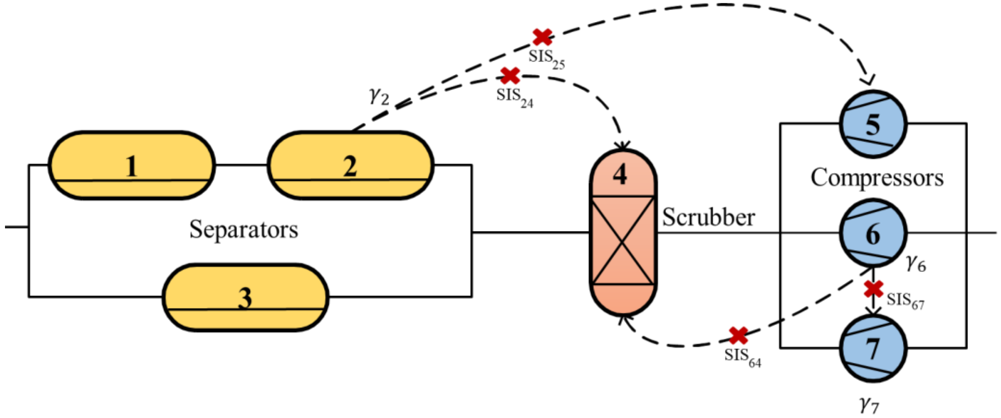


Fig. 13 RBD with CAFs and SISs in case study

Table 1 the parameters of the EUC components in the case study

EUC_i	Components	λ_{EUC} (/hour)	α_{EUC}
1	Separator 1	0.2145	1.4
2	Separator 2	0.1234	1.3
3	Separator 3	0.2367	1.2
4	Scrubber	0.1678	1.5
5	Compressor 1	0.3207	2.1
6	Compressor 2	0.3207	2.1
7	Compressor 3	0.3207	2.1

Table 1 parameters of the SISs in the case study

SIS_{ij}	FOD		FDD
	λ_{SIS}(/hour)	α_{SIS}	(PFD_{avg}, /year)
SIS_{24}	0.4157	2.0	10^{-1}
SIS_{25}	0.3253	2.0	10^{-1}
SIS_{64}	0.4134	2.0	10^{-1}
SIS_{67}	0.1789	2.0	10^{-1}

System reliability

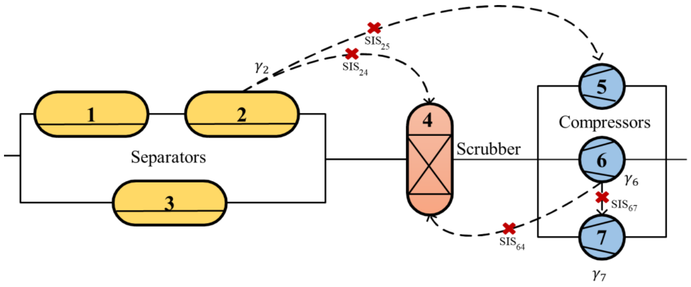


Fig. 13 RBD with CAFs and SISs in case study

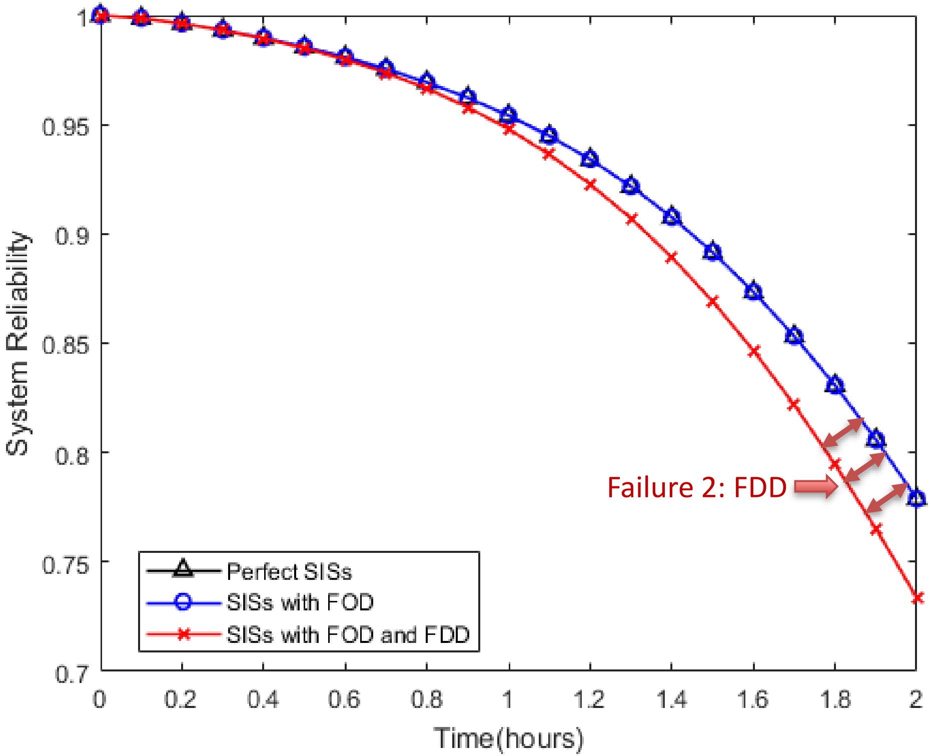


Fig. 14 system reliability profiles with different SISs

Sensitivity analysis

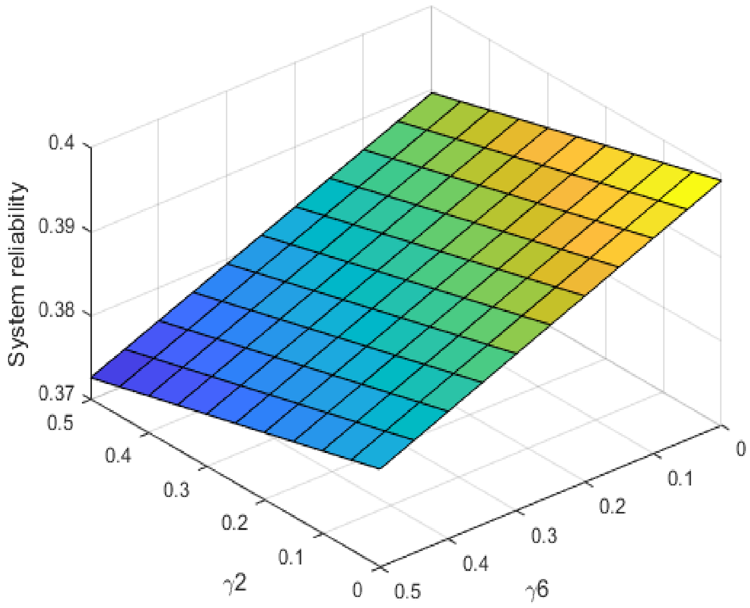
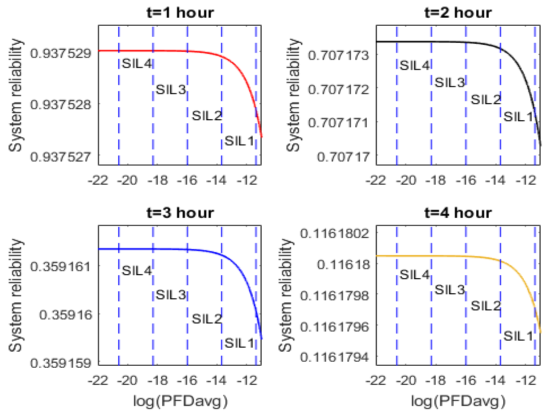
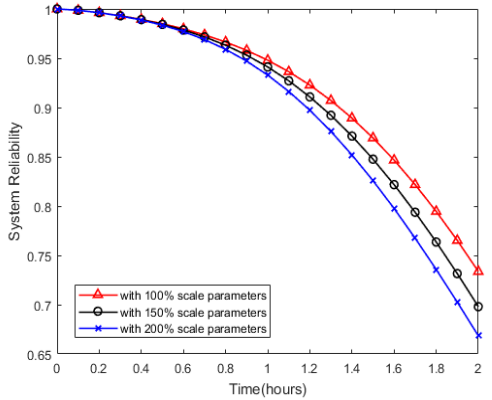


Fig. 15 system reliability with γ_2 and γ_6 at $t = 2$ hours



Failure 1: FOD



Failure 2: FDD

Importance evaluation

Table 3 System reliability with multiple SISs at $t = 2$ hours

No.	SIS	R(t)	$I_B(i\|t)$(%)	cost	I_B/cost(%/a)
1	No	0.56	-	-	-
2	SIS_{24}	0.59	5.60	a	5.60
3	SIS_{25}	0.56	0.02	a	0.02
4	SIS_{64}	0.64	15.60	a	15.6
5	SIS_{67}	0.56	0.02	a	0.02
6	SIS_{24}, SIS_{25}	0.59	5.83	$2a$	2.92
7	SIS_{24}, SIS_{64}	0.68	21.21	$2a$	10.6
8	SIS_{24}, SIS_{67}	0.59	5.60	$2a$	2.80
9	SIS_{25}, SIS_{64}	0.64	15.60	$2a$	7.80
10	SIS_{25}, SIS_{67}	0.56	0.02	$2a$	0.01
11	SIS_{64}, SIS_{67}	0.67	19.98	$2a$	9.99
12	$SIS_{24}, SIS_{25}, SIS_{64}$	0.68	22.25	$3a$	7.42
13	$SIS_{24}, SIS_{25}, SIS_{67}$	0.59	5.83	$3a$	1.94
14	$SIS_{24}, SIS_{64}, SIS_{67}$	0.70	26.37	$3a$	8.79
15	$SIS_{25}, SIS_{64}, SIS_{67}$	0.67	19.98	$3a$	6.66
16	$SIS_{24}, SIS_{25}, SIS_{64}, SIS_{67}$	0.71	26.94	$4a$	6.74

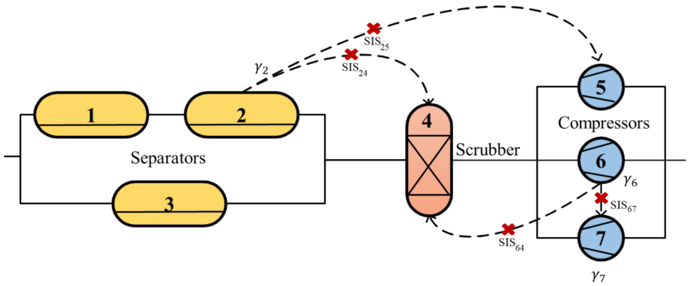


Fig. 13 RBD with CAFs and SISs in case study

Importance evaluation

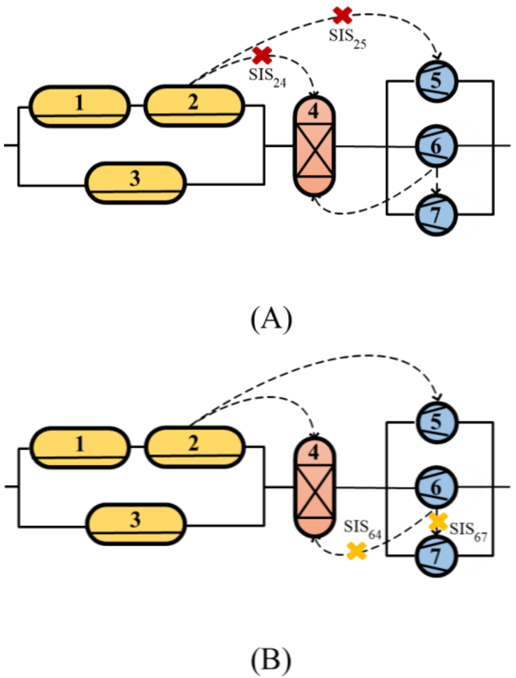


Fig. 16 two options of the SISs against CAFs

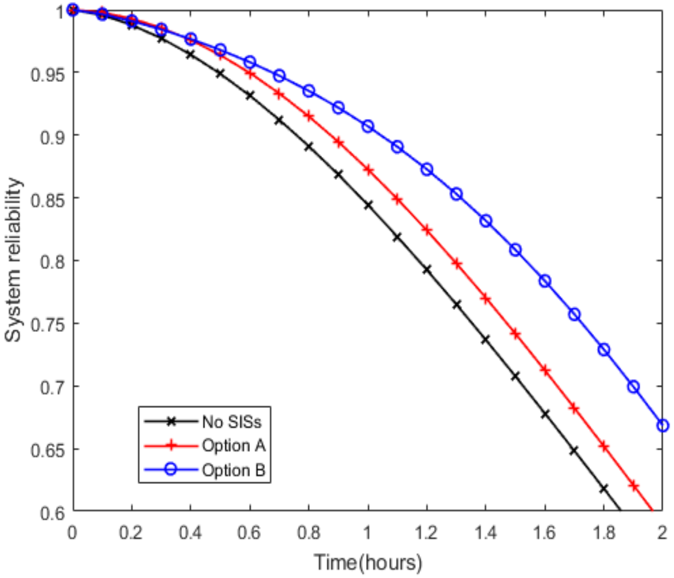


Fig. 17 system reliability of two options of SISs

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Conclusions & future works

- SISs against CAFs within EUC considering FOD and FDD.
- Apply for other industrial series-parallel systems.
- Improve its numerical efficiency.
- Future works can be time-dependent cascading probability, complex systems, maintenance optimization…

Questions……