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

Marco Macchi

Performance framework

Interne

- **Produttività**
  - Capitale
  - Risorse produttive
  - Magazzini

Esterne

- **Qualità**
  - Di progetto
  - Di conformità
  - Affidabilità
  - Assistenza Tecnica
- **Servizio**
  - Personalizzazione
  - Tempestività
  - Puntualità
  - Completezza
- **Flessibilità**
  - Di prodotto
  - Di sistema
  - Di volume
  - Di mix

Overall Equipment Effectiveness

- OEE is an internationally well known performance indicator, which measures the global performances of an production equipment / machineries.
  - OEE is made of three components
  - It can be used as a basis to measure the OEE of the production system

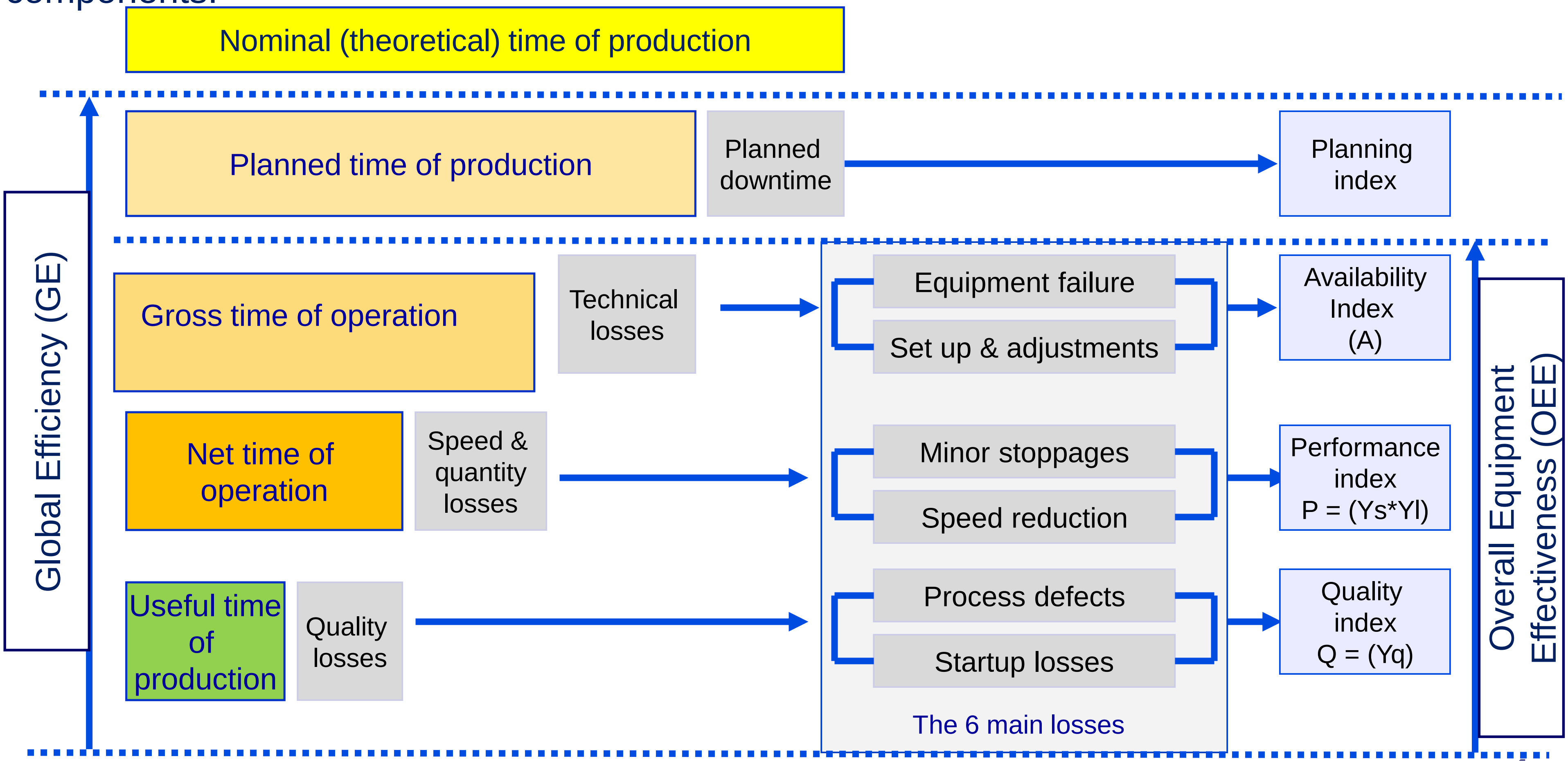
- OEE is used to monitor the improvement process of a production system
  - Measuring the efficiency of a machine along the planned time
  - Does not include when the machine is not planned for production

- Objective:
  - To reduce losses
  - To increase productivity
  - To improve quality (less scraps, reworks, ecc..)

Overall Equipment Effectiveness

OEE = Availability x Performance x Quality

OEE is an internationally well known performance indicator, which measures the global performances of an production equipment / system. OEE is made of the following components:

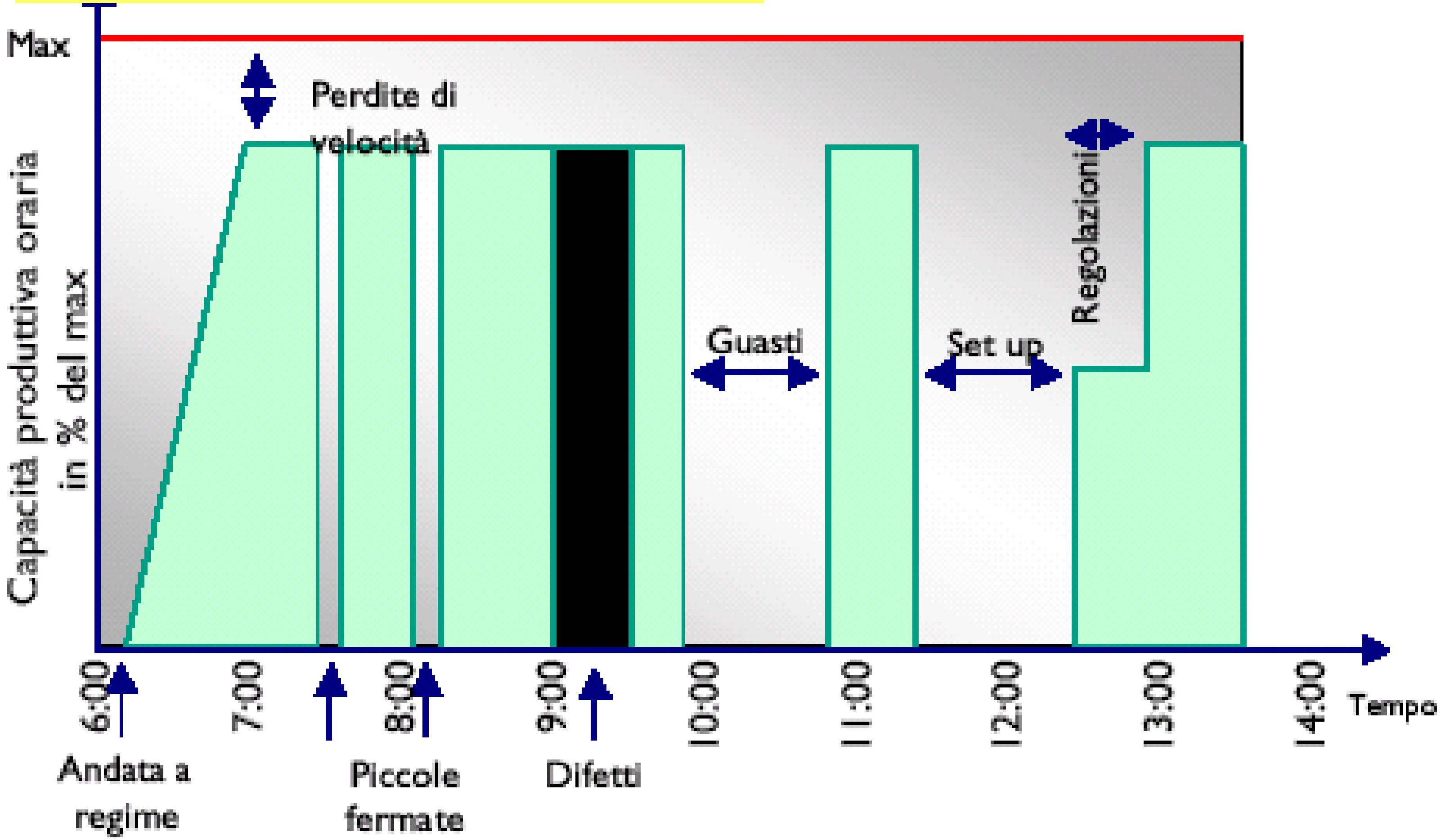


OEE

Effective «good» production

Production theoretically achievable

OEE = Area verde/ Area totale



OEE Calculation exercise

Calculate OEE for a production line of a company that produces mechanical parts, knowing the following data:

Nominal daily Working Time = 525 mins

Lunch break	30 mins/d
Planned maintenance	10 mins/d

Samplings	30 mins/d
Breakdowns	40 mins/d
Changeovers	90 mins/d
Materials waiting	10 mins/d

Total parts produced during operating time = 3869 parts
Nominal speed = 15 parts/min
Defective parts during operating time = 20 parts

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

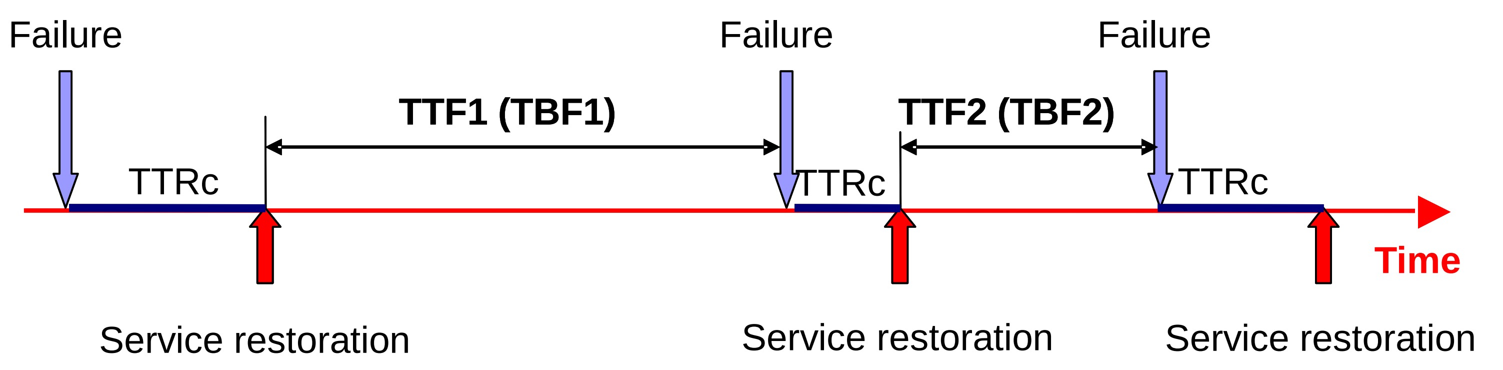
Analysis of failure times

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)



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:

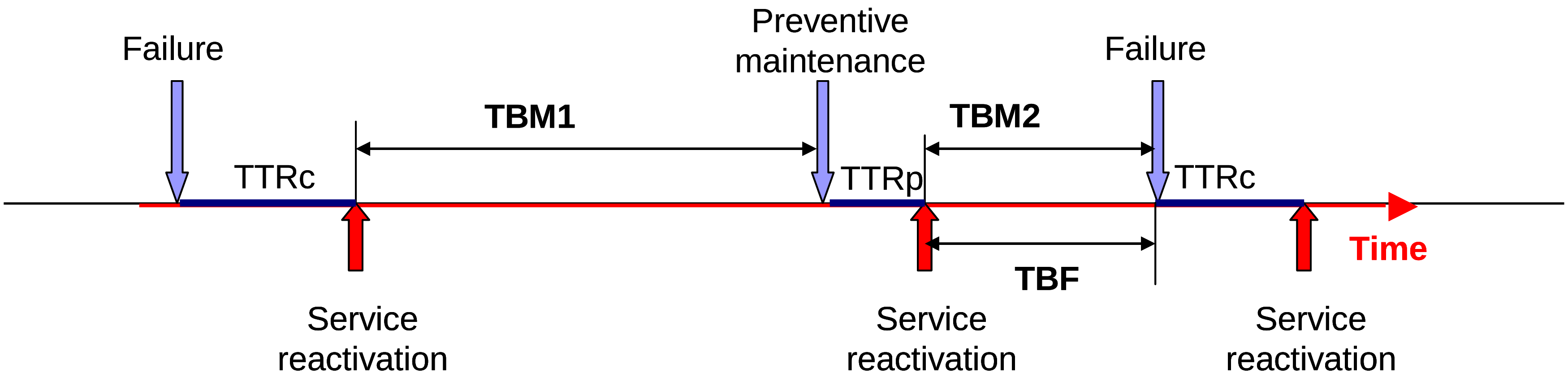
- *TMA: Time for Maintenance Alert* (i.e. administrative time and time for alerting the maintenance service)
- *TD: Time for Diagnosis* (i.e. detection of the failure, discovery/isolation of the failure cause)
- *TLD: Time for Logistic Delay* (i.e. finding of the repair method, of the spare parts and 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 $t \le T$

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

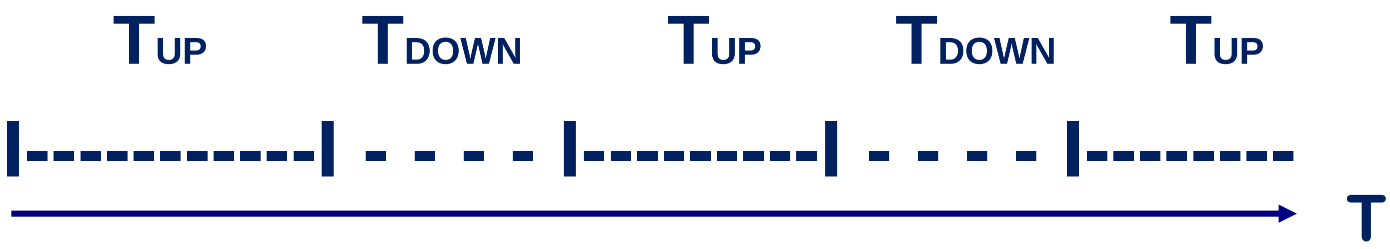
M(T) probability to have a repair for $t \le T$

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.



A(T) may be calculated the following way:

$$A = \frac{\sum T_{UP}}{\sum T_{UP} + \sum T_{DOWN}}$$

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

$$\text{Inherent Availability } A_i = \frac{MTBF}{MTBF + MTTRc}$$ (the same with MTTF)

$$\text{Achieved Availability } A_a = \frac{MTBM}{MTBM + MTTR(c+p)}$$

$$\text{Operational Availability } A_o = \frac{MTBM}{MTBM + MDT(c+p)}$$

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)

Introduction to RBD method

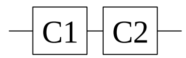
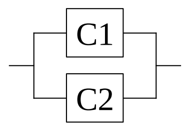
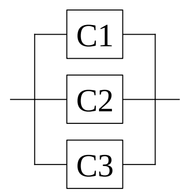
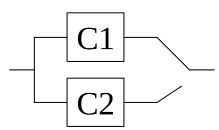
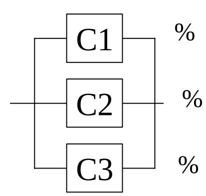
The Reliability Block Diagram (RBD) method is a powerful tool for describing the combined effect of a component failure in a complex system made of many components. In particular it allows to calculate the reliability at system level (overall reliability), taking into account the reliability level of 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		Components C1 and C2 are connected in series
RBD parallel (total redundancy)		Components C1 and C2 are connected in parallel, in total redundancy
RBD parallel (partial redundancy)		Components C1 …Cn are connected in parallel, in partial redundancy (k over n components are required for system to work)
RBD parallel (standby)		Components C1 and C2 are connected in parallel, in total redundancy, with component C2 hold in stand-by
RBD parallel multi state (fractioning)		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

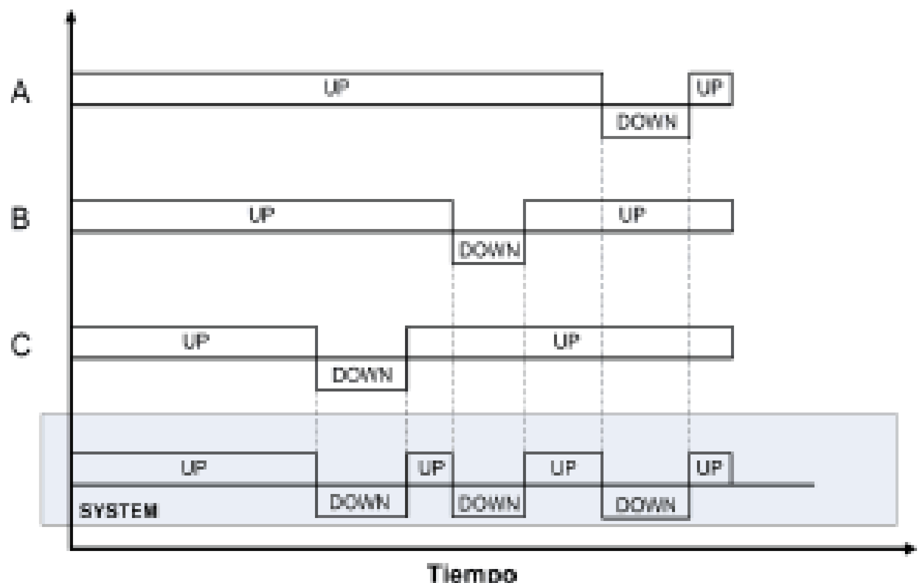
The failure of a single components generates the overall system failure

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

Example:

A	B	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:

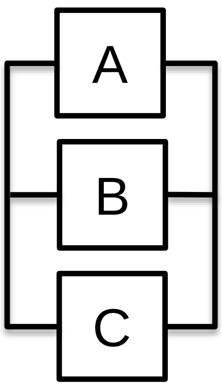
RBD: parallel, total redundancy model

Definition - Calculation formula – Example – Interdependencies

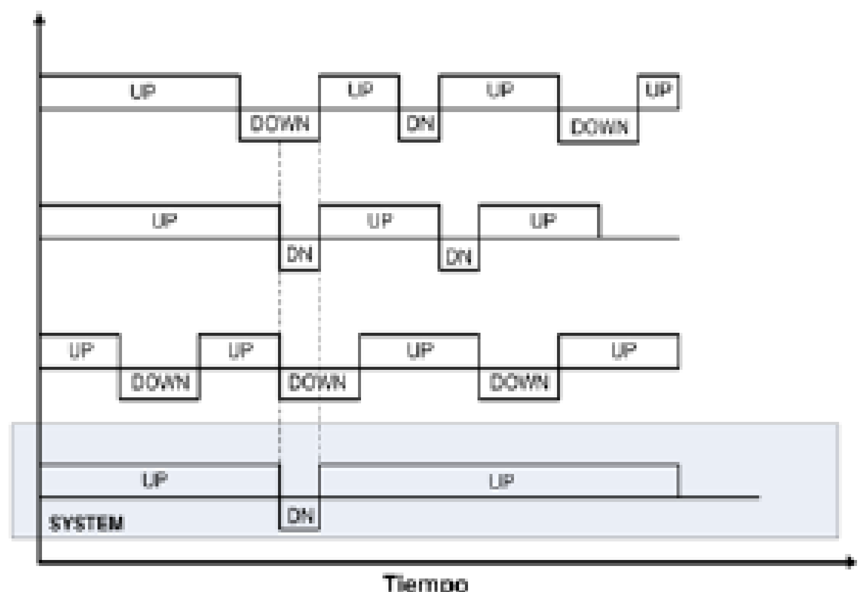
The system is up, if at least one single component is up

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

Example:



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



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

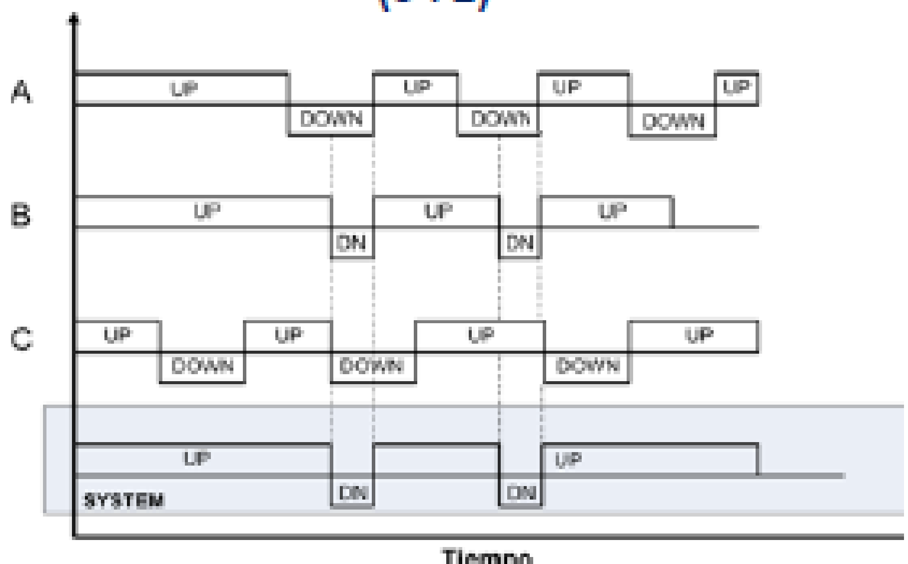
Formula:

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

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

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

(3 : 2)



Interdependencies at system level:

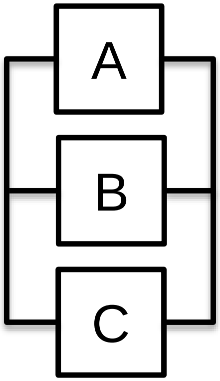
Only if k components over n are down, then the system is down

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

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:

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

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

Notation for RBD models

RBD models are described using the following conventional notation:

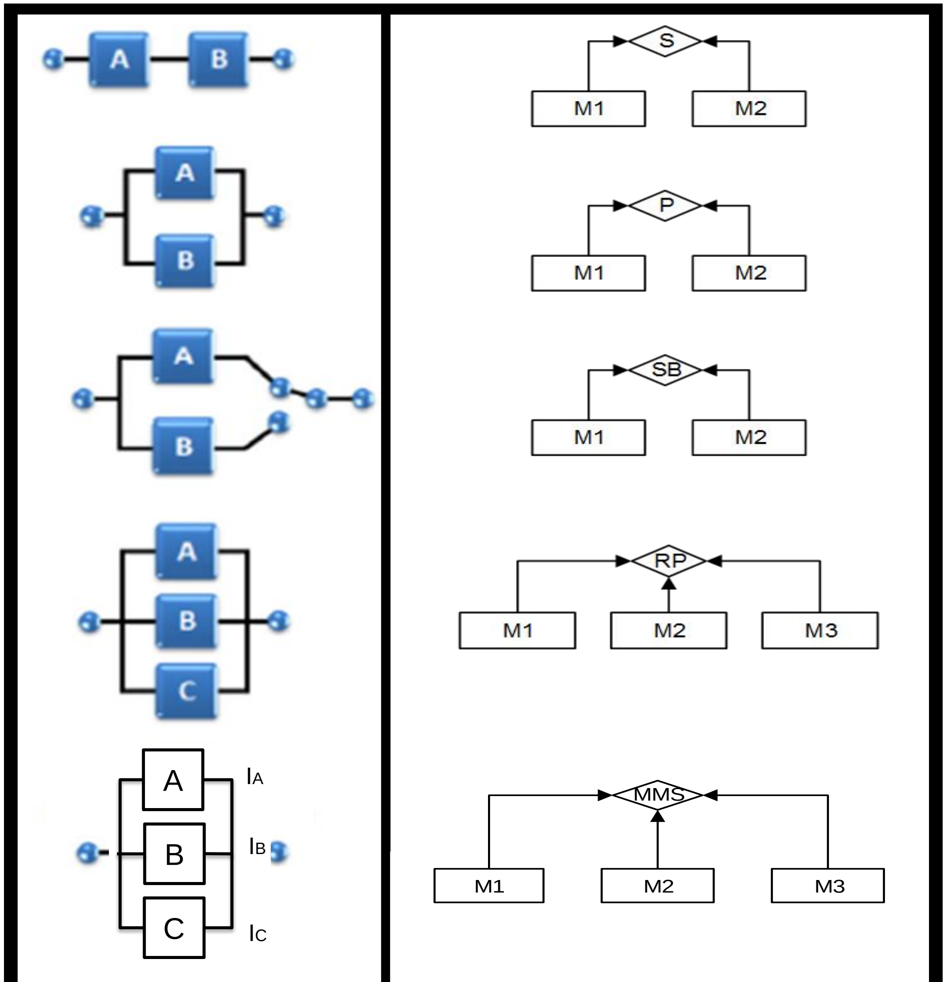
SERIES (S)

PARALLEL (P) (total redundancy)

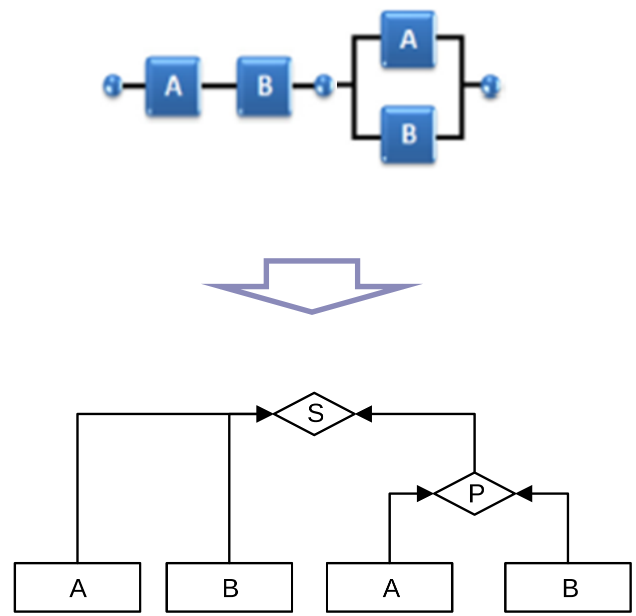
STAND-BY (SB)

PARALLEL (RP) (partial redundancy)

PARALLEL (MMS or F) (multi-state or fractioning)



Example:

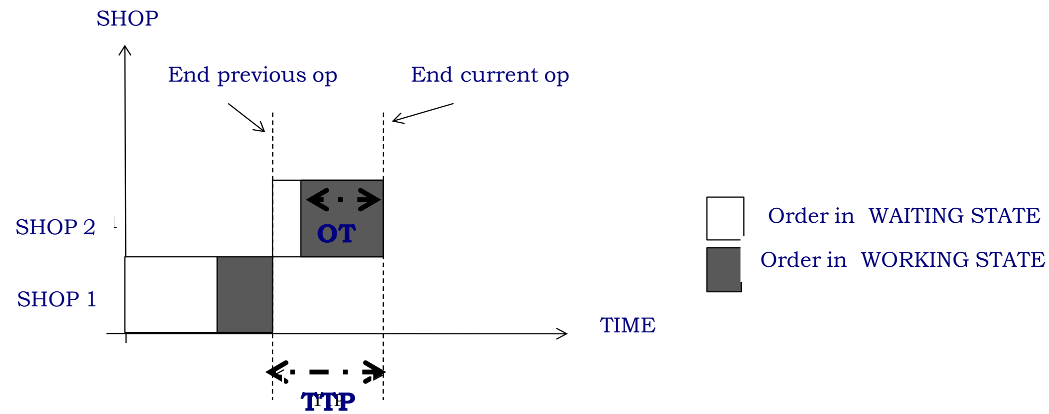


Definition – Operating Time

Performance measure

For each production station, an Operating (working) Time can be calculated, needed to complete the work order / the campaign. OT too is defined for each planned operation in the production cycle.

$$OT = \frac{WC}{OR_{max}}$$



Components:

OR_{max} maximum Output Rate of a given production station.

WC Work Content (of a "work order").

OR_{max} expresses the (working) hours / days provided by a station to perform the requested work order (i.e. it is maximum because it is defined under the hypothesis of perfect workstation efficiency, without performance losses). Therefore, the OT expresses how many working hours /days the workstation is busy, under the hypothesis that it works at its maximum capacity.

Definition – equivalent Operating Time (1)

Performance measure

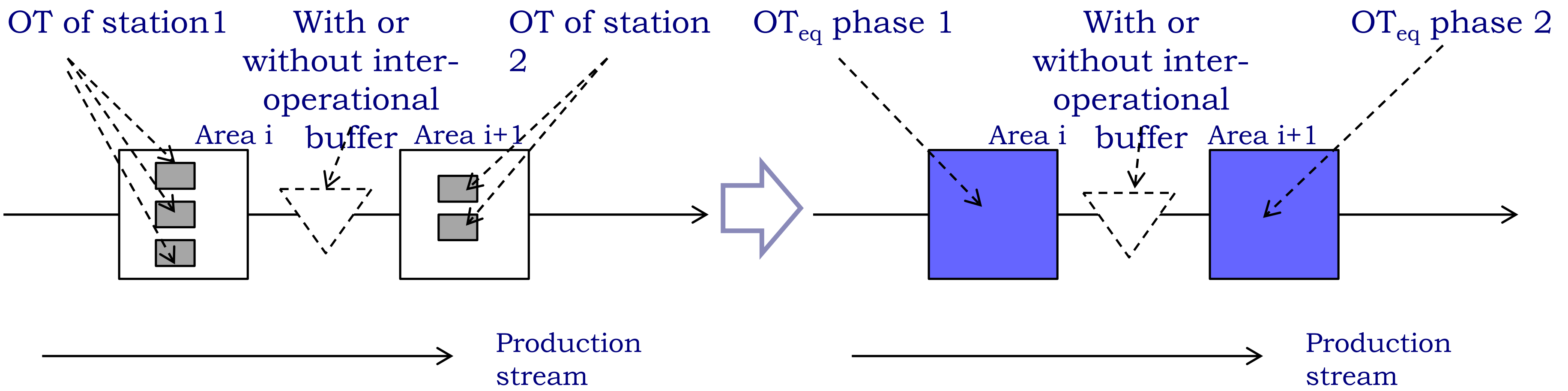
For each area / phase of the production system, a (working) equivalent Operating time may be calculated, to complete the work order / the campaign (this too is defined for each operation planned in the production cycle).

$$OT_{eq.} = \frac{WC}{S \times OR_{\max}}$$

Components:

S is the number of workstations working in parallel in the same area / phase.

Definition – equivalent Operating Time (2)



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 (1)

Performance measure

Each area of the production system has a typical production capacity (also called *throughput*); the nominal value of this capacity is, under the hypothesis of perfect efficiency:

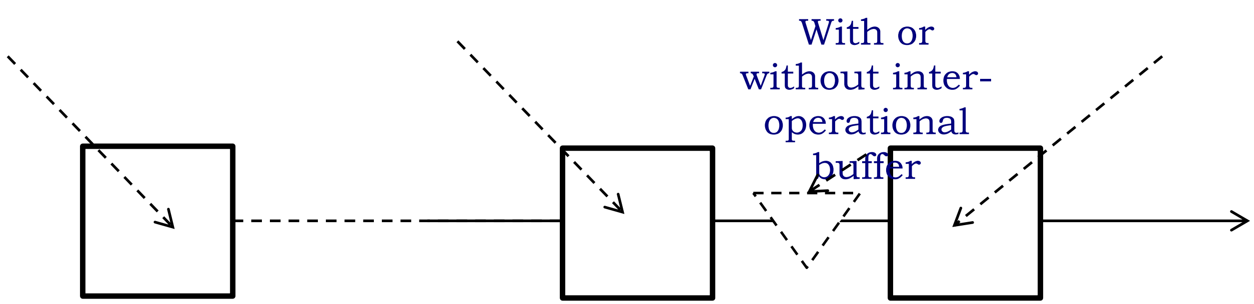
$$TH_i = \frac{1}{OT_{eq.,i}} = \frac{S_i \times OR_{\max,\,i}}{WC_i}$$

The maximum capacity of the production system is given by the bottleneck area / phase (i.e., the area / phase with maximum OT_{eq}, alias minimum TH).

Arrival rate
$\lambda = TH_0$

TH phase 1 = TH_1

TH phase 2 = TH_2



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.

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