POLITECNICO DI MILANO

CRC
Centre de recherche sur les Risques et les Crises

Introduction to Monte Carlo Simulation

The experimental view

Enrico Zio

CONTENTS

- Sampling Random Numbers
- Simulation of system transport
- Simulation for reliability/availability analysis of a component
- Examples

The History of Monte Carlo Simulation

Buffon — *1707-88*

↓

Kelvin — *1824-1907*

↓

Gosset (Student) — *1908*

↓

Fermi, von Neumann, Ulam — *1930-40's*

↓

Neutron transport — *1950's*

↓

System Transport (RAMS) — *1990's*

SAMPLING RANDOM NUMBERS

Example: Exponential Distribution

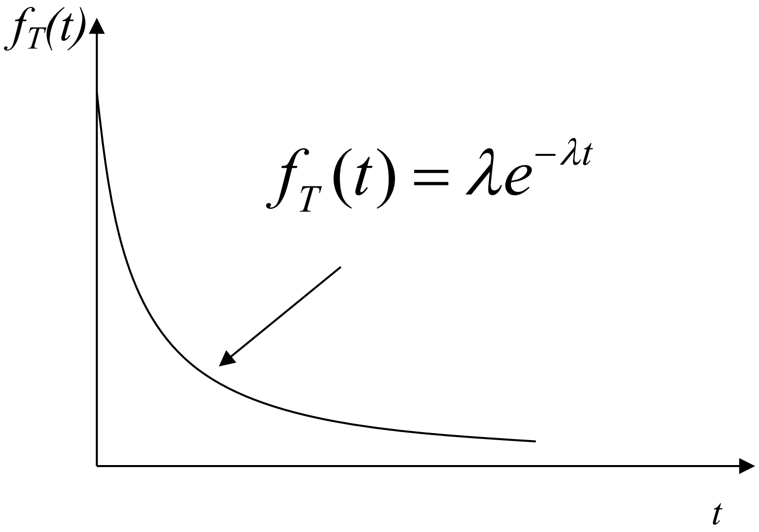
Probability density function:

$$f_T(t) = \lambda e^{-\lambda t} \qquad t \geq 0$$
$$= 0 \qquad t < 0$$

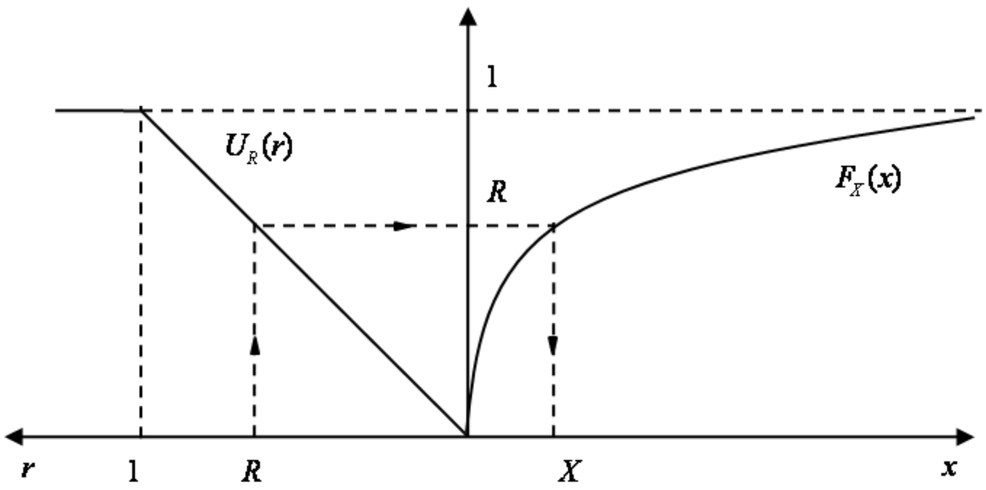
Expected value and variance:

$$E[T] = \frac{1}{\lambda}$$

$$Var[T] = \frac{1}{\lambda^2}$$



Sampling Random Numbers from $F_X(x)$



Sample R from $U_R(r)$ and find X:

$$X = F_X^{-1}(R)$$

Example: Exponential distribution

$$F_X(x) = 1 - e^{-\lambda x}$$

$$R = F_X(x) = 1 - e^{-\lambda x}$$

$$\Downarrow$$

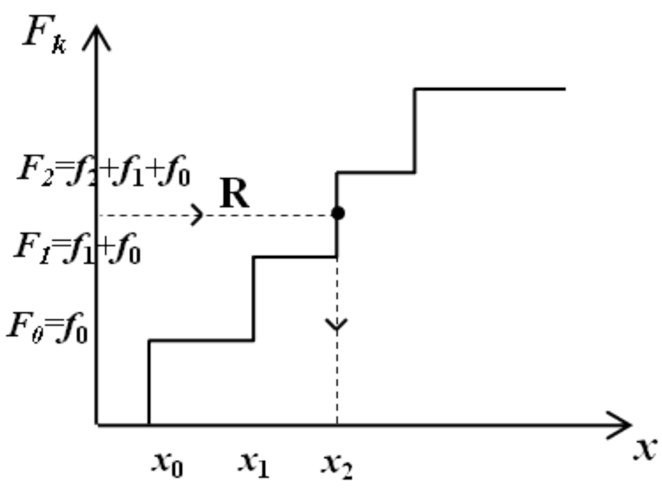
$$X = F_X^{-1}(R) = -\frac{1}{\lambda}\ln(1-R)$$

Sampling from discrete distributions

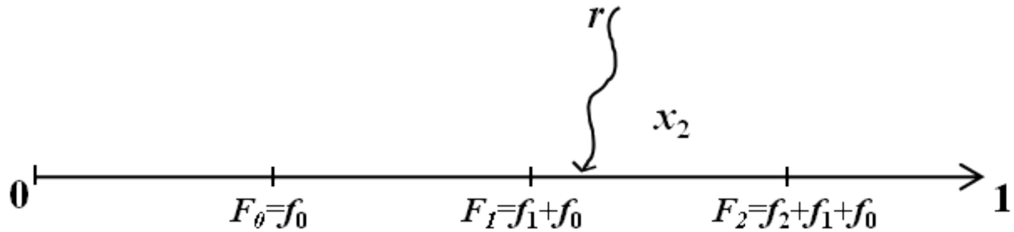
$$\Omega = \{x_0, x_1, \ldots, x_k, \ldots\}$$

$$F_k = P\{X \le x_k\} = \sum_{i=0}^{k} P[X = x_i]$$

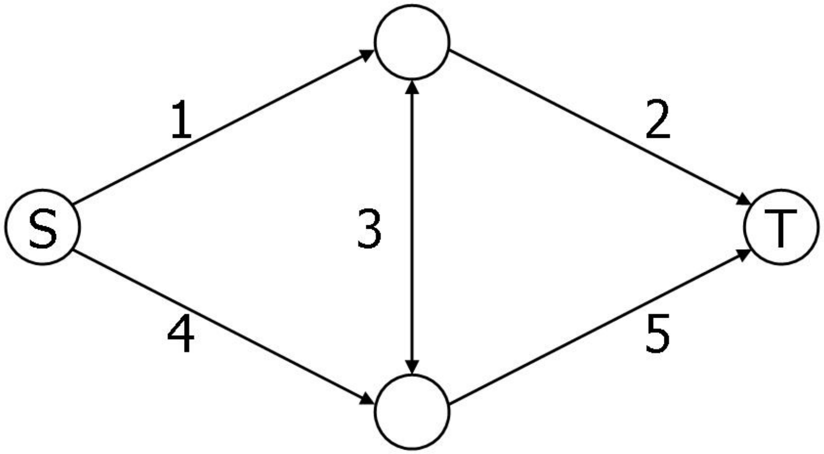
sample an $R \sim U[0,1)$



Graphically:



Failure probability estimation: example



Arc number i	*Failure probability P_i*
1	0.050
2	0.025
3	0.050
4	0.020
5	0.075

- **1- Calculate the analytic solution for the failure probability of the network, i.e., the probability of no connection between nodes S and T**

- **2- Repeat the calculation with Monte Carlo simulation**

SIMULATION OF SYSTEM TRANSPORT

Monte Carlo simulation for system reliability

PLANT = system of *Nc* suitably connected components.

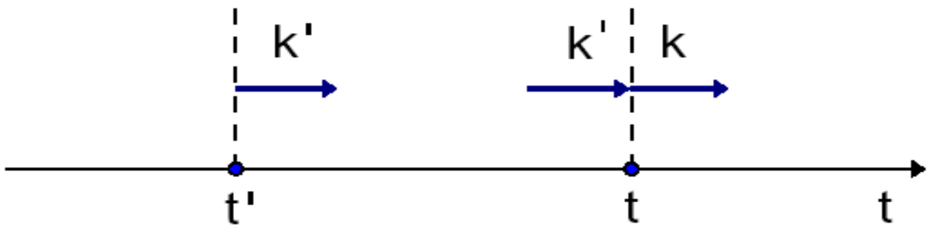
COMPONENT = a subsystem of the plant (pump, valve,...) which may stay in different exclusive (multi)states (nominal, failed, stand-by,...). Stochastic transitions from state-to-state occur at stochastic times.

STATE of the PLANT at t = the set of the states in which the *Nc* components stay at t. The states of the plant are labeled by a scalar which enumerates all the possible combinations of all the component states.

PLANT TRANSITION = when any one of the plant components performs a state transition we say that the plant has performed a transition. The time at which the plant performs the n-th transition is called t_n and the plant state thereby entered is called k_n.

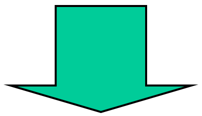
PLANT LIFE = stochastic process.

Stochastic Transitions: Governing Probabilities



- $T(t\,/\,t';\,k')dt$ = conditional probability of a transition at t∈dt, given that the preceding transition occurred at *t'* and that the state thereby entered was *k'*.
- $C(k\,/\,k';\,t)$ = conditional probability that the plant enters state *k*, given that a transition occurred at time *t* when the system was in state *k'*. Both these probabilities form the "trasport kernel":

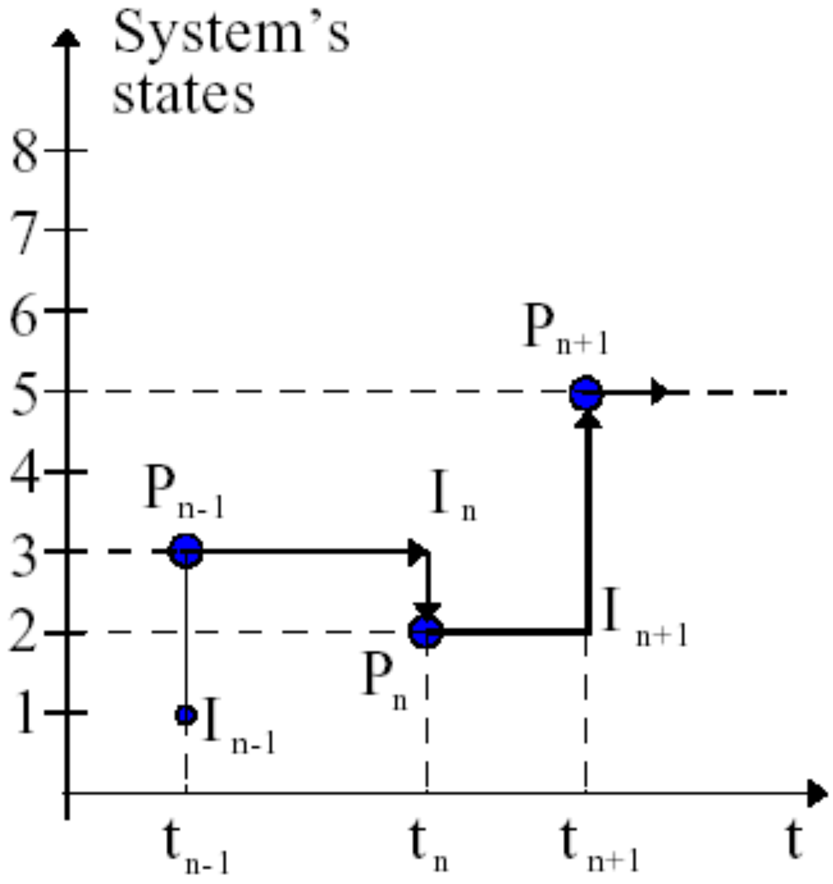
$$K(t;\,k\,/\,t';\,k')dt = T(t\,/\,t';\,k')dt\;C(k\,/\,k';\,t)$$



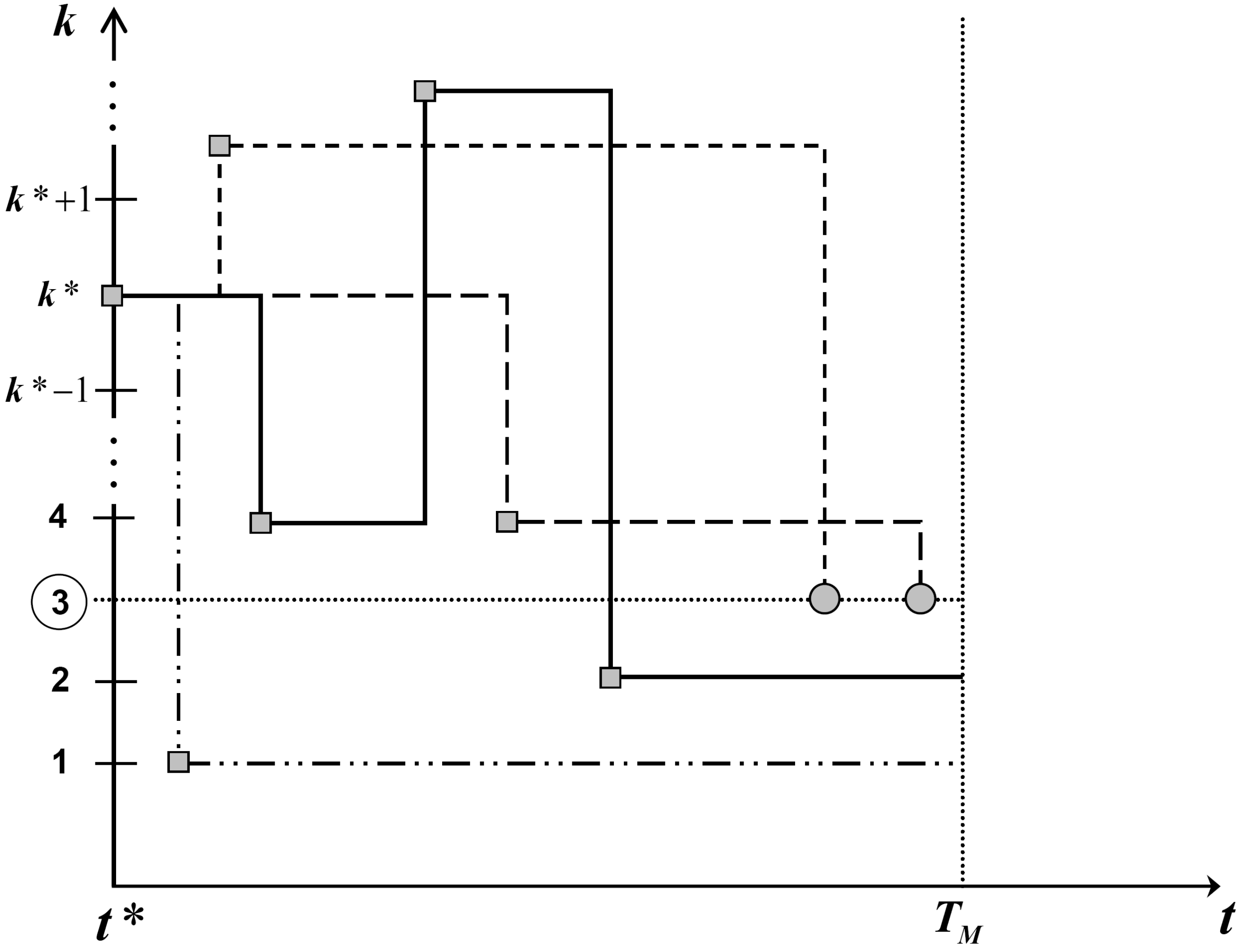
- $\psi(t;\,k)$ = ingoing transition density or probability density function (pdf) of a system transition at *t*, resulting in the entrance in state *k*

Plant life: random walk

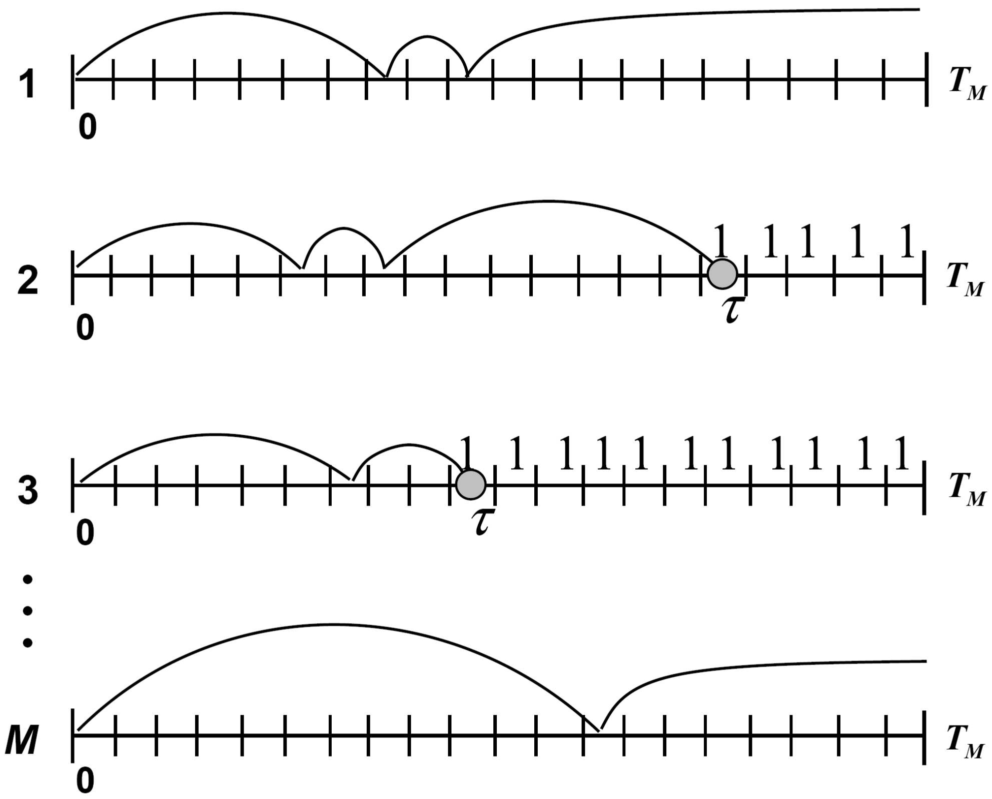
Random walk = realization of the system life generated by the underlying state-transition stochastic process.



Phase Space



Example: System Reliability Estimation



$$C^R(t) = C^R(t) \quad t \in [0, T_M]$$

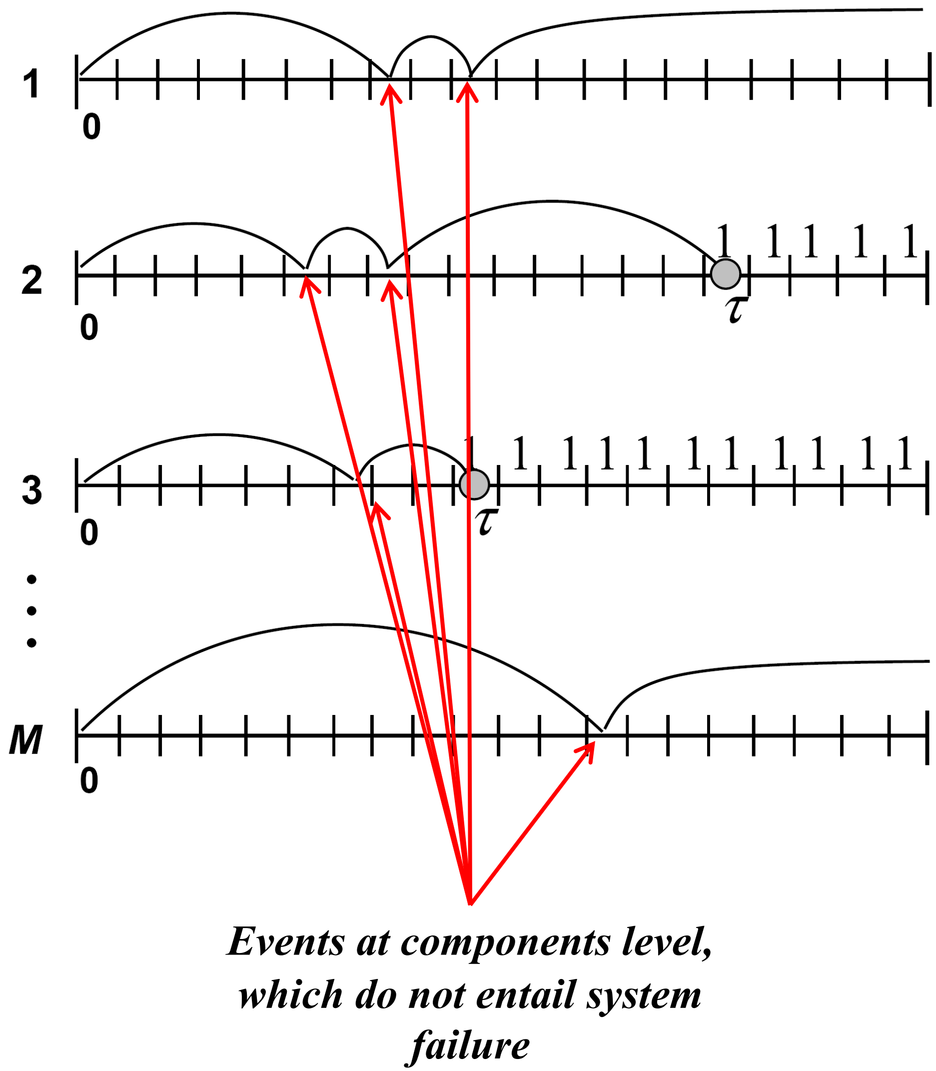
$$C^R(t) = C^R(t) + 1 \quad t \in [\tau, T_M]$$

$$C^R(t) = C^R(t) + 1 \quad t \in [\tau, T_M]$$

$$C^R(t) = C^R(t) \quad t \in [0, T_M]$$

$$\hat{F}_T(t) = \frac{C^R(t)}{M}$$

Example: System Reliability Estimation



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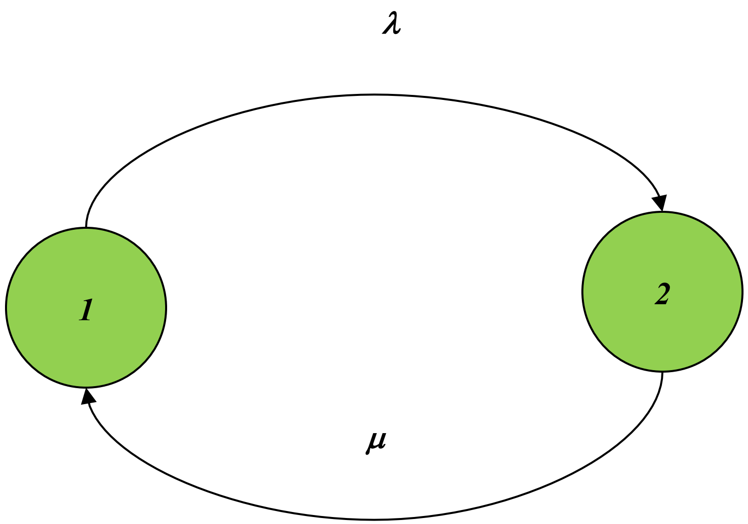
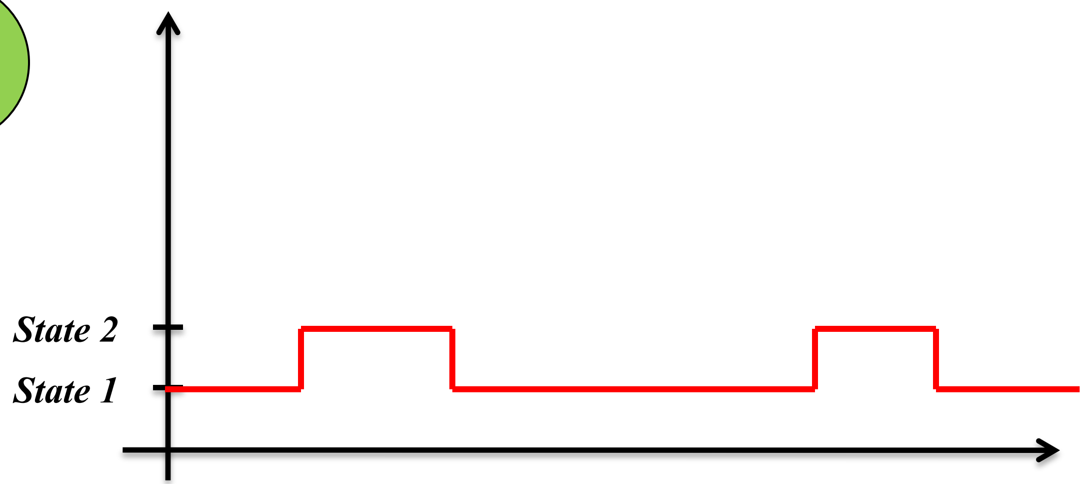
$$C^R(t) = C^R(t) \quad t \in [0, T_M]$$

$$\hat{F}_T(t) = \frac{C^R(t)}{M}$$

SIMULATION OF COMPONENT STOCHASTIC STATE TRANSITION PROCESS FOR AVAILABILITY / RELIABILITY ESTIMATION

One component with exponential distribution of the failure time

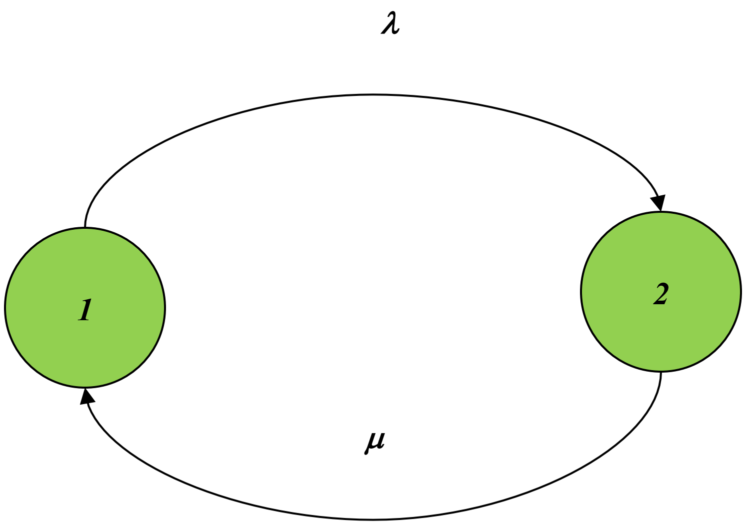


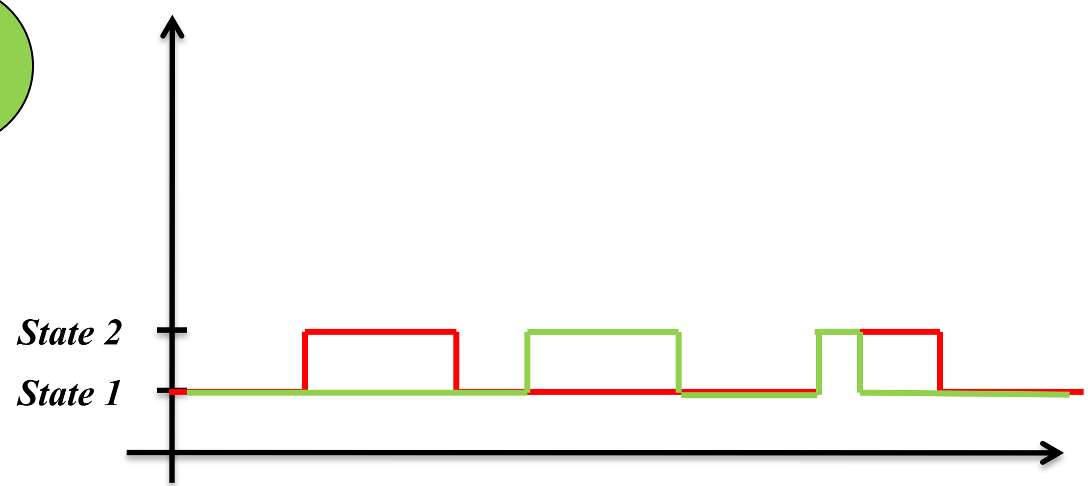


State X=1 → ON

State X=2 → OFF

One component with exponential distribution of the failure time





State X=1 → ON

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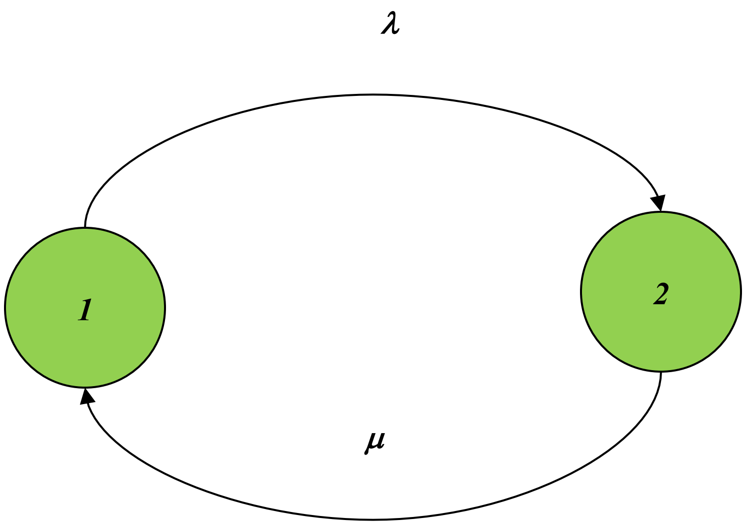
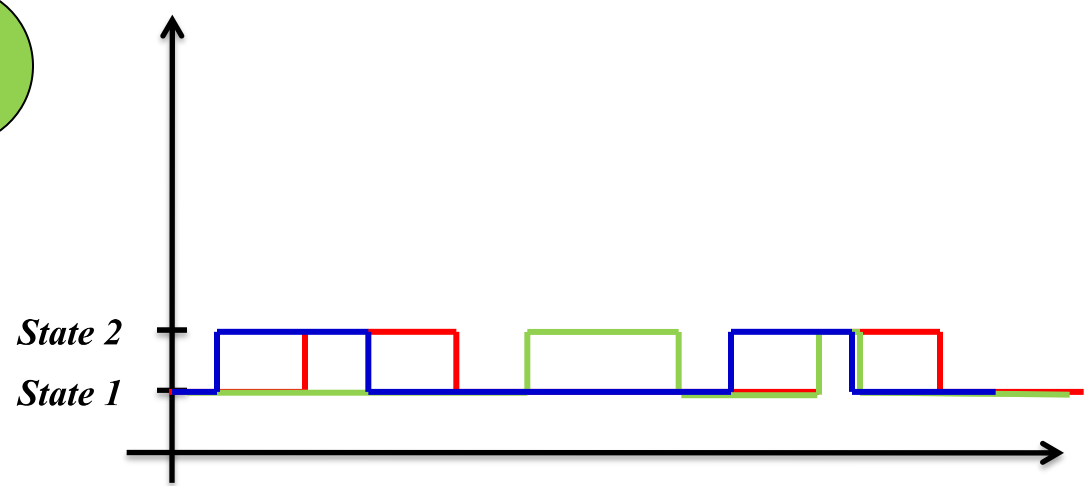
One component with exponential distribution of the failure time

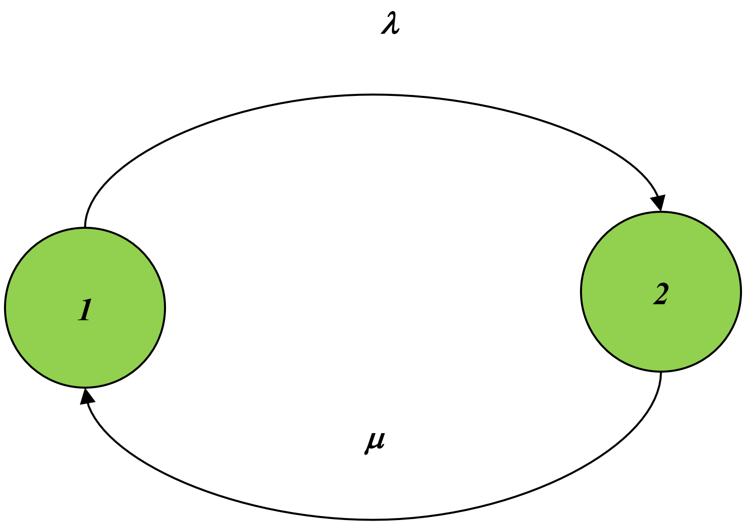




State X=1 → ON

State X=2 → OFF

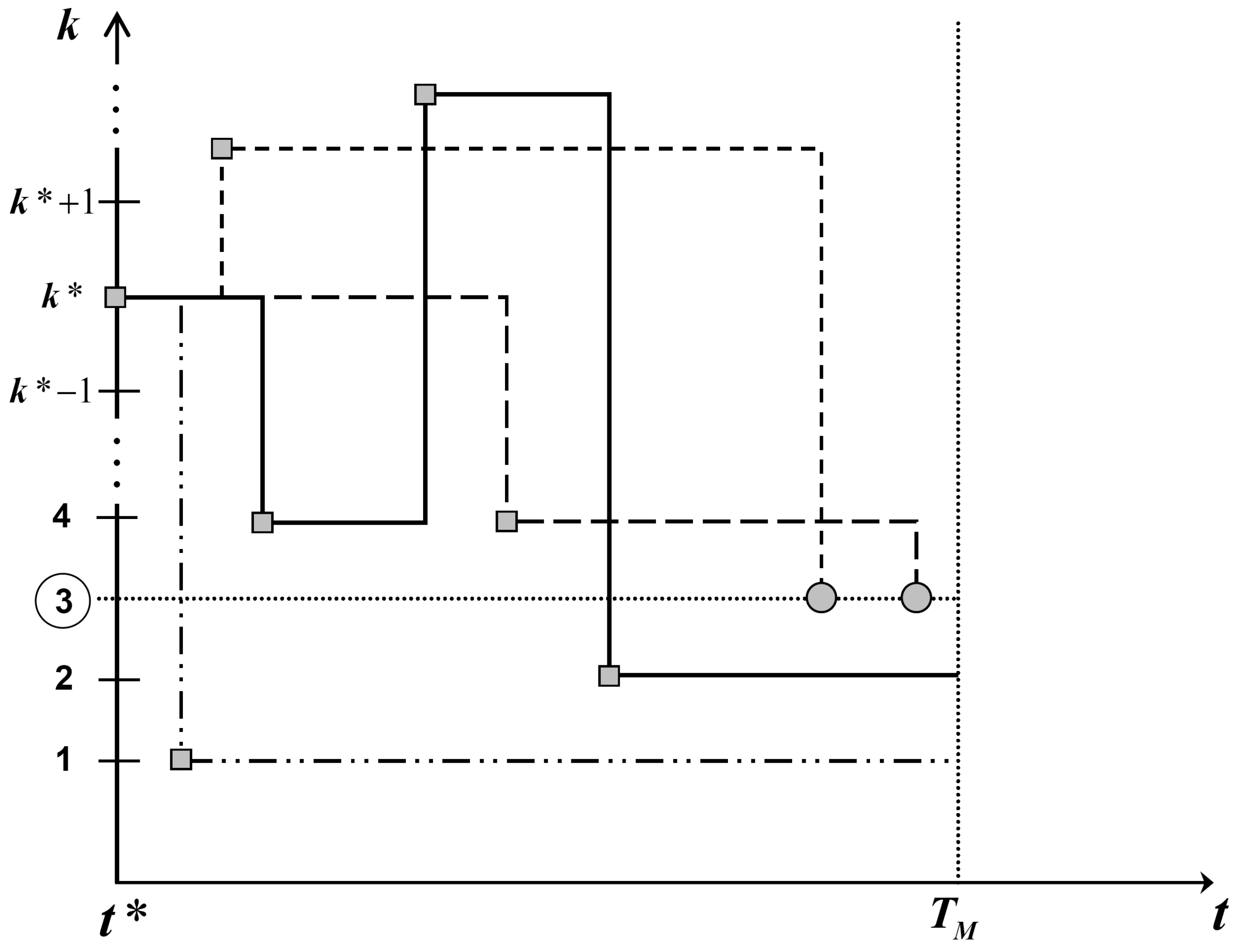
One component with exponential distribution of the failure time



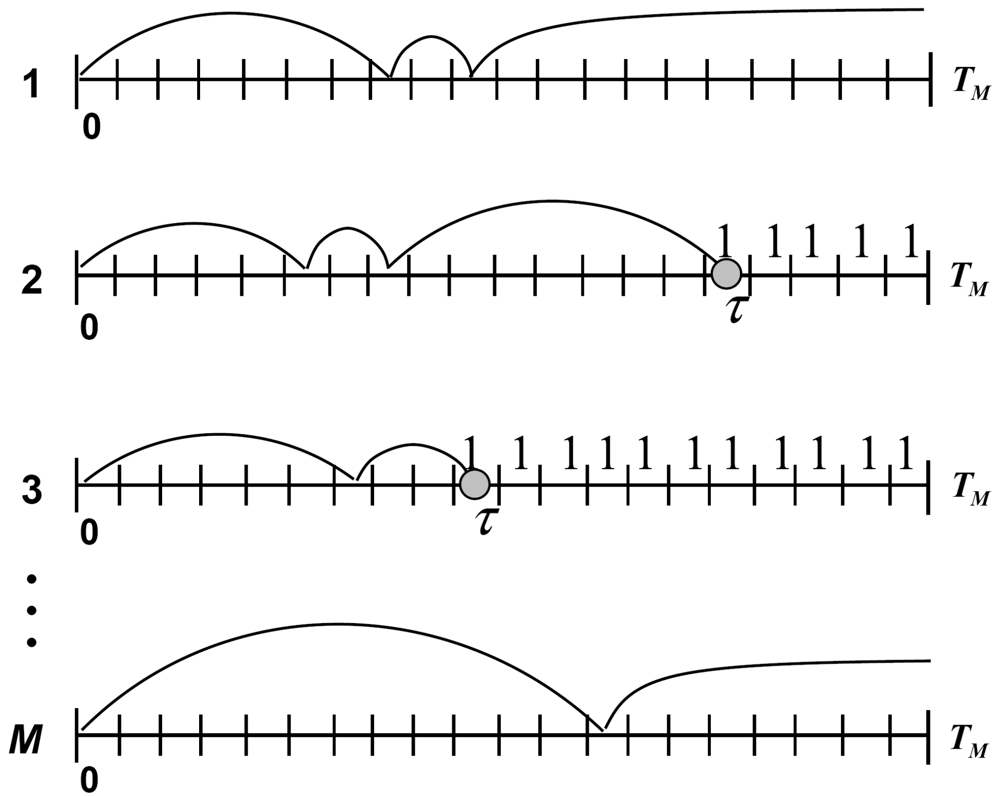
	values
λ	3· 10^{-3} h^{-1}
μ	25· 10^{-3} h^{-1}

SIMULATION OF SYSTEM STOCHASTIC STATE TRANSITION PROCESS FOR AVAILABILITY / RELIABILITY ESTIMATION

Phase Space



Example: System Reliability Estimation



1: $C^R(t) = C^R(t) \quad t \in [0, T_M]$

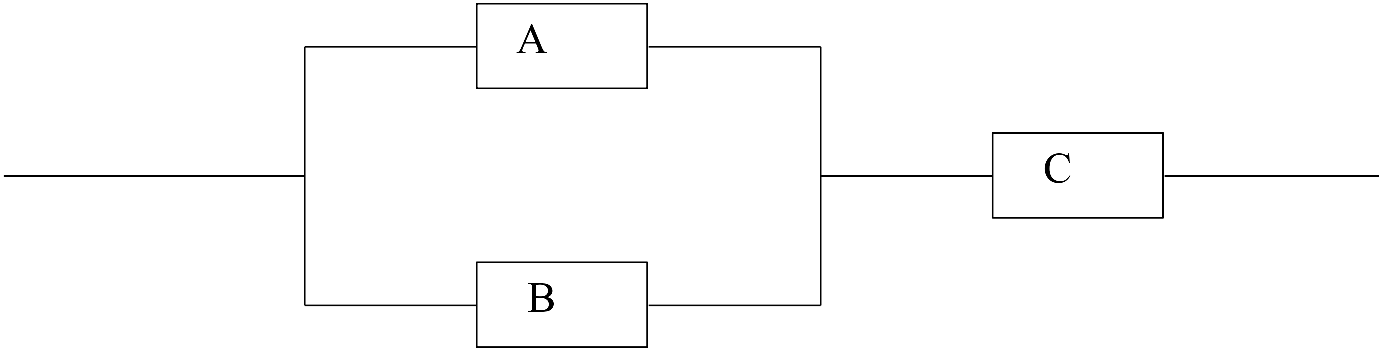
2: $C^R(t) = C^R(t) + 1 \quad t \in [\tau, T_M]$

3: $C^R(t) = C^R(t) + 1 \quad t \in [\tau, T_M]$

M: $C^R(t) = C^R(t) \quad t \in [0, T_M]$

$$\hat{F}_T(t) = \frac{C^R(t)}{M}$$

Indirect Monte Carlo: Example (1)



Components' times of transition between states are exponentially distributed

($\lambda^{i}_{j_i \to m_1}$ = rate of transition of component i going from its state j_i to the state m_i)

Arrival

Initial	1	2	3
1	-	$\lambda^{A(B)}_{1\to 2}$	$\lambda^{A(B)}_{1\to 3}$
2	$\lambda^{A(B)}_{2\to 1}$	-	$\lambda^{A(B)}_{2\to 3}$
3	$\lambda^{A(B)}_{3\to 1}$	$\lambda^{A(B)}_{3\to 2}$	-

Indirect Monte Carlo: Example (2)

Initial \ Arrival	1	2	3	4
1	-	$\lambda^{C}_{1\to 2}$	$\lambda^{C}_{1\to 3}$	$\lambda^{C}_{1\to 4}$
2	$\lambda^{C}_{2\to 1}$	-	$\lambda^{C}_{2\to 3}$	$\lambda^{C}_{2\to 4}$
3	$\lambda^{C}_{3\to 1}$	$\lambda^{C}_{3\to 2}$	-	$\lambda^{C}_{3\to 4}$
4	$\lambda^{C}_{4\to 1}$	$\lambda^{C}_{4\to 2}$	$\lambda^{C}_{4\to 3}$	-

- The components are initially (t=0) in their nominal states (1,1,1)
- One minimal cut set of order 1 (C in state 4:(*,*,4)) and one minimal cut set of order 2 (A and B in 3: (3,3,*)).

Analog Monte Carlo Trial

SAMPLING THE TIME OF TRANSITION

The rate of transition of component A(B) out of its nominal state 1 is:

$$\lambda_1^{A(B)} = \lambda_{1\to 2}^{A(B)} + \lambda_{1\to 3}^{A(B)}$$

- The rate of transition of component C out of its nominal state 1 is:

$$\lambda_1^{C} = \lambda_{1\to 2}^{C} + \lambda_{1\to 3}^{C} + \lambda_{1\to 4}^{C}$$

- The rate of transition of the system out of its current configuration (1, 1, 1) is:

$$\lambda^{(1,1,1)} = \lambda_1^{A} + \lambda_1^{B} + \lambda_1^{C}$$

- We are now in the position of sampling the first system transition time t_1, by applying the inverse transform method:

$$t_1 = t_0 - \frac{1}{\lambda^{(1,1,1)}} \ln(1 - R_t)$$

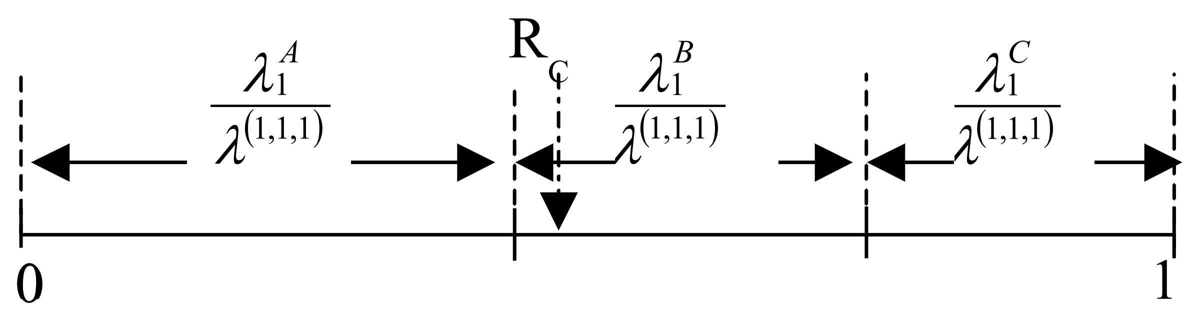
where $R_t \sim U[0,1)$

Sampling the Kind of Transition (1)

- Assuming that $t_1 < T_M$ (otherwise we would proceed to the successive trial), we now need to determine which transition has occurred, i.e. which component has undergone the transition and to which arrival state.
- The probabilities of components A, B, C undergoing a transition out of their initial nominal states 1, given that a transition occurs at time t_1, are:

$$\frac{\lambda_1^A}{\lambda^{(1,1,1)}}, \quad \frac{\lambda_1^B}{\lambda^{(1,1,1)}}, \quad \frac{\lambda_1^C}{\lambda^{(1,1,1)}}$$

- Thus, we can apply the inverse transform method to the discrete distribution

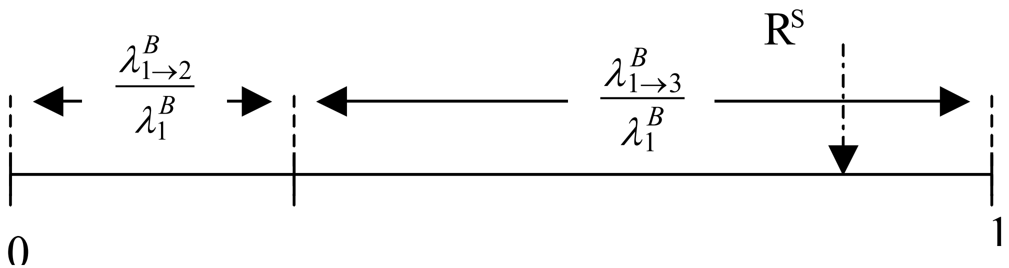


Sampling the Kind of Transition (2)

- Given that at t_1 component B undergoes a transition, its arrival state can be sampled by applying the inverse transform method to the set of discrete probabilities

$$\left\{ \frac{\lambda_{1\to2}^{B}}{\lambda_{1}^{B}}, \frac{\lambda_{1\to3}^{B}}{\lambda_{1}^{B}} \right\}$$

of the mutually exclusive and exhaustive arrival states



$R_S \sim U[0,1)$

- As a result of this first transition, at t_1 the system is operating in configuration (1,3,1).

- The simulation now proceeds to sampling the next transition time t_2 with the updated transition rate

$$\lambda^{(1,3,1)} = \lambda_1^A + \lambda_3^B + \lambda_1^C$$

Sampling the Next Transition

- The next transition, then, occurs at

$$t_2 = t_1 - \frac{1}{\lambda^{(1,3,1)}} \ln(1 - R_t)$$

where $R_t \sim U[0,1)$.

- Assuming again that $t_2 < T_M$, the component undergoing the transition and its final state are sampled as before by application of the inverse trasform method to the appropriate discrete probabilities.

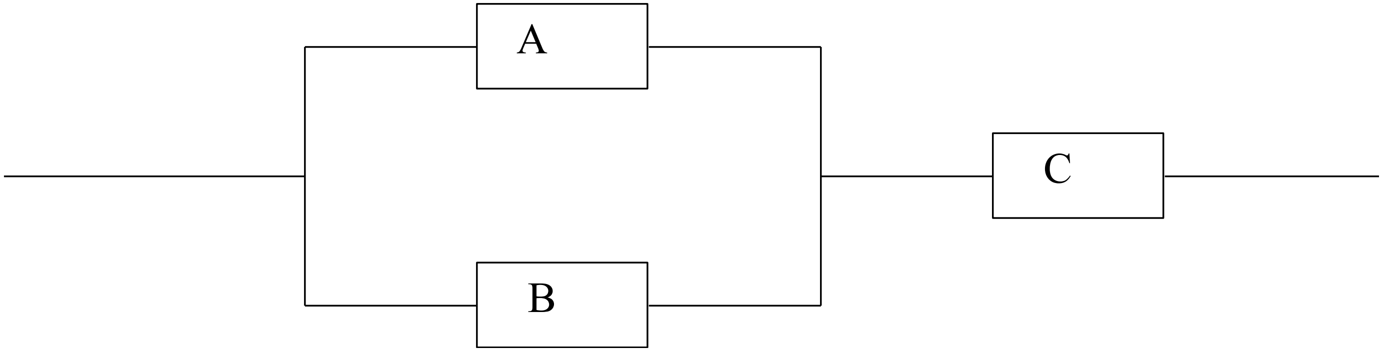
- The trial simulation then proceeds through the various transitions from one system configuration to another up to the mission time T_M.

Unreliability and Unavailability Estimation

- When the system enters a failed configuration (*,*,4) or (3,3,*), where the * denotes any state of the component, tallies are appropriately collected for the unreliability and instantaneous unavailability estimates (at discrete times $t_j \in [0, T_M]$);

- After performing a large number of trials M, we can obtain estimates of the system unreliability and instantaneous unavailability by simply dividing by M, the accumulated contents of $C^R(t_j)$ and $C_A(t_j)$, $t_j \in [0,T_M]$

Direct Monte Carlo: Example (1)



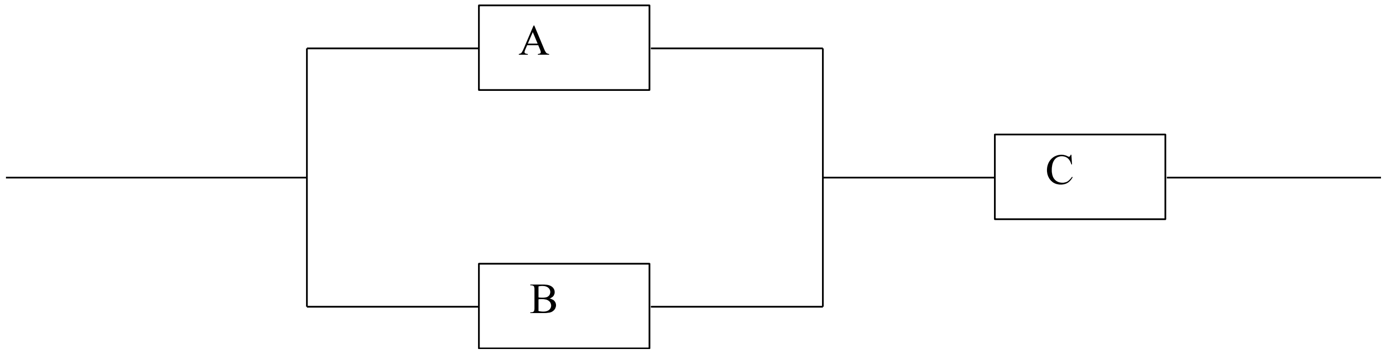
For any arbitrary trial, starting at t=0 with the system in nominal configuration (1,1,1) we would sample all the transition times:

$$t^i_{1\to m_i} = t_0 - \frac{1}{\lambda^i_{1\to m_i}} \ln(1 - R^i_{t,1\to m_i}) \qquad \left.\begin{array}{ll} i = A,B,C & \\ m_i = 2,3 & \text{for } i = A,B \\ m_i = 2,3,4 & \text{for } i = C \end{array}\right\}$$

where $R^i_{t,1\to m_i} \sim U[0,1)$

These transition times would then be ordered in ascending order from t_{min} to $t_{max} \leq T_M$. Let us assume that t_{min} corresponds to the transition of component A to state 3 of failure. The current time is moved to $t_1 = t_{min}$ in correspondence of which the system configuration changes, due to the occurring transition, to (3,1,1) still operational.

Direct Monte Carlo: Example (2)



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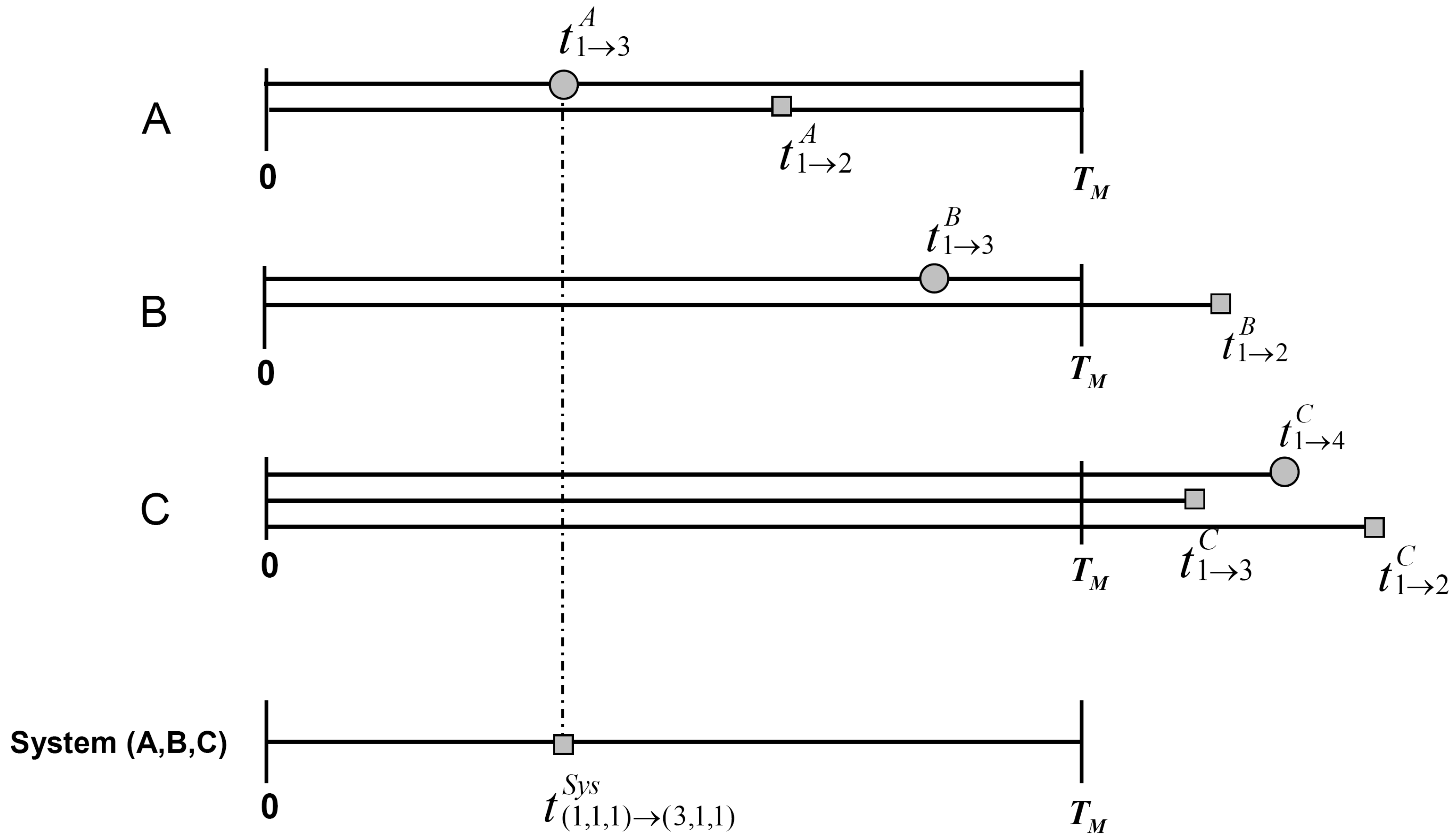
Example (1)


A
$t^{A}_{1\to3}$
$t^{A}_{1\to2}$
0
T_M
B
$t^{B}_{1\to3}$
$t^{B}_{1\to2}$
0
T_M
C
$t^{C}_{1\to4}$
$t^{C}_{1\to3}$
$t^{C}_{1\to2}$
0
T_M
System (A,B,C)
$t^{Sys}_{(1,1,1)\to(3,1,1)}$
0
T_M

Example (2)

The new transition times of component A are then sampled

$$t^A_{3\to m_A} = t_1 - \frac{1}{\lambda^A_{3\to m_A}} \ln(1 - R^A_{t,3\to m_A}) \qquad k = 1,2 \qquad R^A_{t,3\to m_A} \sim U[0,1)$$

and placed at the proper position in the timeline of the succession of occurring transitions

- The simulation then proceeds to the successive times in the list, in correspondence of which a system transition occurs.
- After each transition, the timeline is updated with the times of the transitions that the component which has undergone the last transition can do from its new state.
- During the trial, each time the system enters a failed configuration, tallies are collected and in the end, after M trials, the unreliability and unavailability estimates are computed.

POLITECNICO DI MILANO

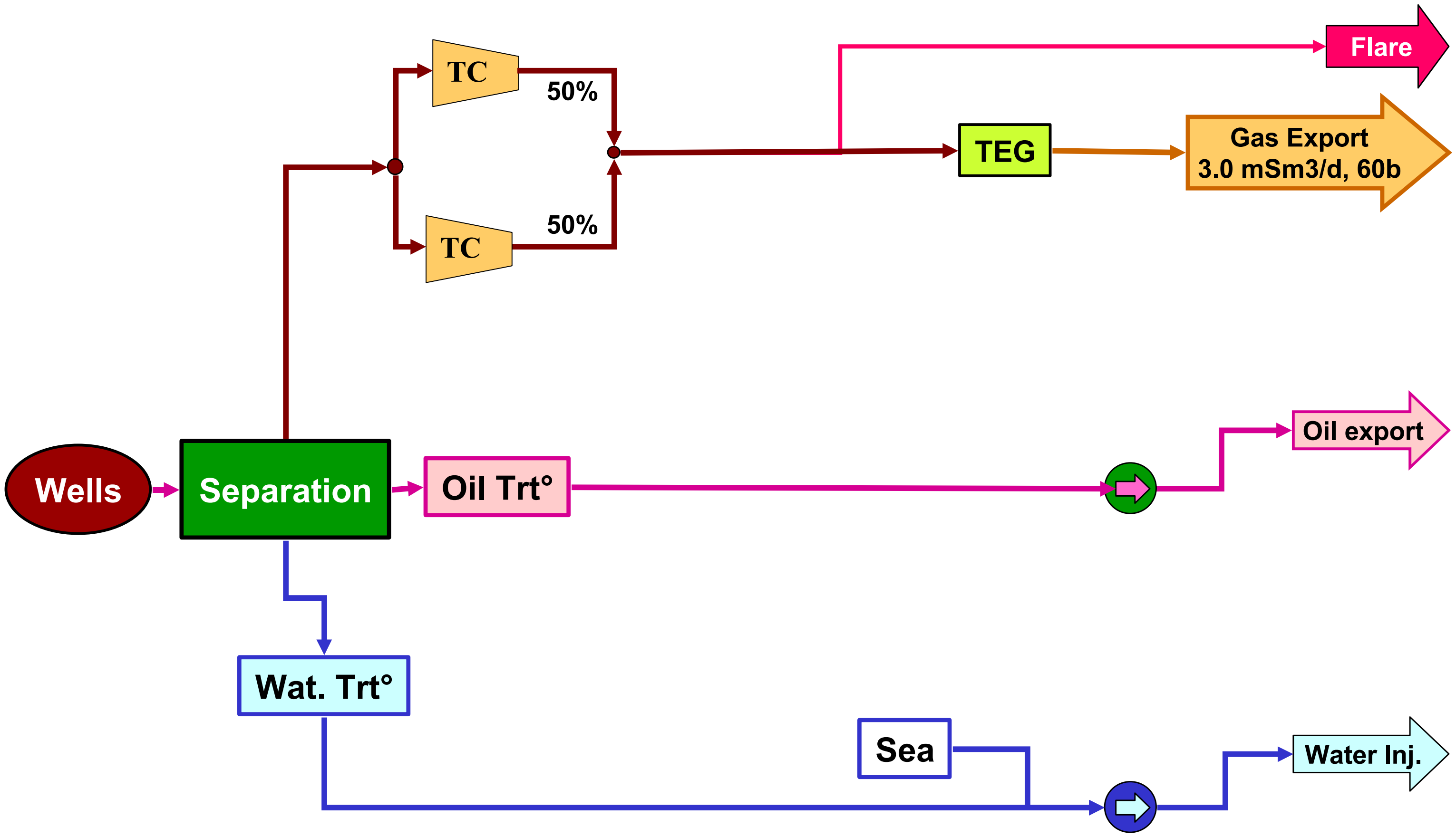
PRODUCTION AVAILABILITY EVALUATION OF AN OFFSHORE INSTALLATION

A real example of Indirect Simulation

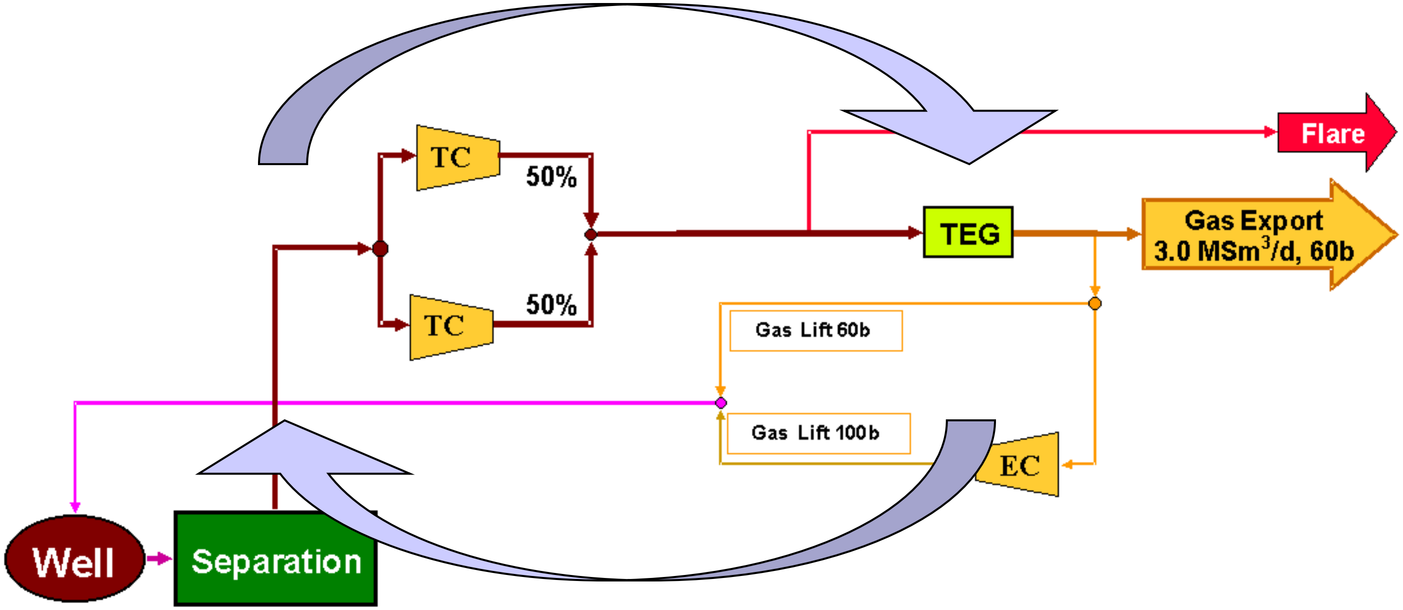
CENTRALE PARIS

Supélec

System description: basic scheme



System description: gas-lift



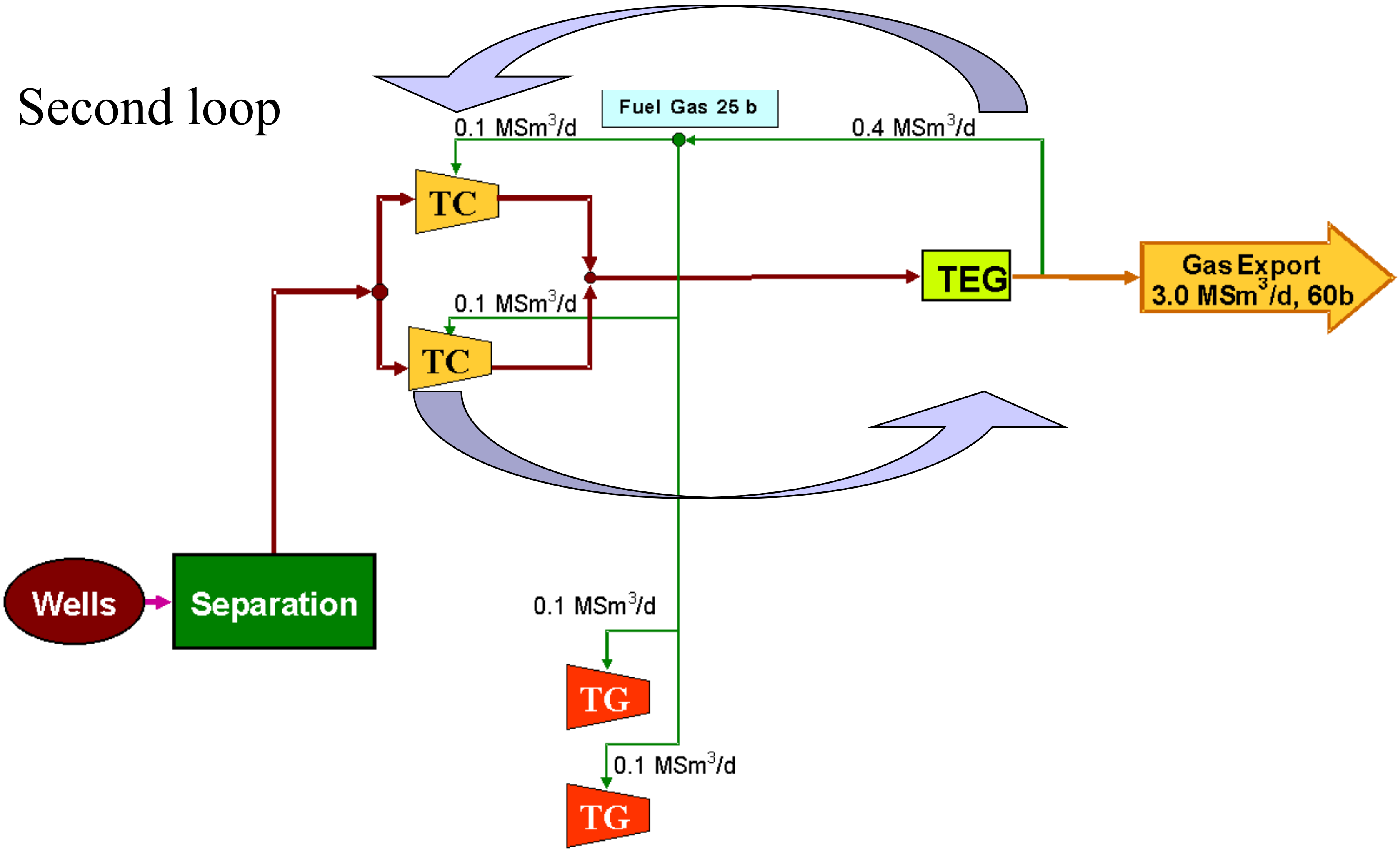
First loop

Gas-lift pressure	Production of the Well
100	100%
60	80%
0	60%

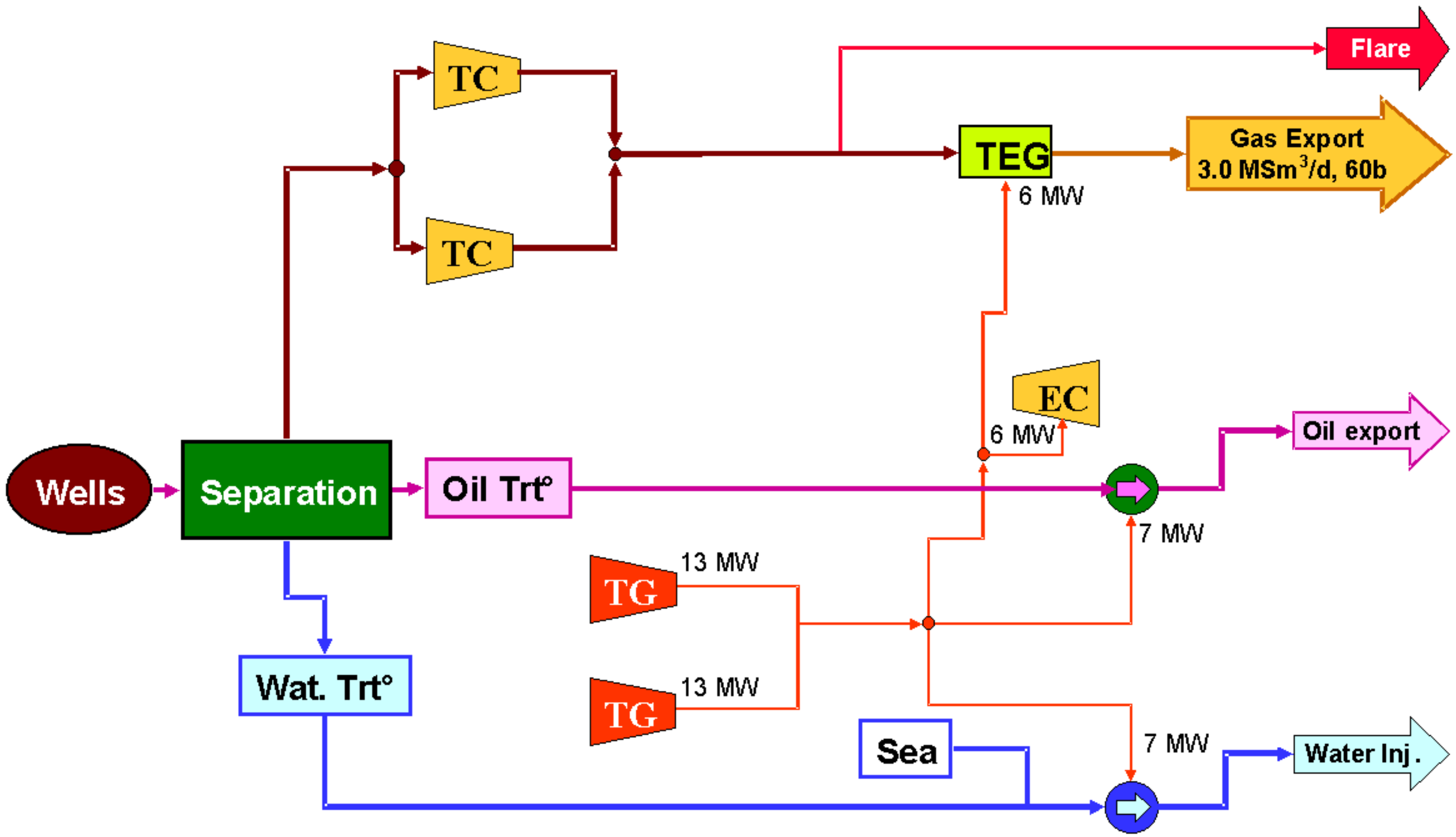
System description:

fuel gas generation and distribution

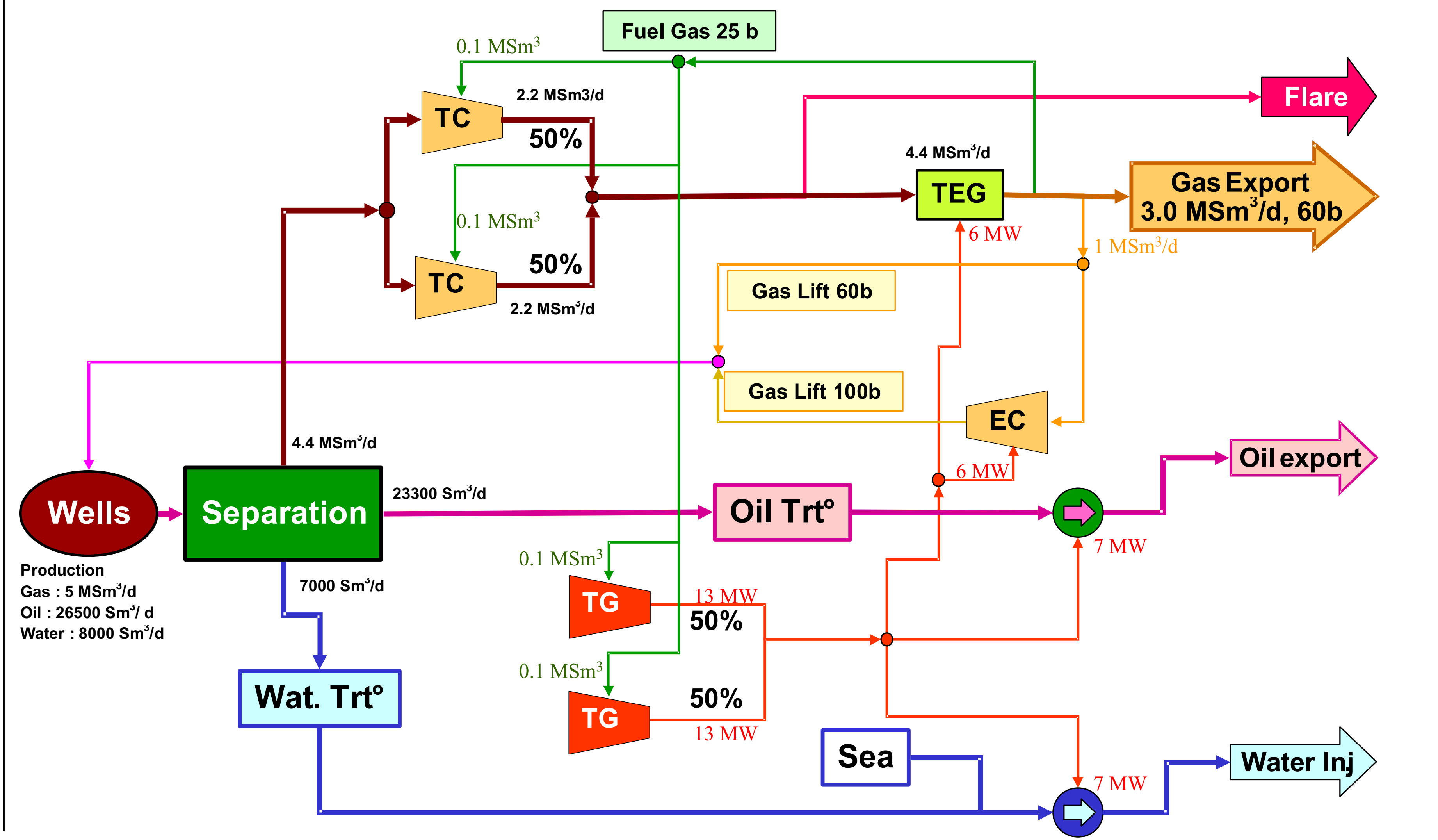
Second loop



System description:
electricity power production and distribution

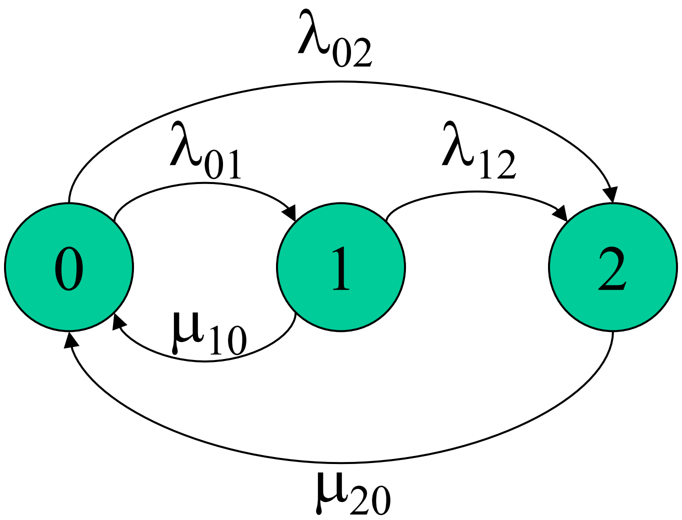


The offshore production plant



back

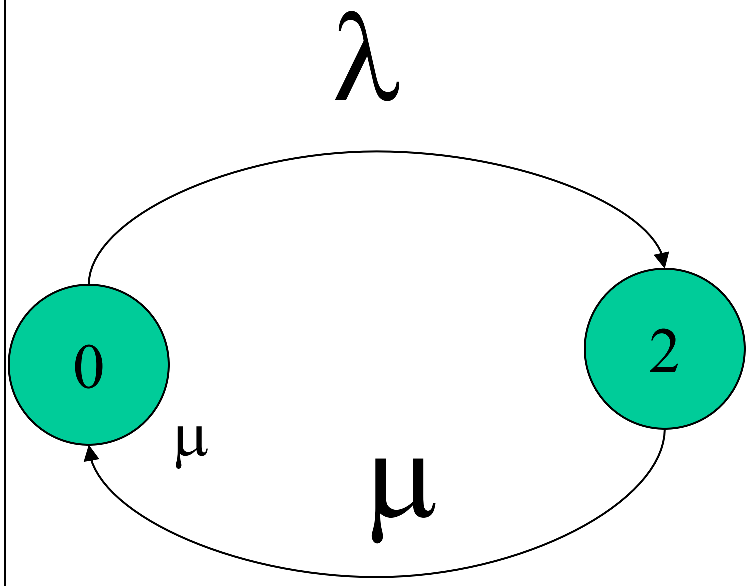
Component failures and repairs: TCs and TGs



	TC	TG
λ_{01}	$0.89 \cdot 10^{-3}\ h^{-1}$	$0.67 \cdot 10^{-3}\ h^{-1}$
λ_{02}	$0.77 \cdot 10^{-3}\ h^{-1}$	$0.74 \cdot 10^{-3}\ h^{-1}$
λ_{12}	$1.86 \cdot 10^{-3}\ h^{-1}$	$2.12 \cdot 10^{-3}\ h^{-1}$
μ_{10}	$0.033\ h^{-1}$	$0.032\ h^{-1}$
μ_{20}	$0.048\ h^{-1}$	$0.038\ h^{-1}$

State 0 = as good as new
State 1 = degraded (no function lost, greater failure rate value)
State 2 = critical (function is lost)

Component failures and repairs: EC and TEG



	EC	TEG
λ	$0.17 \cdot 10^{-3}\ h^{-1}$	$5.7 \cdot 10^{-5}\ h^{-1}$
μ	$0.032\ h^{-1}$	$0.333\ h^{-1}$

State 0 = as good as new

State 2 = critical (function is lost)

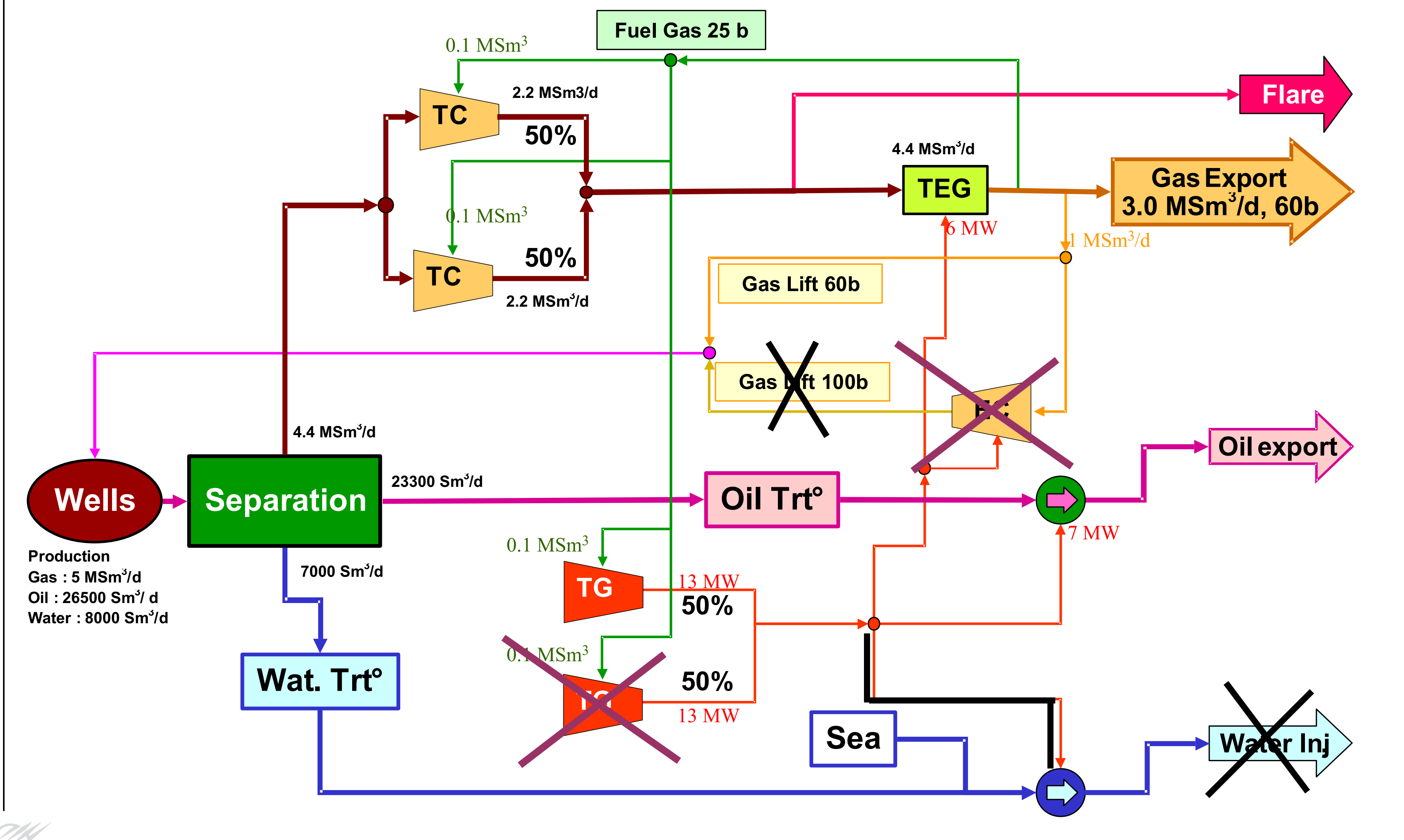
Production priority

When a failure occurs, the system is reconfigured to minimise (in order):

- the impact on the export oil production
- the impact on export gas production

➢ **The impact on water injection does not matter**

Production priority: example



Maintenance policy: reparation

Only 1 repair team

Priority levels of failures:

1. Failures leading to total loss of export oil (both TG's or both TC's or TEG)
2. Failures leading to partial loss of export oil (single TG or EC)
3. Failures leading to no loss of export oil (single TC failure)

Maintenance policy: preventive maintenance

- **Only 1 preventive maintenance team**

- **The preventive maintenance takes place only if the system is in perfect state of operation**

	Type of maintenance	Frequency [hours]	Duration [hours]
Turbo-Generator and Turbo-Compressors	Type 1	2160 (90 days)	4
	Type 2	8760 (1 year)	120 (5 days)
	Type 3	43800 (5 years)	672 (4 weeks)
Electro Compressor	Type 4	2666	113

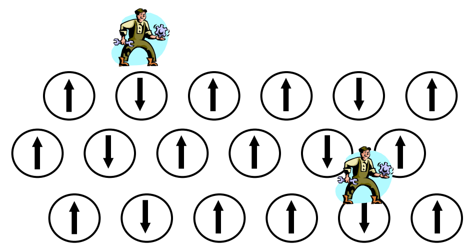
MARKOV APPROACH

Number of components = 6
Number of states for component = 2 or 3

⇨ $2^2 \cdot 3^4$ = **324** plant states

+

1 repair team ⇨ 129 new plant states



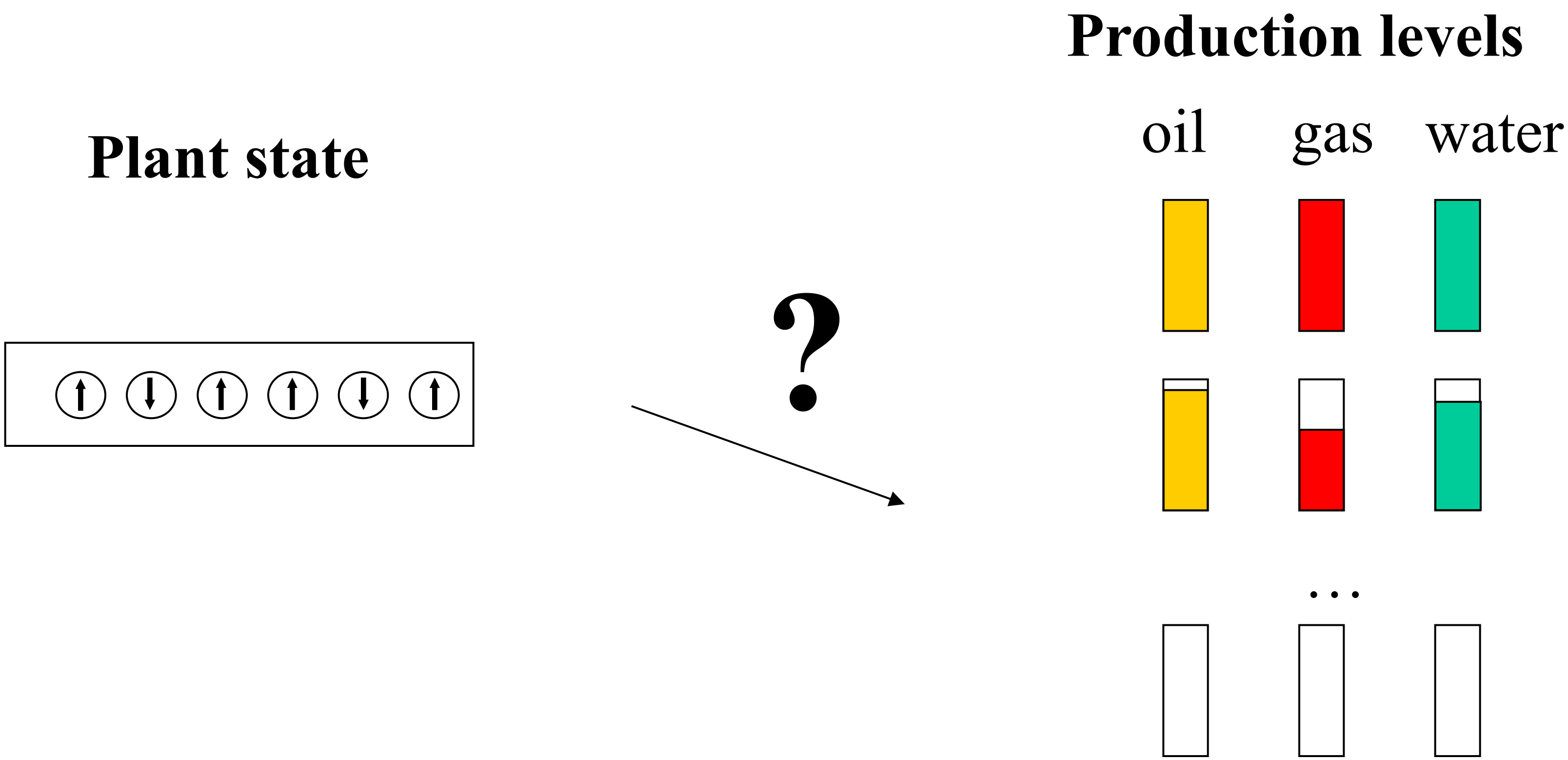
+

1 maintenance team ⇨ Non homogeneous Markov chain

Markov approach too complex

MONTE CARLO APPROACH

MONTE CARLO APPROACH



Associate a production level to each of the 453 plant states ⇨ too long, error prone

A systematic procedure

7 different production levels

⇩

6 different system faults

⇩

6 fault trees

⇩

6 families of mcs

Production Level	Gas [kSm^3/d]	Oil [$k\ m^3/d$]	Water [m^3/d]	mcs	MCS
0=(100%)	3000	23.3	7000		
1	900	23.3	7000	X5, X6	X5,X6
2	2700	21.2	0	X3, X4	X2X3,X2X4
3	1000	21.2	0	X3X5, X3X6, X4X5, X4X6	X2X3X5, X2X3X6, X2X4X5, X2X4X6
4	2600	21.2	6400	X2	X2
5	900	21.2	6400	X2X5, X2X6	X2X5, X2X6
6	0	0	0	X1, X3X4, X5X6	X1X2X3X4X5X6

Numerical results

Case A: corrective maintenance and no preventive maintenance (T_{miss}= $1\cdot 10^3$ hours, trials=10^6)

CPU time ≈ 15 min

Case B: perfect system (no failures) and preventive maintenance (T_{miss}= 10^4 hours, trials=10^5)

CPU time ≈ 12 min

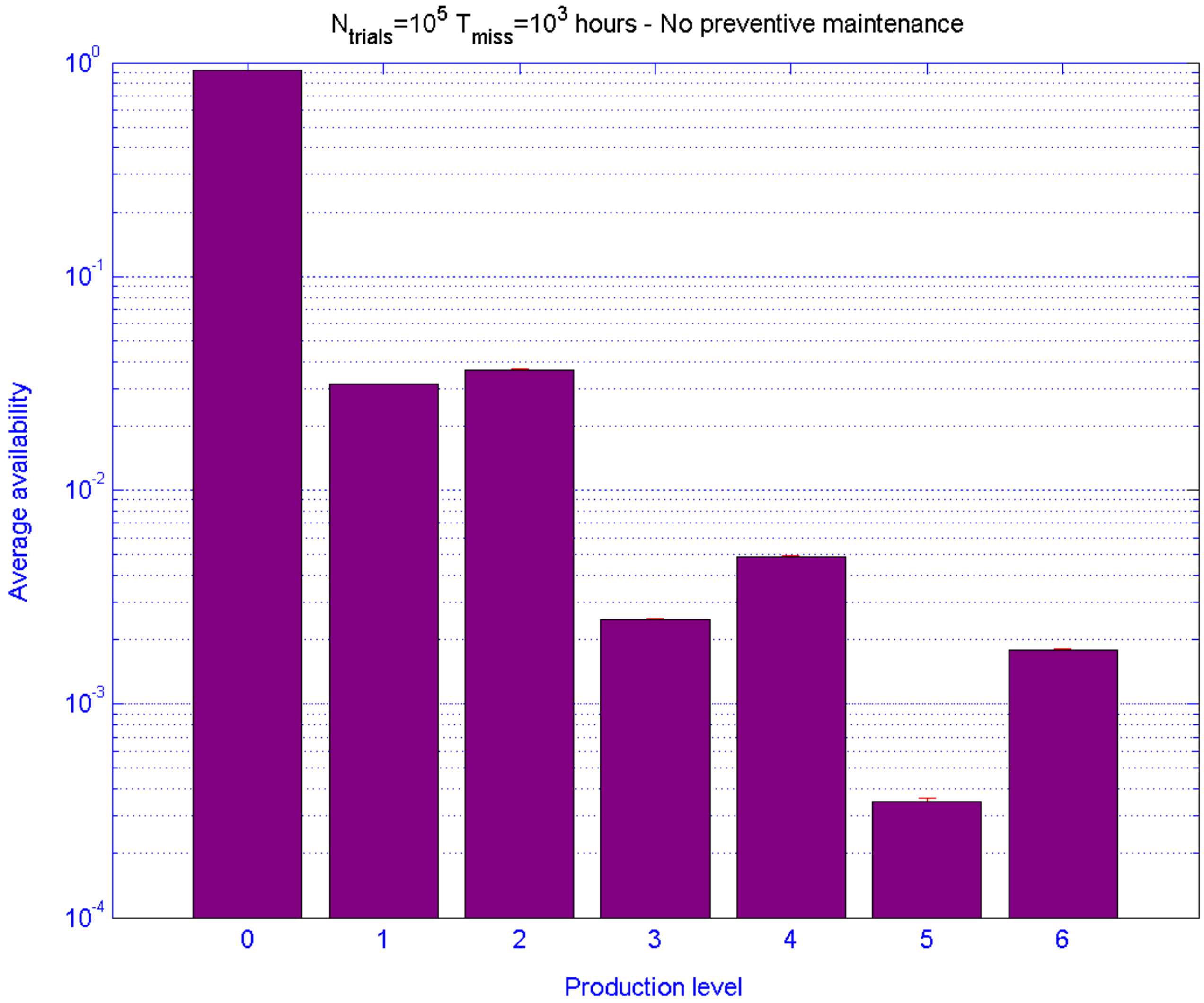
Case C: corrective and preventive maintenance

(T_{miss}=$5\cdot 10^5$ hours, trials=10^5)

CPU time ≈ 20 h

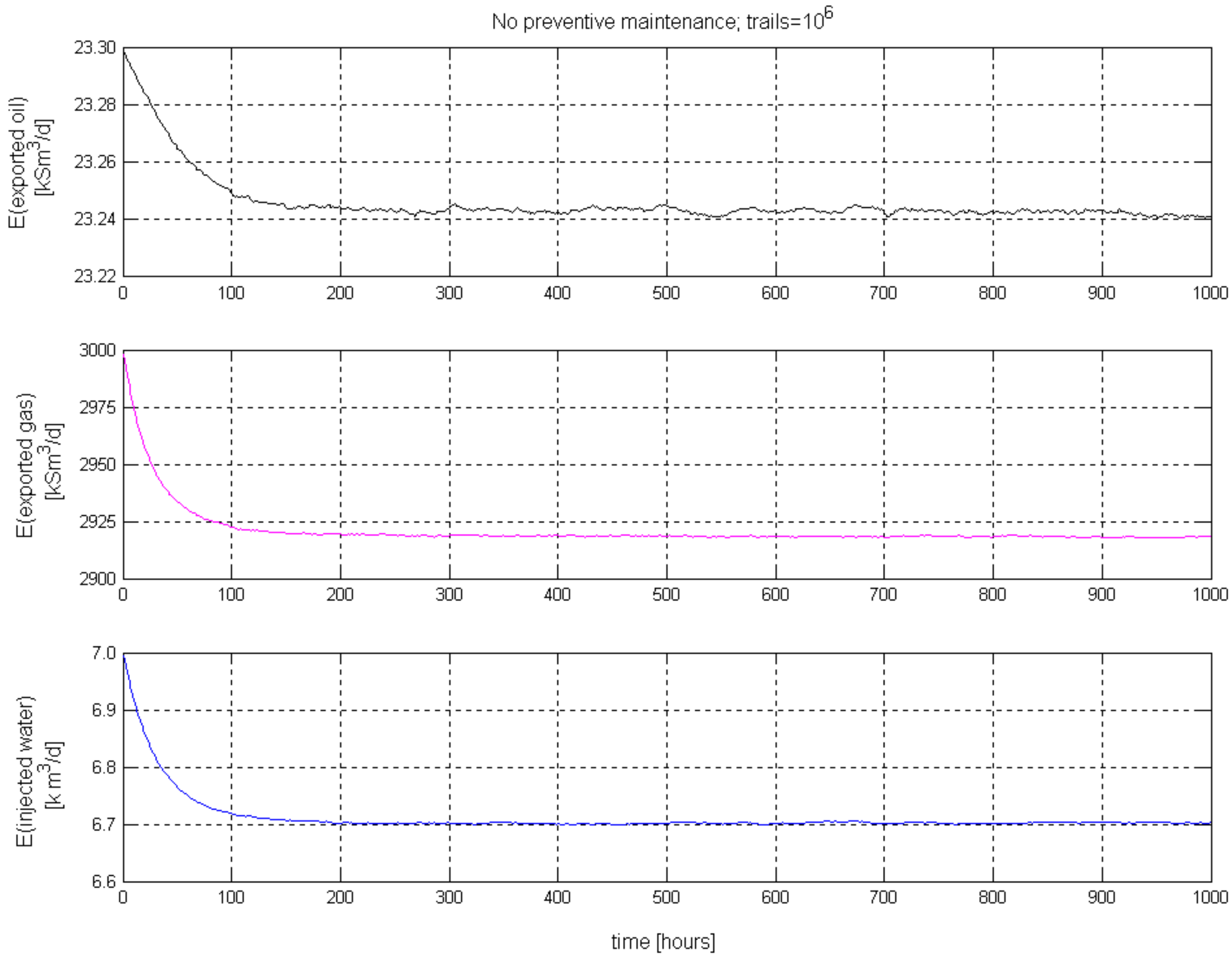
Case A: no preventive maintenances

Production level	Average availability
0	9.23E-1
1	3.13E-2
2	3.67E-2
3	2.47E-3
4	4.88E-3
5	3.50E-4
6	1.79E-3



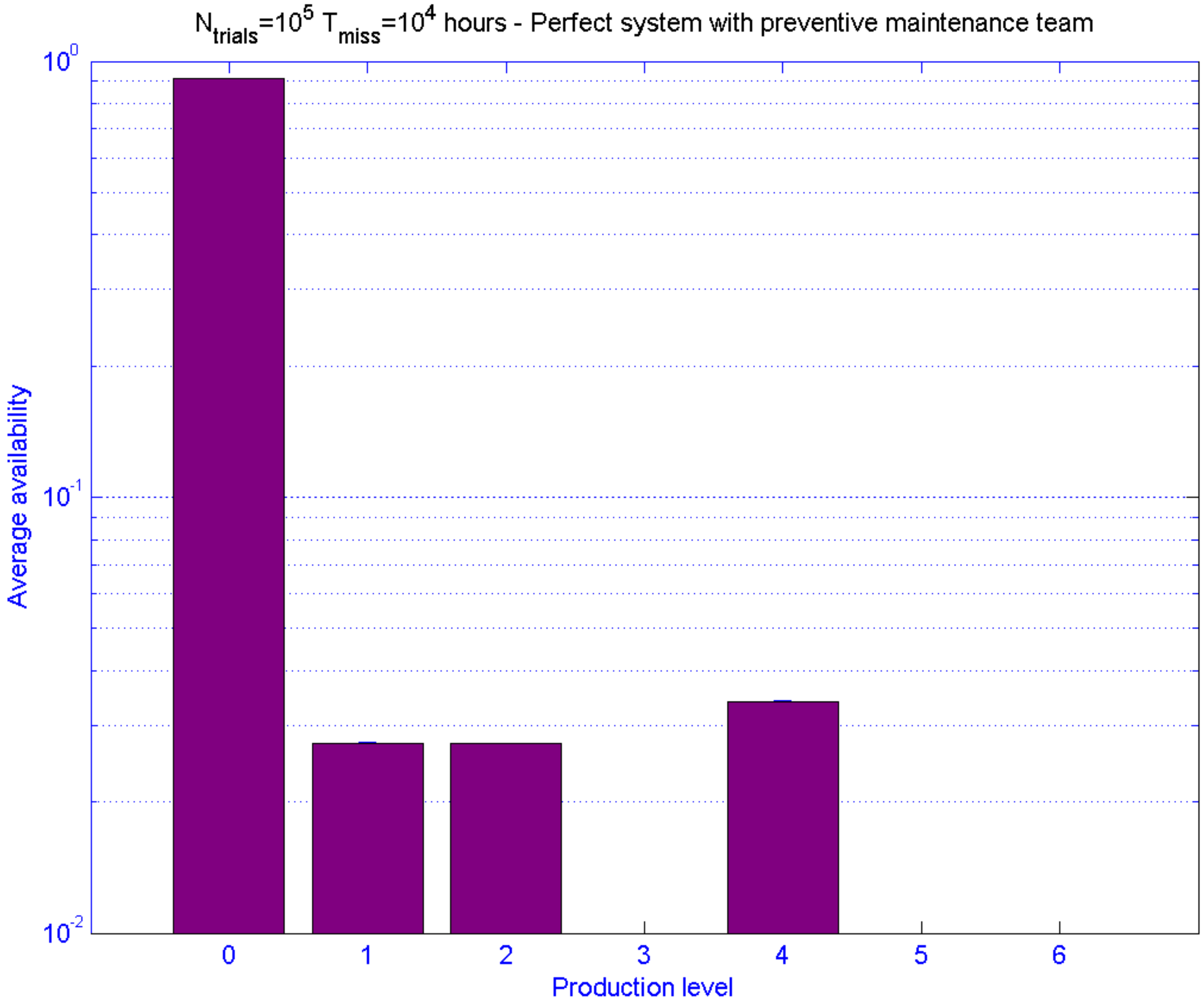
Case A: no preventive maintenances

	Asymptotic values
Oil [k m³/d]	23.24
Gas [k Sm³/d]	2918
Water [k m³/d]	6.703



Case B: perfect system and preventive maintenances

Production level	Average availability
0	9.12E-1
1	2.73E-2
2	2.72E-2
3	0.00
4	3.40E-2
5	0.00
6	0.00

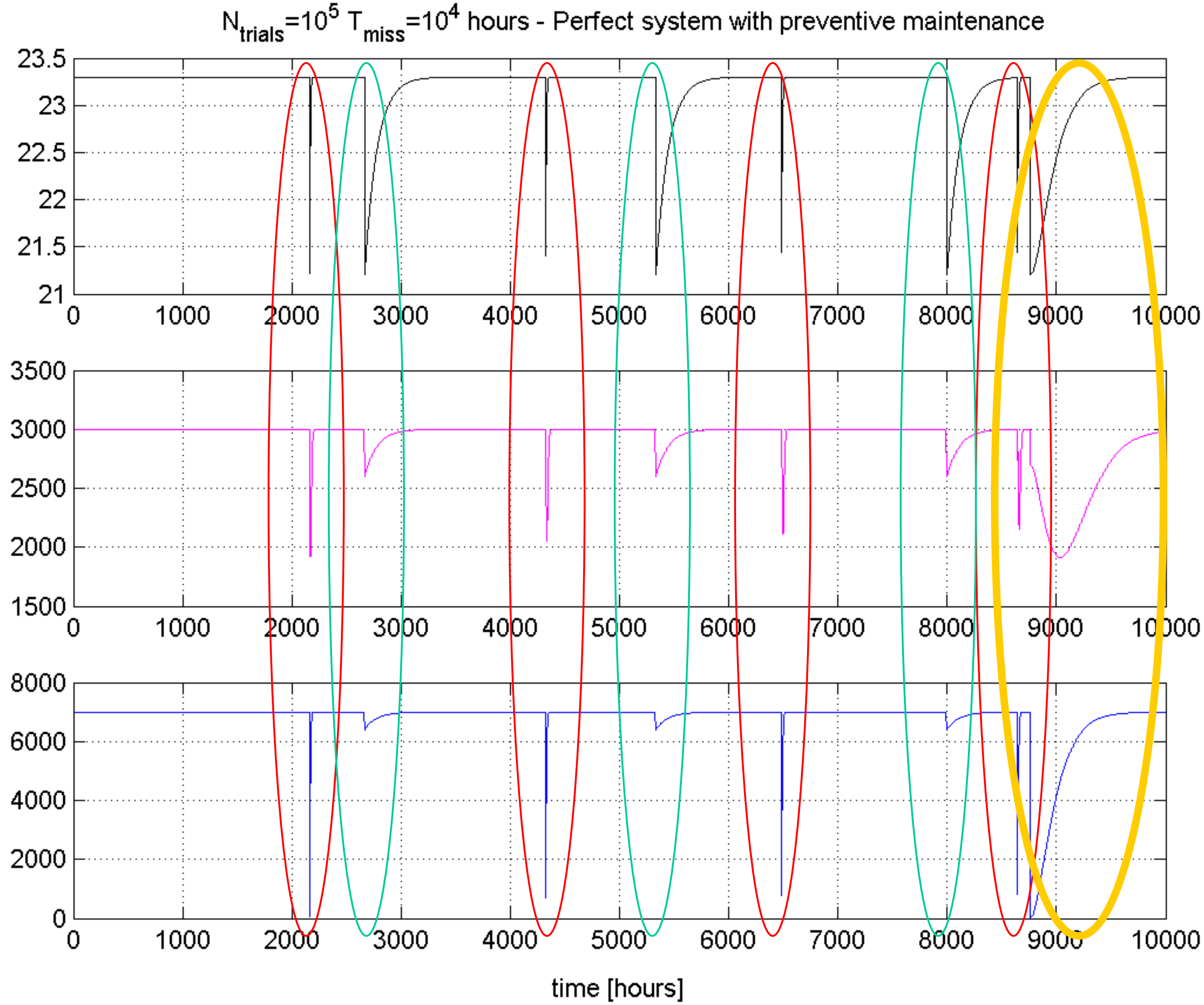


Case B: perfect system and preventive maintenances

P.Maintenance Type 1 (TC,TG)

P.Maintenance Type 2 (EC)

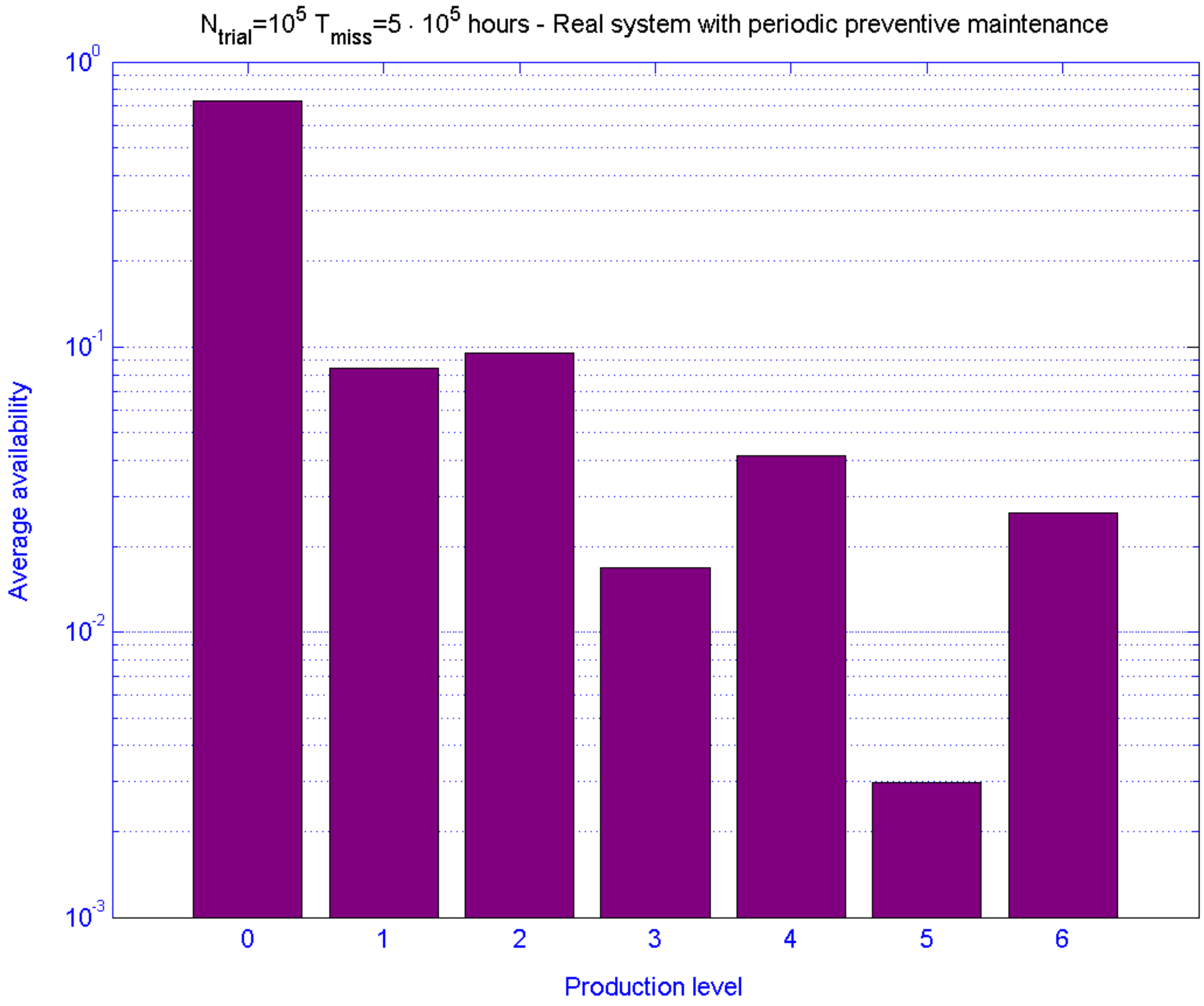
P.Maintenance Type 3 (TC,TG)



	Mean	Std
Oil [k m³/d]	23.230	0.263
Gas [k Sm³/d]	2929	194.0
Water [k m³/d]	6.811	0.883

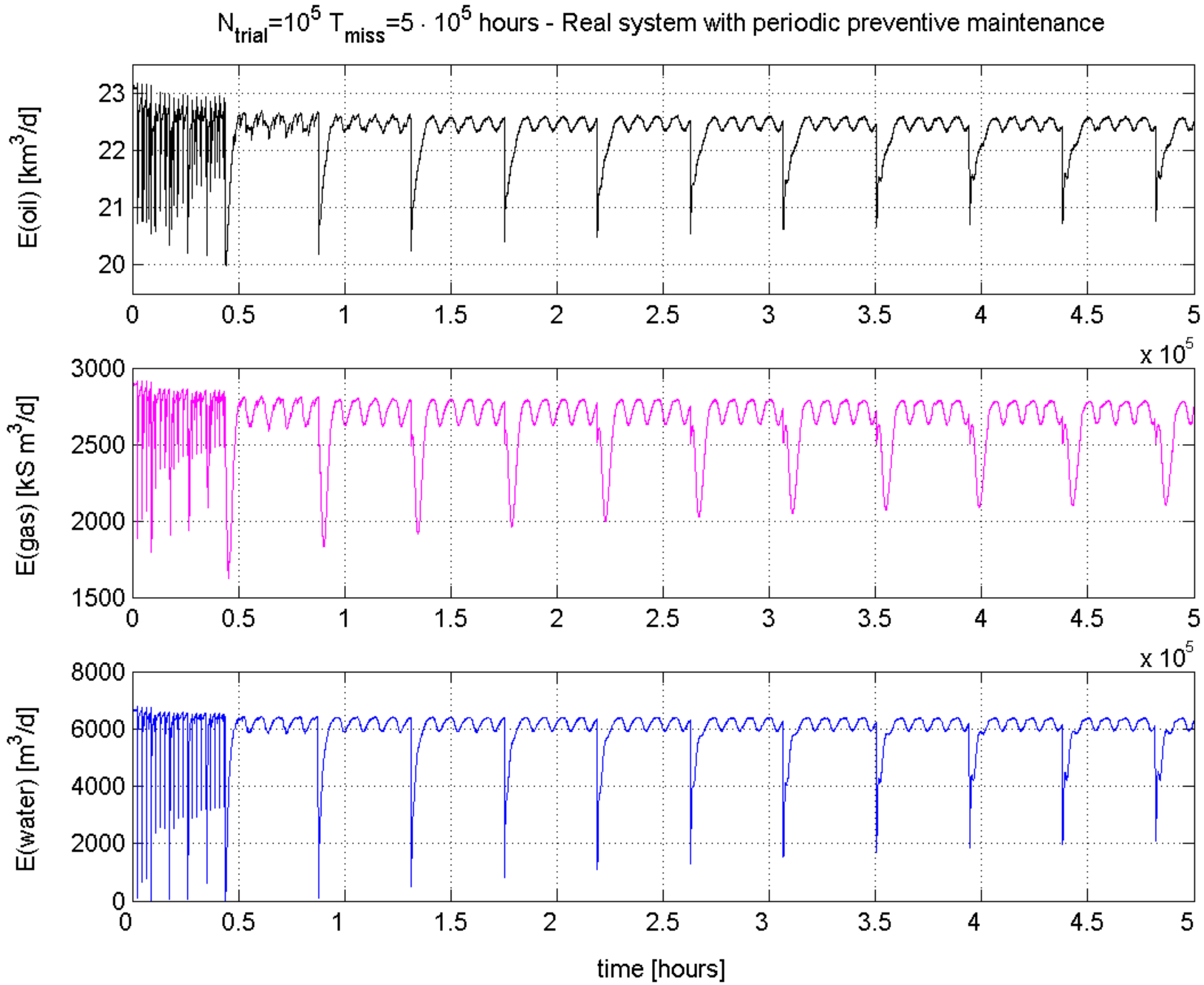
Case C: real system with preventive maintenances

Production level	Average availability
0	8.13E-1
1	5.68E-2
2	6.58E-2
3	1.19E-2
4	3.55E-2
5	2.34E-3
6	1.50E-2



Case C: real system with preventive maintenances

	Mean	Std
Oil [k m^3/d]	22.60	0.42
Gas [k Sm^3/d]	2687	194.3
Water [k m^3/d]	6.04	0.76

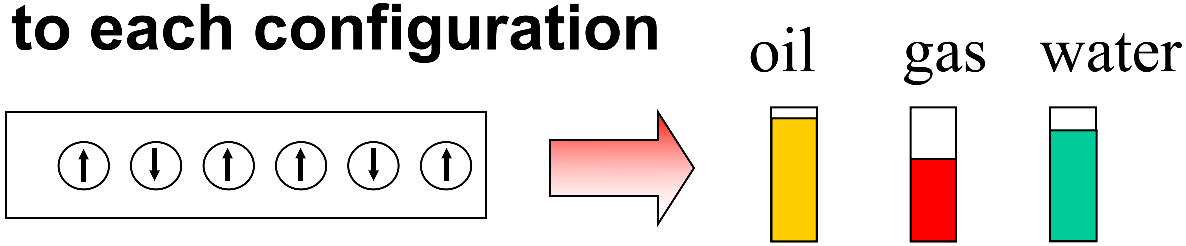


Conclusions

- **Complex multi-state system with maintenance and operational loops**

MC simulation

- **Systematic procedure to assign a production level to each configuration**



- **Investigation of effects maintenance on production**

POLITECNICO DI MILANO

Centre de recherche sur les Risques et les Crises

Introduction to Monte Carlo Simulation

The theroetical view

Enrico Zio

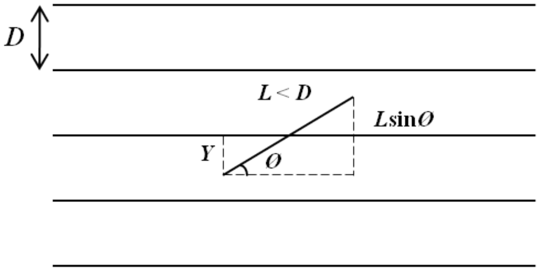
CONTENTS

- Sampling
- Evaluation of definite integrals
- Simulation of system transport
- Simulation for reliability/availability analysis

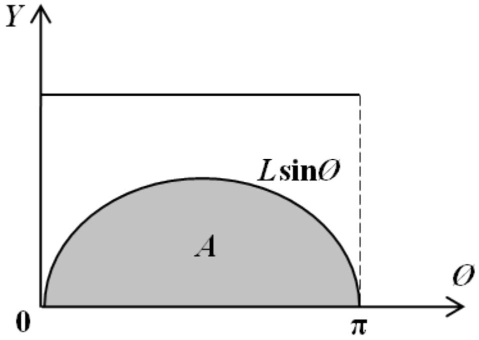
SAMPLING

Buffon's needle

Buffon considered a set of parallel straight lines a distance *D* apart onto a plane and computed the probability *P* that a needle of length *L* < *D* randomly positioned on the plane would intersect one of these lines.



$$P = P\{Y \leq L \sin \varnothing\}$$

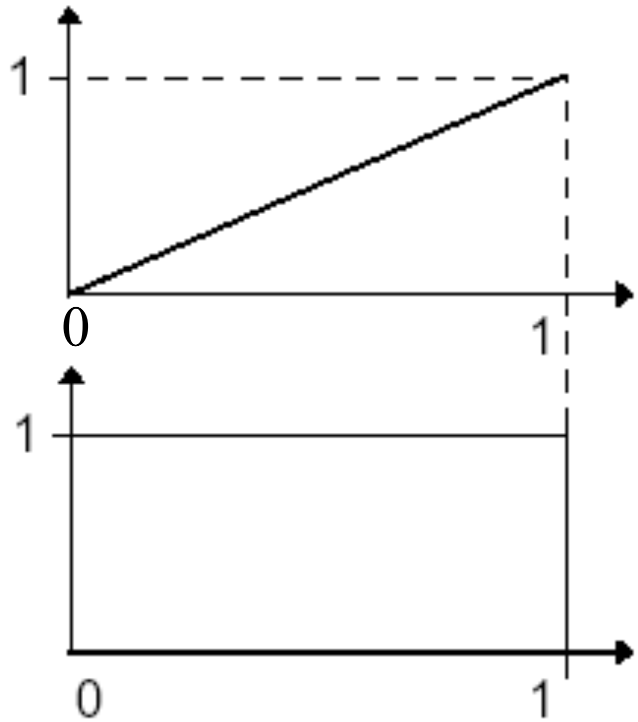


$$f_Y(y) = \frac{1}{D} \qquad y \in [0, D]$$

$$f_\varnothing(\varphi) = \frac{1}{\pi} \qquad \varphi \in [0, \pi]$$

$$P = \iint_A \frac{dy}{D} \cdot \frac{d\varphi}{\pi} = \frac{L/D}{\pi/2}$$

Sampling (pseudo) Random Numbers Uniform Distribution



cdf : $U_R(r) = P\{R \le r\} = r$

pdf : $u_R(r) = \dfrac{dU_R(r)}{dr} = 1$

Sampling (pseudo) Random Numbers Uniform Distribution

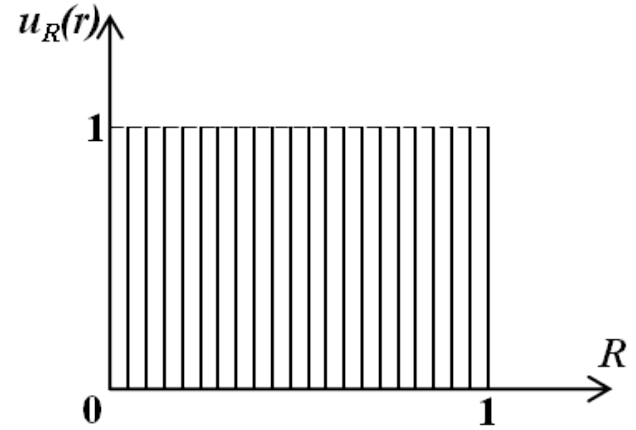
$$R \sim U[0,1)$$

$$x_i = \left(a x_{i-1} + c\right) \bmod m$$

where $a, c \in [0, m-1]$

$m \gg 1$

$$r_i = \frac{x_i}{m}$$



Example: $a = 5$, $c = 1$, $m = 16$

$$x_0 = 2 \Rightarrow r_0 = \frac{2}{16}$$

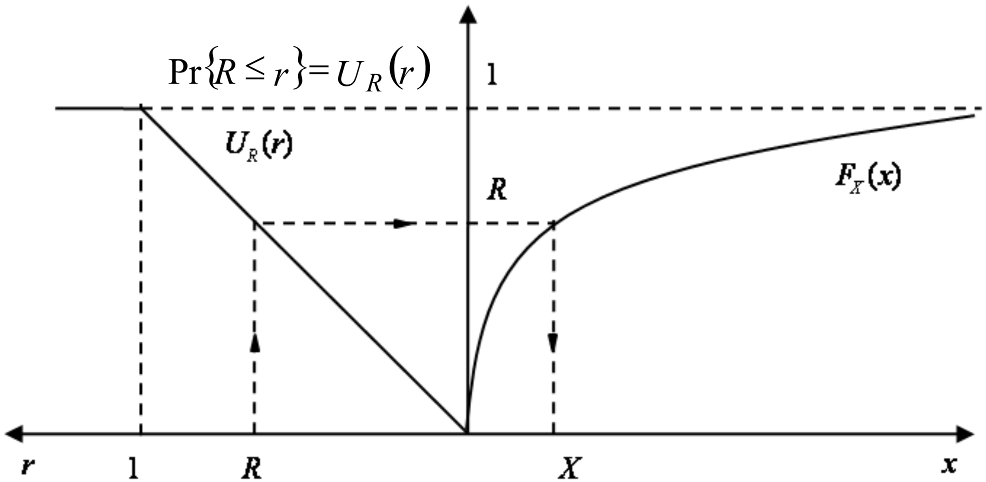
$$x_1 = (5 \cdot 2 + 1) \bmod 16 = 11 \Rightarrow r_1 = \frac{11}{16}$$

...

$$x_{15} = 13 \Rightarrow r_{15} = \frac{13}{16}$$

$$x_{16} = 2$$

Sampling (pseudo) Random Numbers Generic Distribution



Sample R from $U_R(r)$ and find X:

$$X = F_X^{-1}(R)$$

Question: which distribution does X obey?

$$P\{X \leq x\} = P\{F_X^{-1}(R) \leq x\}$$

Application of the operator F_x to the argument of P above yields

$$P\{X \leq x\} = P\{R \leq F_X(x)\} = F_X(x)$$

Summary:

From an $R \sim U_R(r)$ we obtain an $X \sim F_X(x)$

Example: Exponential Distribution

- Markovian system with two states (good, failed)
- hazard rate, λ = constant

$$F_T(t) = P\{T \le t\} = 1 - e^{-\lambda t}$$

- cdf

$$f_T(t) \cdot dt = P\{t \le T < t + dt\} = \lambda e^{-\lambda t} \cdot dt$$

- pdf

$$R \equiv F_R(r) = F_T(t) = 1 - e^{-\lambda t}$$

- Sampling a failure time T

⇓

$$T = F_T^{-1}(R) = -\frac{1}{\lambda}\ln(1 - R)$$

Example: Weibull Distribution

•hazard rate, λ = constant

• cdf

$$F_T(t) = P\{T \le t\} = 1 - e^{-\beta t^{\alpha}}$$

pdf

$$f_T(t) \cdot dt = P\{t \le T < t + dt\} = \alpha\beta t^{\alpha-1} e^{-\beta t^{\alpha}} \cdot dt$$

•Sampling a failure time *T*

$$R \equiv F_R(r) = F_T(t) = 1 - e^{-\lambda t^{\alpha}}$$

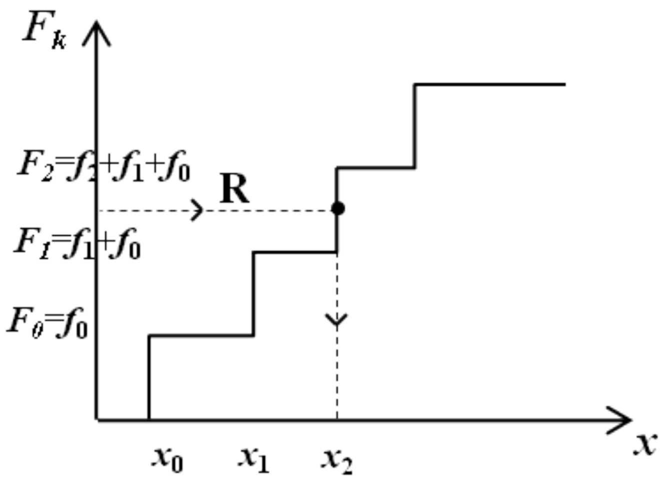
⇓

$$T = F_T^{-1}(R) = \left(-\frac{1}{\beta} \ln(1 - R) \right)^{\frac{1}{\alpha}}$$

Sampling by the Inverse Transform Method: Discrete Distributions

$$\Omega = \{x_0, x_1, \dots, x_k, \dots\}$$

$$F_k = P\{X \le x_k\} = \sum_{i=0}^{k} P[X = x_i]$$



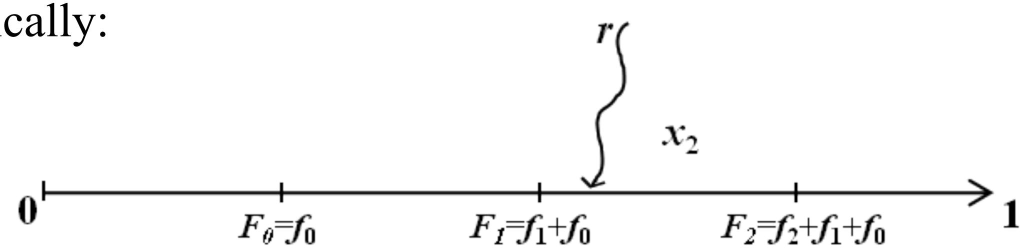
sample an $R \sim U[0,1)$

$$P[F_{k-1} < R \le F_k] = F_R(F_k) - F_R(F_{k-1})$$

$$R \sim U[0,1) \text{ and } F_R(r) = r$$

$$\Rightarrow P[F_{k-1} < R \le F_k] = F_k - F_{k-1} = f_k = P[X = x_k]$$

Graphically:

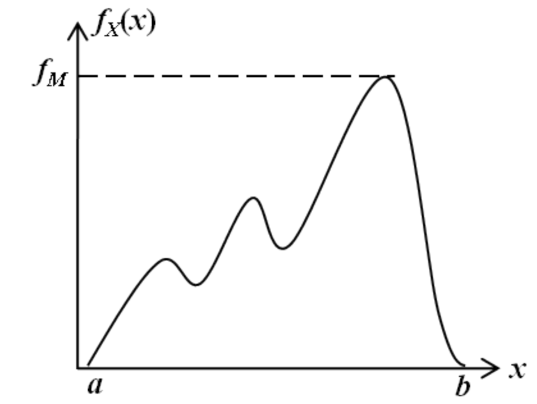


Sampling by the Rejection Method: von Neumann Algorithm

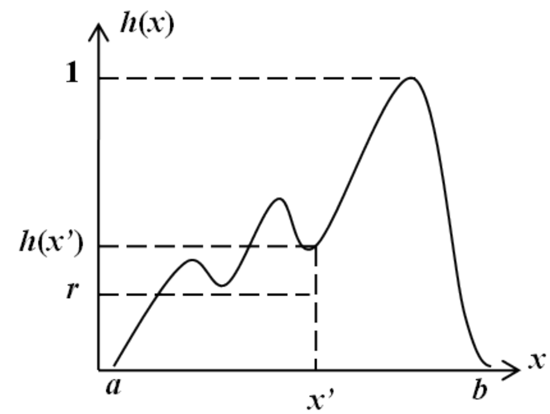
- Given a pdf $f_X(x)$ limited in (a,b), let

$$h(x) = \frac{f_X(x)}{f_M}$$

so that $0 \le h(x) \le 1, \forall x \in (a,b)$



- The operative procedure to sample a realization of X from $f_X(x)$:
  - sample $X' \sim U(a,b)$, the tentative value for X, and calculate $h(X')$
  - sample $R \sim U[0,1)$. If $R <= h(X')$ the value X' is accepted; else start again.



Sampling by the Rejection Method: von Neumann Algorithm

- More generally:

$$X \sim f_X(x) = g_{X'}(x) \cdot H(x)$$

$$B_H : \max_x H(x)$$

$$h(x) = \frac{H(x)}{B_H}, \quad 0 \le h(x) \le 1$$

- The operative procedure:
  - sample $X' \sim g_{X'}(x)$, and calculate $h(X')$
  - sample $R \sim U[0,1)$. If $R \le h(X')$ the value X' is accepted; else start again.

- We show that the accepted value is actually a realization of X sampled from $f_X(x)$

1. $$P\left[X' \le x \mid \text{accepted}\right] = \frac{P\left[X' \le x \cap \text{accepted}\right]}{\text{P}\left[\text{accepted}\right]} = \frac{P\left[X' \le x \cap \text{R} \le \text{h(X')}\right]}{\text{P}\left[\text{accepted}\right]}$$

Sampling by the Rejection Method: von Neumann Algorithm

2. $$P\left[z \le X' \le z + dz \cap \text{accepted}\right] = P\left[z \le X' \le z + dz\right] P\left[R \le h(z)\right] =$$
$$= g_{X'}(z)dz \cdot h(z)$$

3. $$P\left[X' \le x \cap R \le h(X')\right] = \int_{-\infty}^{x} g_{X'}(z)dz \cdot h(z)$$

4. $$P\left[\text{accepted}\right] = \int_{-\infty}^{\infty} g_{X'}(z)dz \cdot h(z) =$$
$$= \frac{1}{B_H} \int_{-\infty}^{\infty} g_{X'}(z)dz \cdot H(z) = \frac{1}{B_H} \int_{-\infty}^{\infty} f_X(x)dx = \frac{1}{B_H}$$

Sampling by the Rejection Method: von Neumann Algorithm

$$P\left[X' \le x \middle| \text{accepted}\right] = \frac{P\left[X' \le x \cap R \le h(x')\right]}{P[\text{accepted}]} = \frac{\int_{-\infty}^{x} g_{X'}(z)dz \cdot h(z)}{\frac{1}{B_H}}$$

$$= \int_{-\infty}^{x} g_{X'}(z)dz \cdot H(z) = \int_{-\infty}^{x} f_X(z)dz = F_X(x)$$

- The efficiency of the method is given by the probability of accepted:

$$\varepsilon = P[\text{accepted}] = \int_{-\infty}^{\infty} g_{X'}(z)h(z)dz = \frac{1}{B_H}$$

Example

- Sample from the pdf:

$$f_X(x) = \frac{2}{\pi} \cdot \frac{1}{(1+x)\sqrt{x}} \qquad 0 \le x \le 1$$

CONTENTS

- Sampling
- Evaluation of definite integrals
- Simulation of system transport
- Simulation for reliability/availability analysis

EVALUATION OF DEFINITE INTEGRALS

MC Evaluation of Definite Integrals (1D)

Analog Case

$$G = \int_a^b g(x) f(x) dx$$

$$f(x) \equiv \text{pdf} \quad \rightarrow \quad f(x) \geq 0 \quad ; \quad \int f(x) dx = 1$$

MC analog dart game: sample x from $f(x)$

- the probability that a shot hits $x \in dx$ is $f(x)dx$
- the award is $g(x)$

Consider N trials with result $\{x_1, x_2, \ldots, x_n\}$: the average award is

$$G_N = \frac{1}{N} \sum_{i=1}^{N} g(x_i)$$

MC Evaluation of Definite Integrals (1D)

Example

$$G = \int_0^1 \cos\left(\frac{\pi}{2} x\right) dx$$

MC Evaluation of Definite Integrals (1D) Example

Consider the Weibull Distribution:

$$F_T(t) = 1 - e^{-\beta t^{\alpha}}, \qquad f_T(t) = \alpha\beta t^{\alpha-1} e^{-\beta t^{\alpha}}$$

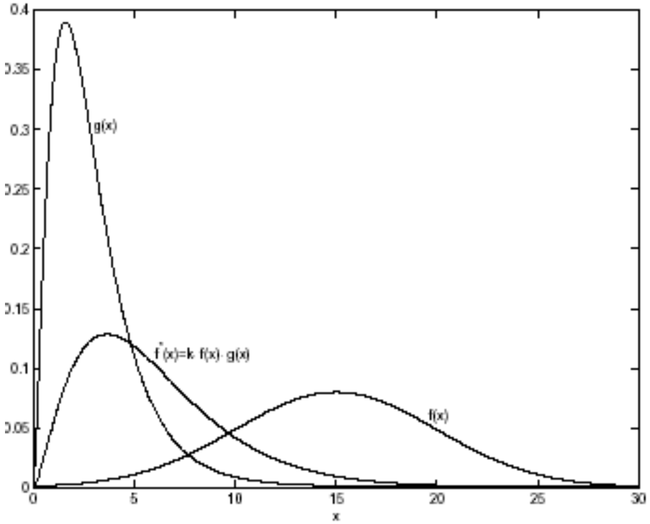
With $\alpha = 1.5, \beta = 1$

1. Sample *N* = 1000 values from $f_T(t)$
2. Verify that the 1000 sample are distributed according to $f_T(t)$
3. Provide an estimate G_N of $\int_0^{+\infty} t \cdot f_T(t)dt$
4. Estimate the variance of G_N
5. Draw your conclusion considering that:

$$\int_0^{+\infty} t \cdot f_T(t)dt = \Gamma(5/3) = 0.90275$$

MC Evaluation of Definite Integrals (1D)

Biased Case



The expression for *G* may be written

$$G = \int_D \left[\frac{f(x)}{f_1(x)} g(x) \right] f_1(x) dx \equiv \int_D g_1(x) f_1(x) dx$$

MC biased dart game: sample *x* from $f_1(x)$

- the probability that a shot hits $x \in dx$ is $f_1(x)dx$
- the award is

$$g_1(x) = \frac{f(x)}{f_1(x)} g(x) \quad \Rightarrow \quad G_{1N} = \frac{1}{N} \sum_{i=1}^{N} g_1(x_i)$$

MC Evaluation of Definite Integrals (1D)

Example

$$G = \int_0^1 \cos\left(\frac{\pi}{2}x\right)dx$$

The pdf $f_1^*(x)$ is: $f_1^*(x) = a - bx^2$ $\quad a = \frac{3}{2} = 1.5$

SIMULATION OF SYSTEM TRANSPORT

Monte Carlo simulation for system reliability

PLANT = system of *Nc* suitably connected components.

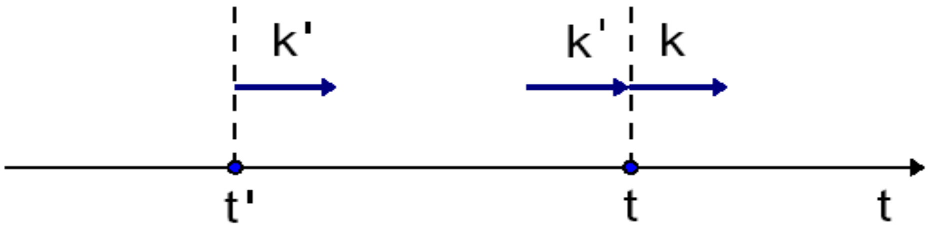
COMPONENT = a subsystem of the plant (pump, valve,...) which may stay in different exclusive (multi)states (nominal, failed, stand-by,...). Stochastic transitions from state-to-state occur at stochastic times.

STATE of the PLANT at t = the set of the states in which the *Nc* components stay at t. The states of the plant are labeled by a scalar which enumerates all the possible combinations of all the component states.

PLANT TRANSITION = when any one of the plant components performs a state transition we say that the plant has performed a transition. The time at which the plant performs the n-th transition is called t_n and the plant state thereby entered is called k_n.

PLANT LIFE = stochastic process.

Stochastic Transitions: Governing Probabilities



$T(t \,/\, t'; k')dt$ = conditional probability of a transition at $t \in dt$, given that the preceding transition occurred at t' and that the state thereby entered was k'.

$C(k \,/\, k'; t)$ = conditional probability that the plant enters state k, given that a transition occurred at time t when the system was in state k'.

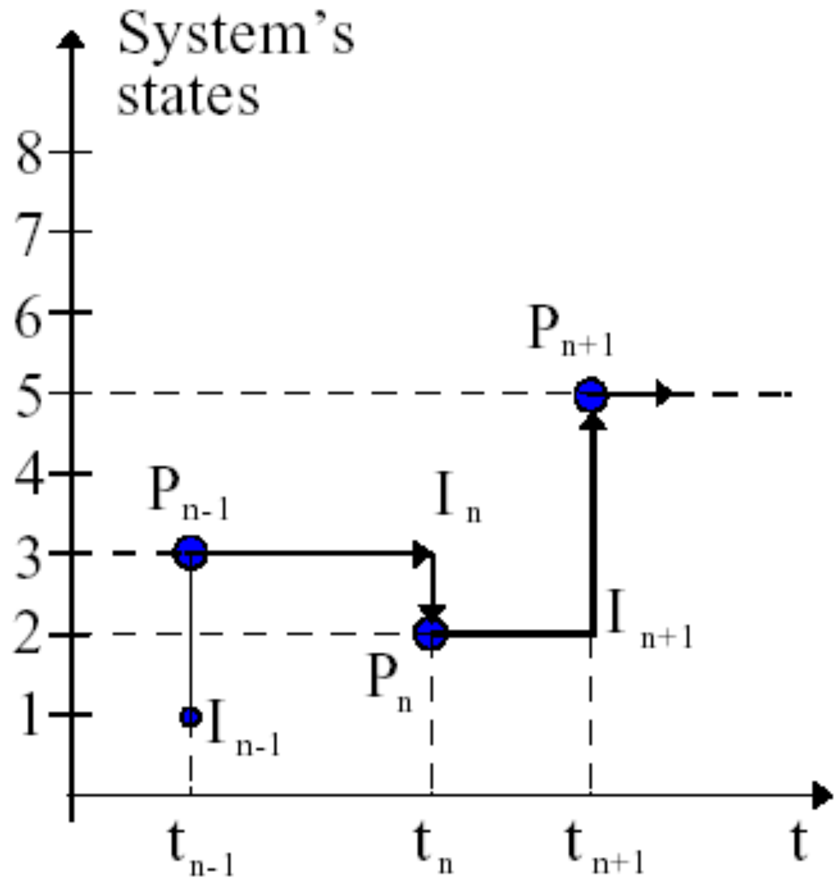
Both these probabilities form the ”trasport kernel” :

$$K(t; k \,/\, t'; k')dt = T(t \,/\, t'; k')dt\, C(k \,/\, k'; t)$$

$\psi(t; k)$ = ingoing transition density or probability density function (pdf) of a system transition at t, resulting in the entrance in state k

Plant life: random walk

Random walk = realization of the system life generated by the underlying state-transition stochastic process.



The von Neumann's Approach and the Transport Equation

The transition density $\psi(t; k)$ is expanded in series of the partial transition densities:

$\psi^n(t; k)$ = pdf that the system performs the n–th transition at t, entering the state k.

Then, $$\psi(t,k) = \sum_{n=0}^{\infty} \psi^n(t,k) =$$

$$= \psi^0(t,k) + \sum_{k'} \int_{t_0}^{t} dt' \psi(t',k') K(t,k \mid t',k')$$

Transport equation for the plant states

Monte Carlo Solution to the Transport Equation (1)

Von Neumann approach:

- Initial Conditions: $t_0 = t^*$, $k_0 = k^*$, $P_0 \equiv P^*$
- The subsequent transition densities in the random walk:

$$\psi^1(t_1, k_1) = K(t_1, k_1 | t_0, k_0)$$

$$\psi^2(t_2, k_2) = \sum_{k_1} \int_{t^*}^{t_2} \psi^1(t_1, k_1) dt_1 K(t_2, k_2 | t_1, k_1)$$

$$\cdots\cdots$$

$$\psi^n(t_n, k_n) = \sum_{k_{n-1}} \int_{t^*}^{t_n} \psi^{n-1}(t_{n-1}, k_{n-1}) dt_{n-1} K(t_n, k_n | t_{n-1}, k_{n-1})$$

- Changing notation:

$$t_n \rightarrow t \qquad k_{n-1} \rightarrow k'$$

$$t_{n-1} \rightarrow t' \qquad k_n \rightarrow k$$

Monte Carlo Solution to the Transport Equation (2)

$$\psi^{n}(t,k) = \sum_{k'} \int_{t^*}^{t} \psi^{n-1}(t',k')dt'K(t,k \mid t',k')$$

$$\Rightarrow \psi(t,k) = \sum_{n=0}^{\infty} \psi^{n}(t,k) = \psi^{0}(t,k) +$$

$$+ \sum_{k'} \int_{t^*}^{t} \underbrace{\sum_{n-1=0}^{\infty} \psi^{n-1}(t',k')}_{\psi(t',k')} dt' K(t,k \mid t',k')$$

$$\left(\sum_{n-1=0}^{\infty} \psi^{n-1}(t',k') = \psi(t',k') \right)$$

Monte Carlo Solution to the Transport Equation (3)

Initial Conditions: (t*, k*)

Formally rewrite the partial transition densities:

$$\psi^1(t_1,k_1) = \sum_{k_0}\int_{t^*}^{t_1} dt_0 \psi^0(t_0,k_0) K(t_1,k_1|t_0,k_0) = K(t_1,k_1|t^*,k^*)$$

$$\psi^2(t_2,k_2) = \sum_{k_1}\int_{t^*}^{t_2} dt_1 \psi^1(t_1,k_1) K(t_2,k_2|t_1,k_1) =$$

$$= \sum_{k_1}\int_{t^*}^{t_2} dt_1 K(t_1,k_1|t^*,k^*) K(t_2,k_2|t_1,k_1)$$

……

$$\psi^n(t,k) = \sum_{k_1,k_2,\ldots,k_{n-1}} \int_{t^*}^{t_n} dt_{n-1} \int_{t^*}^{t_{n-1}} dt_{n-2} \ldots$$

$$\ldots \int_{t^*}^{t_2} dt_1 K(t_1,k_1|t^*,k^*) K(t_2,k_2|t_1,k_1) \cdots K(t,k|t_{n-1},k_{n-1})$$

MC Evaluation of Definite Integrals

$$G = \int_a^b g(x) f(x) dx$$

$$f(x) \equiv \text{pdf} \quad \rightarrow \quad f(x) \geq 0 \quad ; \quad \int f(x) dx = 1$$

•MC analog dart game: sample $x = (t1, k1; t2, k2; ...)$ from

$f(x) = \; K(t_1, k_1 | t^*, k^*) K(t_2, k_2 | t_1, k_1) \cdots K(t, k | t_{n-1}, k_{n-1})$

• the probability that a shot hits $x \in dx$ is $f(x)dx$

• the award is $g(x)=1$

Consider N trials with result $\{x_1, x_2, \ldots, x_n\}$: the average award is

$$G_N = \frac{1}{N} \sum_{i=1}^{N} g(x_i)$$

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SIMULATION FOR SYSTEM RELIABILITY ANALYSIS

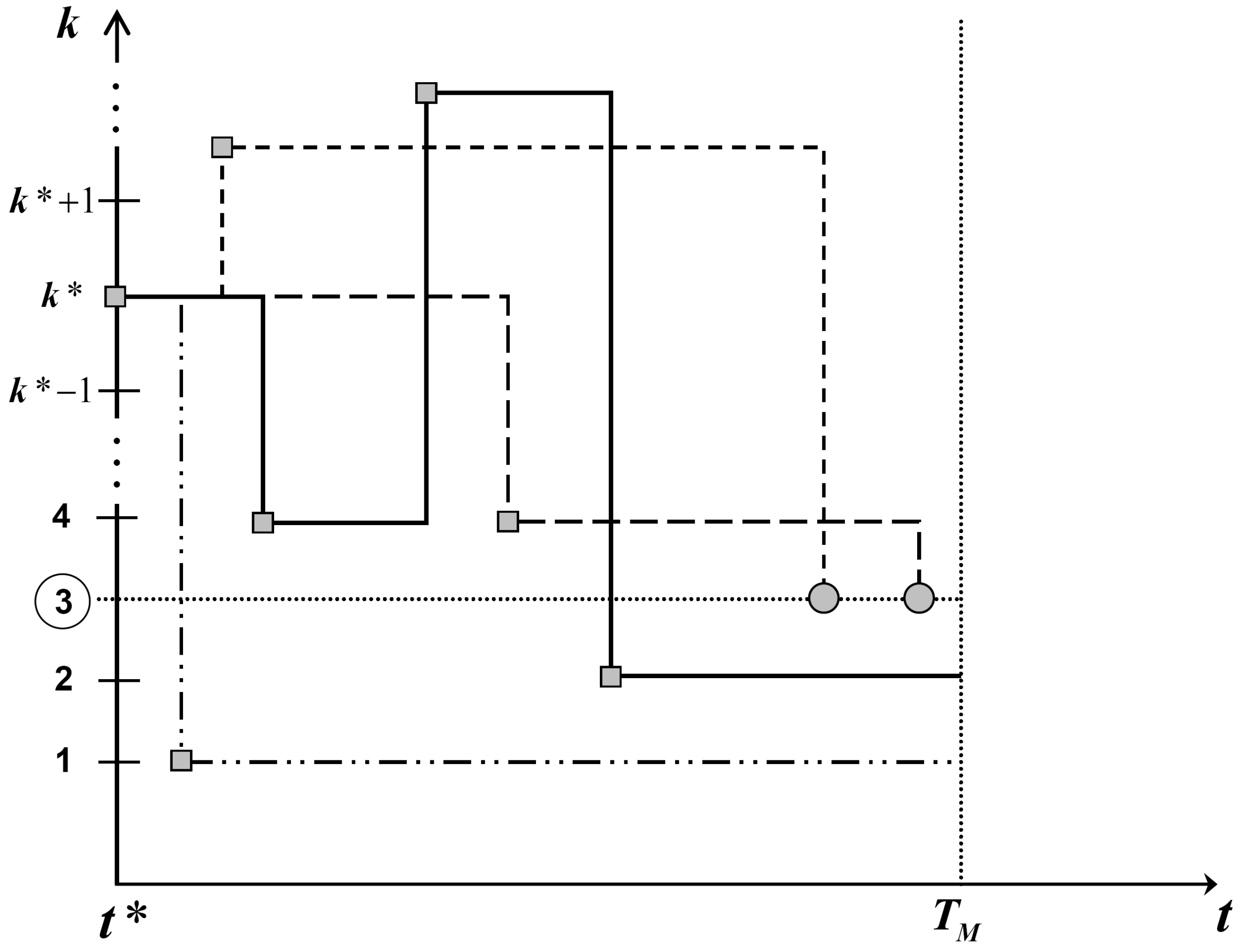
Monte Carlo Simulation in RAMS

$$G(t) = \sum_{k \in \Gamma} \int_0^t \psi(\tau, k) R_k(\tau, t) d\tau$$ Expected value

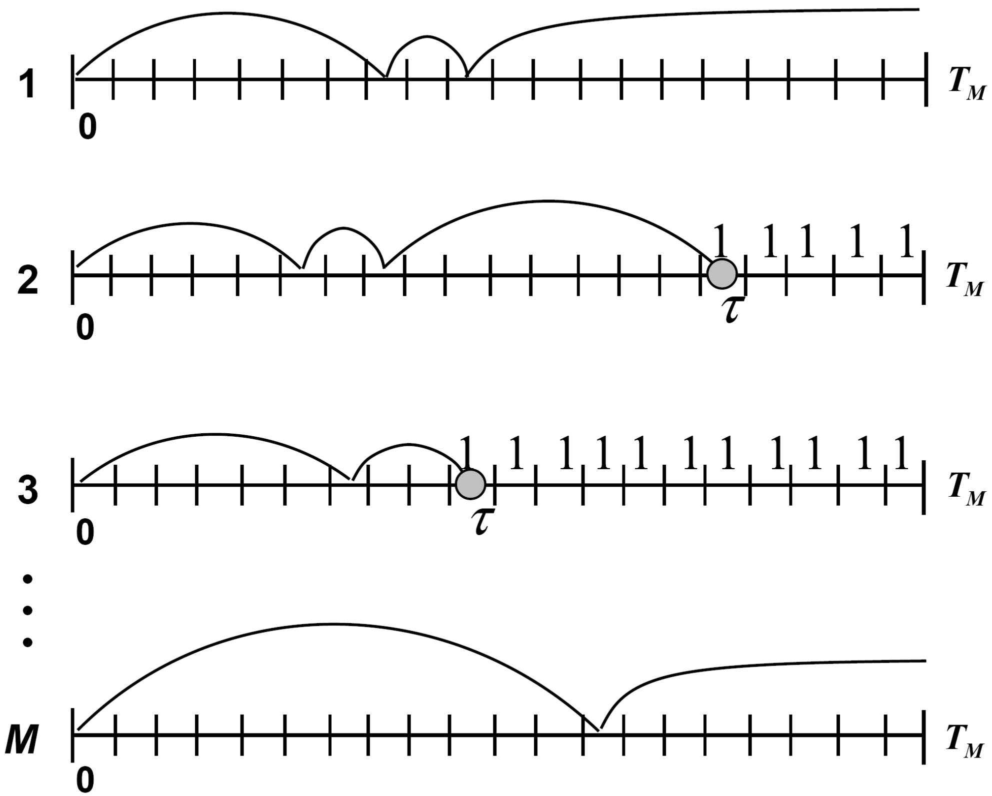
- *Γ = subset of all system failure states*
- *$R_k(\tau,t) = 1 \Rightarrow G(t) =$ unreliability*
- *$R_k(\tau,t) =$ prob. system not exiting before t from the state k entered at $\tau < t$*

  $\Rightarrow G(t) =$ unavailability

Monte Carlo solution of a definite integral: expected value ≅ sample mean



k
k*+1
k*
k*−1
4
3
2
1
t*
T_M
t



$$C^R(t) = C_R(t) \quad t \in [0, T_M]$$

$$C^R(t) = C^R(t) + 1 \quad t \in [\tau, T_M]$$

$$C^R(t) = C^R(t) + 1 \quad t \in [\tau, T_M]$$

$$C_R(t) = C^R(t) \quad t \in [0, T_M]$$

$$\hat{F}_T(t) = \frac{C_R(t)}{M}$$

Monte Carlo Simulation Approaches

- Each trial of a Monte Carlo simulation consists in generating a random walk which guides the system from one configuration to another, at different times.

- During a trial, starting from a given system configuration k' at t', we need to determine when the next transition occurs and which is the new configuration reached by the system as a consequence of the transition.

- This can be done in two ways which give rise to the so called "indirect" and "direct" Monte Carlo approach.

Indirect Monte Carlo

The <u>indirect approach</u> consists in:

1. Sampling first the time t of a system trans$T\left(t|t',k'\right)$om the corresponding conditional probability density of the system performing one of its possible transitions out of k' entered at time t'.

2. Sampling the transition to the new configuration k from the conditional probability $C\left(k|t,k'\right)$ that the system enters the new state k given that a transition has occurred at t starting from the system in state k'.

3. Repeating the procedure from k' at time t to the next transition.

Direct Monte Carlo (1)

The direct approach differs from the previous one in that the system transitions are not sampled by considering the distributions for the whole system but rather by sampling directly the times of all possible transitions of all individual components of the system and then arranging the transitions along a timeline, in accordance to their times of occurrence. Obviously, this timeline is updated after each transition occurs, to include the new possible transitions that the transient component can perform from its new state. In other words, during a trial starting from a given system configuration k' at t':

1. We sample the times of transition $t^{i}_{j'_i \to m_i}$, $m_i = 1,2,...,N_{S_i}$, of each component i, i = 1, 2,…, N_c leaving its current state j'_i and arriving to the state m_i from the corresponding transition time probability distributions $f_T^{i,j'_i \to m_i}(t|t')$.
2. The time instants $t^{i}_{j'_i \to m_i}$ thereby obtained are arranged in ascending order along a timeline from t_{min} to $t_{max} \leq T_M$

Direct Monte Carlo (2)

3. The clock time of the trial is moved to the first occurring transition time t_{min}= t* in correspondence of which the system configuration is changed, i.e. the component i* undergoing the transition is moved to its new state m_i*.

4. At this point, the new times of transition $t^{i^*}_{m_i^* \rightarrow l_i^*}$, $l_i^* = 1,2,\ldots, N^{i^*}_S$, of component i* out of its current state m_i* are sampled from the corresponding transition time probability distributions, $f_T^{i^*, m_i^* \rightarrow l_i^*}(t | t^*)$, and placed in the proper position of the timeline.

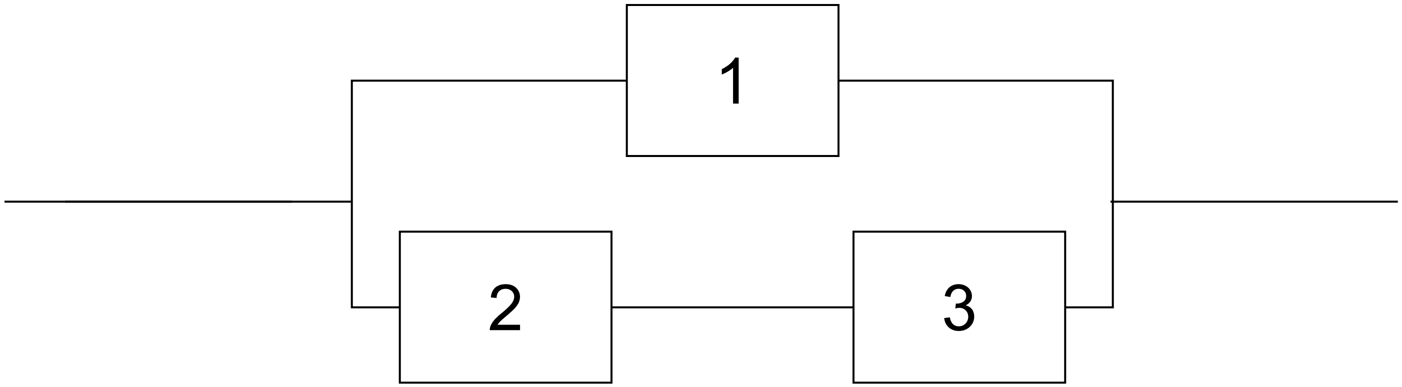
5. The clock time and the system are then moved to the next first occurring transition time and corresponding new configuration, respectively.

6. The procedure repeats until the next first occurring transition time falls beyond the mission time, i.e. $t_{min} > T_M$.

Compared to the previous indirect method, the direct approach is more suitable for systems whose components' failure and repair behaviours are represented by different stochastic distribution laws.

Exercise

- Consider the following system



- Transition rates:

Failure: $\lambda_1 = 0.001$; $\lambda_2 = 0.002$; $\lambda_3 = 0.005$;

Repair: $\mu_1 = 0.1$; $\mu_2 = 0.15$; $\mu_3 = 0.05$;

- Estimate the **reliability** and **availability** of the system over a mission time $T_{miss} = 500$

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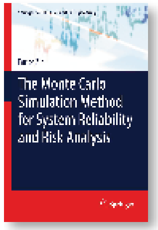

2013, 2013, XIV, 198 p. 69 illus., 24 in color.

Printed book

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