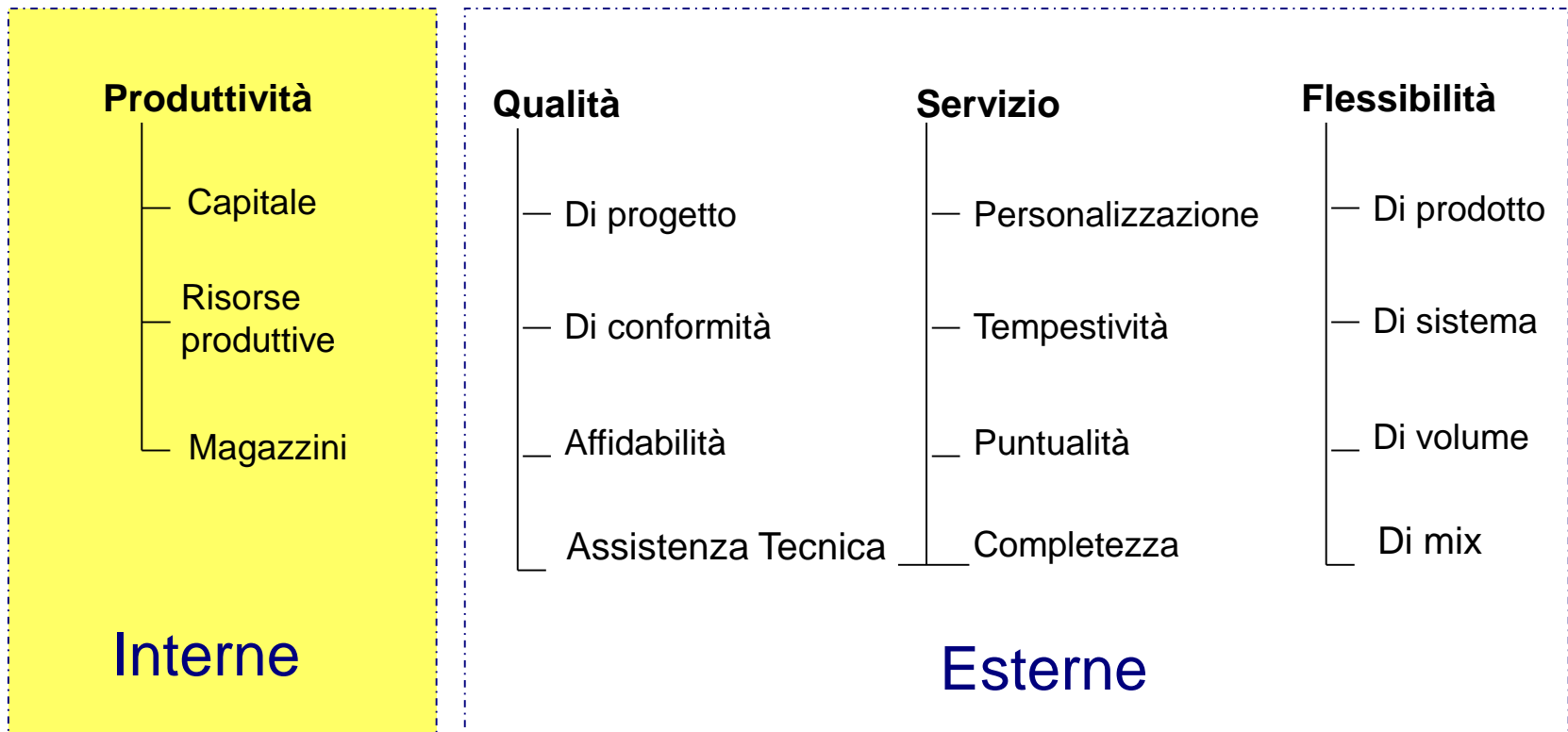# Performance analysis of production systems – methods for reliability and availability analysis

Marco Macchi

Performance framework

Reliability

The Reliability analysis deals with the statistical analysis of failures.

The main outcomes from the Reliability theory are:

- the ability to forecast the life duration of an entity
- the evaluation of the entity availability
- the estimation of the entity life cycle cost

Reliability is evaluated based on experiments or historical data.

Reliability

Reliability is defined as the **probability** that an entity (an industrial asset, as a machine or production equipment) **is working regularly** (i.e. it delivers its standard service), after a given **time T** and under **assigned working conditions**.

T is expressed with a reference variable of the usage of the entity (time, number of operating cycle, number of travelled kilometers)
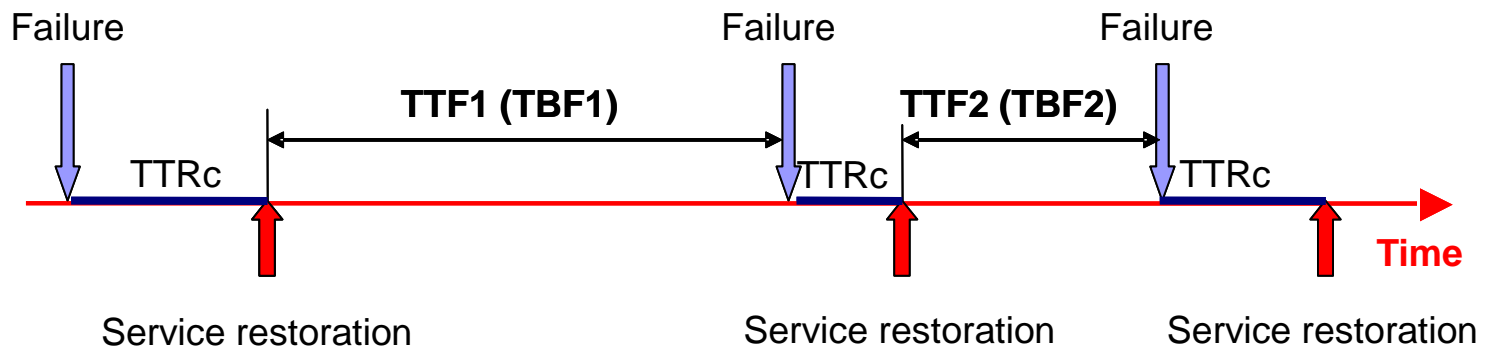
Example:
- for a neon tube, in interiors, reliability R may be 98%, at 2000 hours
- for the same neon tube, in outside installation, R = 93% at 2000 hours

Analysis of failure times

TTF or TBF (**Time To Failure, Time Between Failures**): it is the calendar time intercurring between 2 sequential failures (for a repairable/not repairable entity).

OTTF or OTBF (**Operating Time To/Between Failures**): it is the time between 2 sequential failure measured on the cumulated operating time (for a repairable/not repairable entity).

- MTTF (Mean Time To Failure): it is the **mean time to failure of non repairable entities** (it can be evaluated considering both the calendar or the operating time , i.e. OTTF)

- MTBF (Mean Time Between Failures): it is the **mean time between failures of repairable entities** (also, it can be evaluated considering both the calendar or the operating time, i.e. OTBF)

Failure   Failure   Failure

TTF1 (TBF1)   **TTF2 (TBF2)**

TTRc   TTRc   TTRc

Time

Service restoration   Service restoration   Service restoration

Maintenance repair times

TTR (Time To Repair) is defined as the time necessary to recover an entity from the fault state to its full functionality.

The **Time To Repair (TTR)** is made of the following components:

- ☐ *TMA: Time for Maintenance Alert* (i.e. administrative time and time for alerting the maintenance service)
- ☐ *TD: Time for Diagnosis* (i.e. detection of the failure, discovery/isolation of the failure cause)
- ☐ *TLD: Time for Logistic Delay* (i.e. finding of the repair method, of the spare parts and fixtures, set-up time for repairing)
- ☐ *TAR: Time for Active Repair* (i.e. net time of repair)
- ☐ *TRS: Time for Service Re-activation* (i.e. entity restart time after repair)

NB: the duration of every time component is affected in a random way by disturbances of various types.
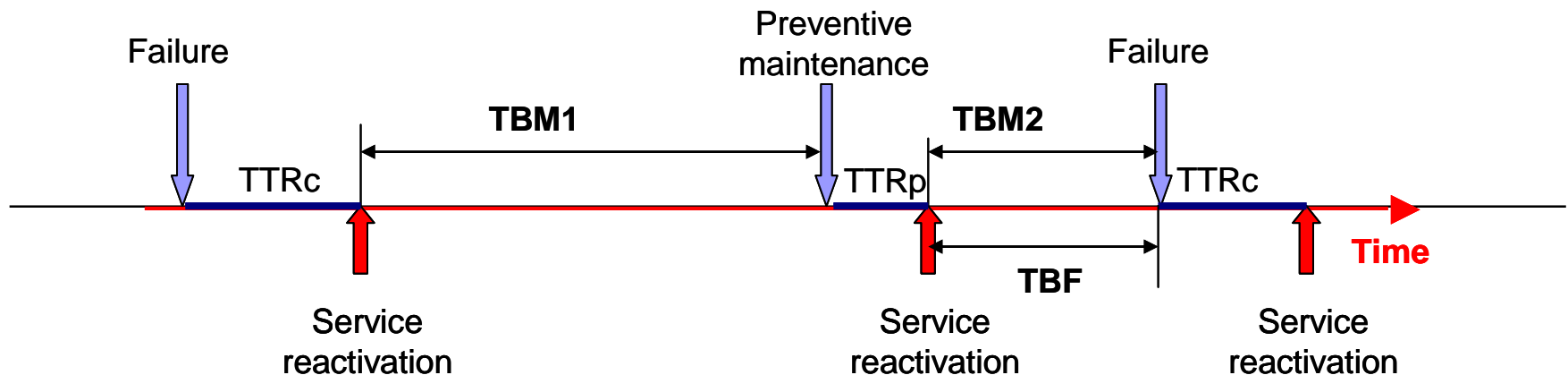
Mean Time Between Maintenance

Considering the policies (corrective & preventive) another indicator can be defined, i.e. the TBM = Time Between Maintenance

TBF= Time Between Failures
TBM = Time Between Maintenance
MTBM = Mean Time Between Maintenance

MTBM = Mean Time Between Maintenance
If failure data are known, then MTBM can be calculated this way:

$$MTBM = \sum_{i}^{N} \frac{TBM_i}{N}$$

MTBM value depends on TBF values and on the preventive service interval.

Reliability & Maintenability indicators

Reliability

R(T) probability not to have a failure for t<=T

Mean Time To Failure (not repairable entities)

    MTTF (Mean Time To Failure) = 1 / λ (only for λ = constant)

Mean Time Between Failures (repairable entities)

    MTBF (Mean Time Between Failures) = 1 / λ (only for λ = constant)

Mean Time Between Maintenance (also preventive)

    MTBM (Mean Time Between Maintenance)
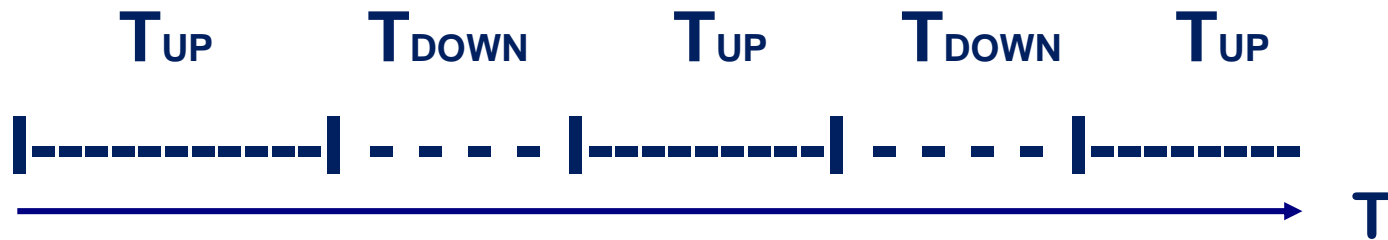
Maintenability

M(T) probability to have a repair for t<=T

MTTR (Mean Time To Repair) (average of TTR values)

MDT (Mean Down Time) (average of DT values)

Availability (1)

Availability A(T) of an entity is defined as the service level it is capable to offer, for a given time period T and for a given standard working condition.

$$T_{UP} \qquad T_{DOWN} \qquad T_{UP} \qquad T_{DOWN} \qquad T_{UP}$$

|-----------| - - - - |----------| - - - - |--------

$$\longrightarrow T$$

A(T) may be calculated the following way:

$$A = \frac{\Sigma\, T_{UP}}{\Sigma\, T_{UP} + \Sigma\, T_{DOWN}}$$

Availability (2)

Thus Availability is the percentage of the effective service time to the total time of service request.

Example: A (T) = 95% > the percentage of available service time of the equipment is 95% over time T of service request.

Availability indicators

Inherent Availability $Ai = \dfrac{MTBF}{MTBF + MTTRc}$ (the same with MTTF)

Achieved Availability $Aa = \dfrac{MTBM}{MTBM + MTTR(c+p)}$

Operational Availability $Ao = \dfrac{MTBM}{MTBM + MDT(c+p)}$

MTBF : Mean Time Between Failures
MTTF : Mean Time To Failure
MTBM: Mean Time Between Maintenance
MTTRc : Mean Time To Repair (corrective policy)
MTTR(c+p) : Mean Time To Repair (corrective & preventive policy)
MDT(c+p) : Mean Down Time (corrective & preventive policy)

Maintenance policies

We call **maintenance policies** the criteria and strategies we use in making maintenance.

Maintenance policies are the following:

A) ***Corrective Maintenance (after the failure)***

B) ***Preventive Maintenance (before the failure)***
   B.1 – Cyclic maintenance (clock based/age based) -> TBM (time based maint.)
   B.2 – Condition based maintenance (on condition) -> CBM
      B.2.1 – Predictive maintenance (trend analysis of the condition)

Besides, some accompanying maintenance measures are considered:
   ☐ *Opportunistic maintenance*
   ☐ *Productive maintenance*

Maintenance policies

A) **Corrective Maintenance (CM)**:

maintenance intervention is performed after failure occurrence

B) **Preventive Maintenance (PM)**:

maintenance intervention is performed before failure occurence

We have 3 types of PM:

B.1) **Cyclic Maintenance, TBM**: PM actions are carried out at i) set-times (clock-based) or ii) at a fixed age/usage of the component (age-based)

B.2) **Condition Based Maintenance, CBM**: PM actions are based on the condition of the component being maintained. This involves monitoring of one or more parameters characterizing the wear process (e.g. crack growth in a mechanical component).

B.2.1) **Predictive Maintenance**: PM actions are based on the evaluation of the trend of one or more parameters, that are clearly linked to the wear process (normally through a mathematical model).
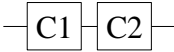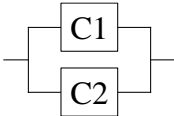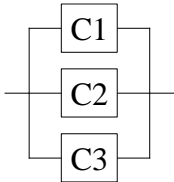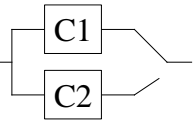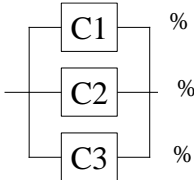
Introduction to RBD method

The Reliability Block Diagram (RBD) method is a powerful tool for describing the combined effect of a component failure in a complex system made of many components. In particular it allows to calculate the reliability at system level (overall reliability), taking into account the reliability level of each component and the configuration of components into the system.

The RBD method is deployed in two main steps:

- **Logical – functional analysis** of the system configuration (e.g. through the flow sheet) for translating it into the so called Block Diagram (RBD)

- **Reliability calculation** (on the basis of the RBD map)

Introduction to RBD method

Types of RBD models for different components relationships:

| RBD Model	RBD	Semantics
RBD series	C1 — C2	Components C1 and C2 are connected in series
RBD parallel (total redundancy)	C1 / C2	Components C1 and C2 are connected in parallel, in total redundancy
RBD parallel (partial redundancy)	C1 / C2 / C3	Components C1 …Cn are connected in parallel, in partial redundancy (k over n components are required for system to work)
RBD parallel (standby)	C1 / C2	Components C1 and C2 are connected in parallel, in total redundancy, with component C2 hold in stand-by
RBD parallel multi state (fractioning)	C1 % / C2 % / C3 %	Components C1, C2 and C3 are connected in parallel and they have different capacity, therefore a component's failure involves a loss of capacity corresponding to the impact factor % of the failed component.

RBD: series model

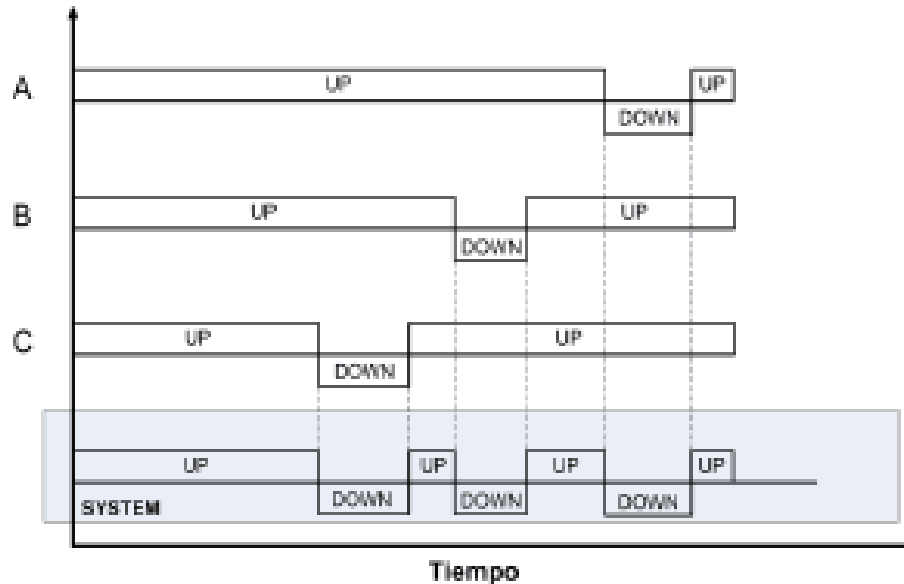## Definition - Calculation formula – Example – Interdependencies

The failure of a single components generates the overall system failure

Formula:
$$R_{series}(T) = \prod_{i=1}^{n} R_{components\_i}(T)$$

Example:

$$\boxed{A} - \boxed{B} - \boxed{C}$$
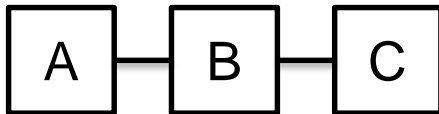
$$R_{system}(T) = R_A(T) * R_B(T) * R_C(T)$$

Every time a component is down, then the system is down
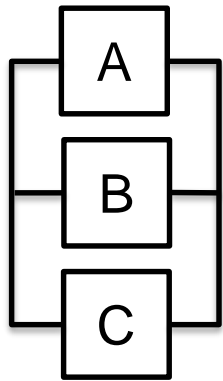
Interdependencies at system level:

RBD: parallel, total redundancy model

Definition - Calculation formula – Example – Interdependencies
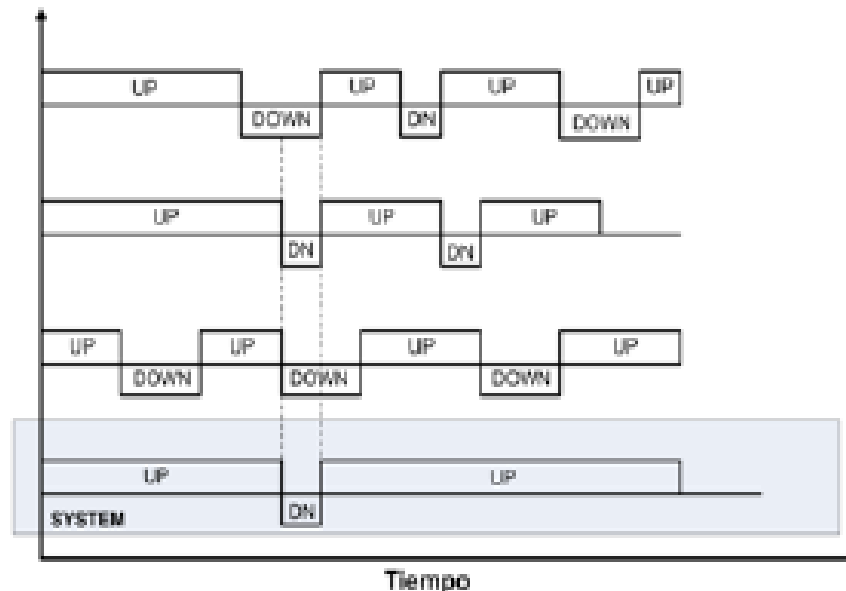
<u>The system is up, if at least one single component is up</u>

Formula:
$$R_{parallel,total\_redundancy}(T) = 1 - \prod_{i=1}^{n}(1 - R_{component\_i}(T))$$

Example:

$$R_{system}(T) = 1 - ((1 - R_A(T)) * (1 - R_B(T)) * (1 - R_C(T)))$$

A

B

C

Every time a component is up, the system is up

Interdependencies at system level:

RBD: parallel, partial redundancy model

Definition - Calculation formula – Example – Interdependencies

The system is a parallel model of n components, but it requires al least k components over n for working

Formula:

$$R_{S,k\_out\_of\_n}(T) = \sum_{j=k}^{n}\left(\binom{n}{j}R_{component}^{j}(1-R_{component})^{n-j}\right)$$

where: $\binom{n}{k} = \frac{n!}{k!(n-k)!}$.

with $R_{component\_i} = R_{component}$; $\forall i$

(3 : 2)

Only if k components over n are down, then the system is down

Interdependencies at system level:

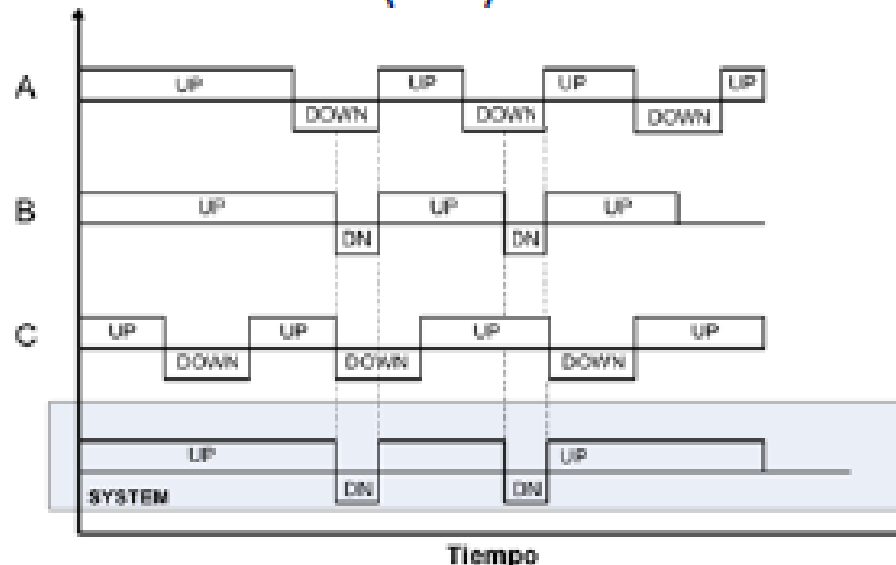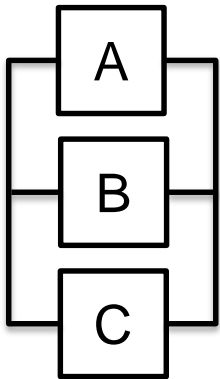# RBD: parallel, partial redundancy model

Definition - Calculation formula – Example – Interdependencies

<u>The system is a parallel model of n components, but it requires al least k components over n for working</u>

Example: Ra = Rb = Rc = R = 0,8 (case of components with same reliability)

$$R_{S,2\_out\_of\_3}(T) = \sum_{j=2}^{3}\left(\binom{3}{j}R_{component}^{j}(1-R_{component})^{3-j}\right)$$

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} \;.$$

$$R_{S,2\_out\_of\_3}(T) = \binom{3}{2}R^2 * (1-R)^{3-2} + \binom{3}{3}R^3 * (1-R)^{3-3} = 3R^2 * (1-R) + R^3$$

RBD: parallel, fractioning model

Multi-state system (MSS) logic -> system model with multi-states

• an extension to the traditional RBD parallel model:

   • it enables to model a component unit / a subsystem working at different states (rather than only at the two states of working and fault) corresponding to different **performance levels / rates**;

   • an ′impact factor′ is adopted, to express the reduction with respect to the nominal performance level / rate of the subsystem, when a component fails.

E.g. 2 machines, the former having an ′impact factor′, when it fails, equal to 25 % of the nominal performance rate of the subsystem, the latter with an ′impact factor′, when it fails, equal to 75 %.

Properties of series systems

The reliability of a "series" system is always lower than the reliability of the less reliable system component.

E.g., with 4 installed pumps:

$R_{series}(T) = 0,7 * 0,8 * 0,8 * 0,9 = 0,403 = 40,3 \% < 0,7 =$

$= \min \{R_A(T), R_B(T), R_C(T), R_D(T)\}$

The reliability of a "series" system is a decreasing function of the number of system components.

If we consider only 3 pumps (A, B, C) instead of 4, we have:

$R_{series}(T) = R_A(T) R_B(T) R_C(T) = 0,7*0,8*0,8 = 0,448 = 44,8 \% >$

$R_{series}(T) = R_A(T) R_B(T) R_C(T) R_D(T) = 0,7*0,8*0,8*0,9 = 0,403 = 40,3 \%$

Properties of parallel systems

The reliability of a total "redundancy parallel system" is higher than the reliability of the most reliable system component.

In case of parallel "1 out of 3":

$R_{parallel, total redundancy}(T) = 1- (1-0,7)*(1-0,8)*(1-0,9) = 0,994 = 99,4 \% > 0,9 = \max \{R_A(T), R_B(T), R_C(T)\}$
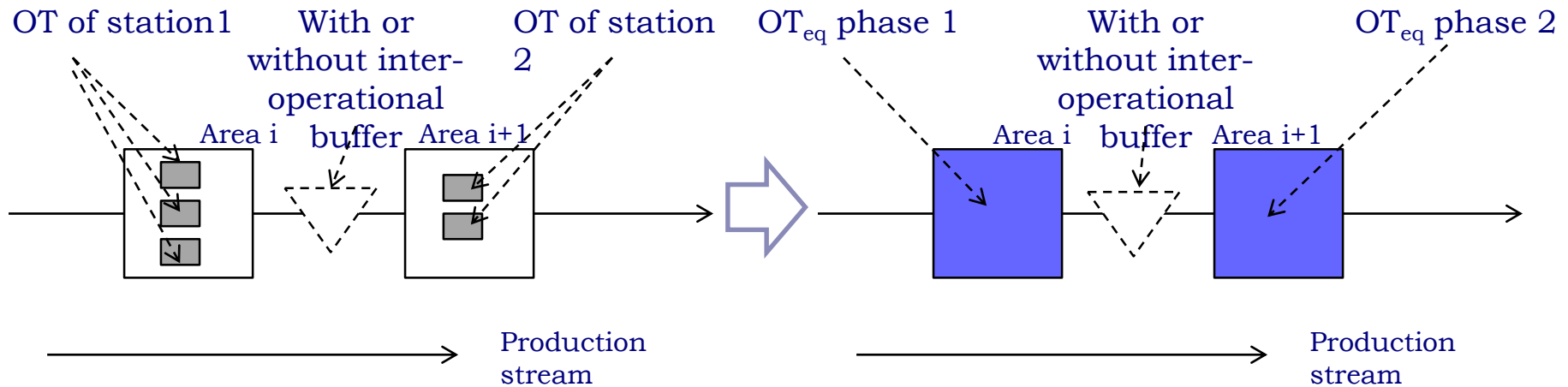
The reliability of a total "redundancy parallel system" is an increasing function of the number of system components.

Adding a pump (D) with $R_D(T) = 0,8$, we have:

$R_{parallel, total redundancy}(T) = 1- (1-0,7) * (1-0,8) * (1-0,8) * (1-0,9) = 0,9988 = = 99,88 \% >$

$R_{parallel, total redundancy}(T) = 1- (1-0,7) * (1-0,8) * (1-0,9) = 0,994 = 99,4 \%$

Definition – equivalent Operating Time (2)

OT of station1   With or without inter-operational buffer   OT of station 2 OT_{eq} phase 1   With or without inter-operational buffer OT_{eq} phase 2

Area i   Area i+1   Area i   Area i+1

Production stream   Production stream

OT of each workstation   →   OT of each phase

TH of a workstation   →   TH of a production phase

For a rough analysis (both nominal and effective value)
- TH phase i = Sum TH station j in phase / area i

To analyse reliability / availability of system
- it is needed to analyze the system in a logical-functional analysis (RBD scheme)

Nominal Throughput analysis (2)

Performance measure

From the analysis of the production capacity (throughput), it is possible to calculate directly the level of utilization of the different areas / phases of the production system.

$$UT_i = \frac{OT_{eq.,i}}{\max_i OT_{eq.,i}} = \frac{\min_i TH_i}{TH_i}$$

Arrival rate
$\lambda = TH_0$

UT phase 1 = UT_1

With or without inter-operational buffer

UT phase 2 = UT_2