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MANMADE
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NEST PATHFINDER
Sub-Priority Tackling Complexity in Science

Work Package 5 – D5.1
Logical framework of the impact of the electric power supply on a logistic-production system

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The context

A generic logistic-production system is basically composed of machines for working and assembling, of facilities for transportation, storing and handling and of quality control stations. A supply chain can be defined as a network of several logistic-production systems characterized by exchanges of materials and information among each other.
Since the present research is aimed at modelling the impact of the electric power supply quality on a supply chain, it is necessary to set the problem with reference to its fundamental module, i.e. a logistic-production system. The system considered at this stage of the research is simplified and composed of a job shop with machine-tools and quality control stations supplying a downstream customer.

Faults in electric power supply can have several effects of different relevance on the functioning of a logistic-production system. In particular, both academicians and practitioners agree that an insufficient quality of electric power supply can determine:

1. machine-tool stoppages, which can result in defective parts and/ or in parts to be re-worked. Here it is worth to point out that equipments have to be designed to not autonomously restart for avoiding more damages;
2. defective parts even if machine-tool stoppages do not occur. This happens for variations of electric power voltage or frequency. Normally, when these variations are in a +/- 10% range, defective parts are not generated. Out of this range, even if the equipment does not stop, defective parts are generated;
3. decrease of quality control effectiveness that causes the growth of defective parts delivered to the downstream nodes of the supply chain which the logistic-production system is part of .

Such effects have an impact more or less relevant on the logistic-production system operative performances, i.e. production costs, on-time delivery and production goodness, which influence the global service level assured by the system. Any kind of physical effects on people is not considered here because it is assumed that the connected risks are analysed and solved in equipment designing,
In particular, as figure 1 depicts, when the ‘non-quality (faults) of electric power supply’ increases the effectiveness of quality control decreases, the defective parts increase as well as the parts to be re-worked and the machine-tool stoppages.

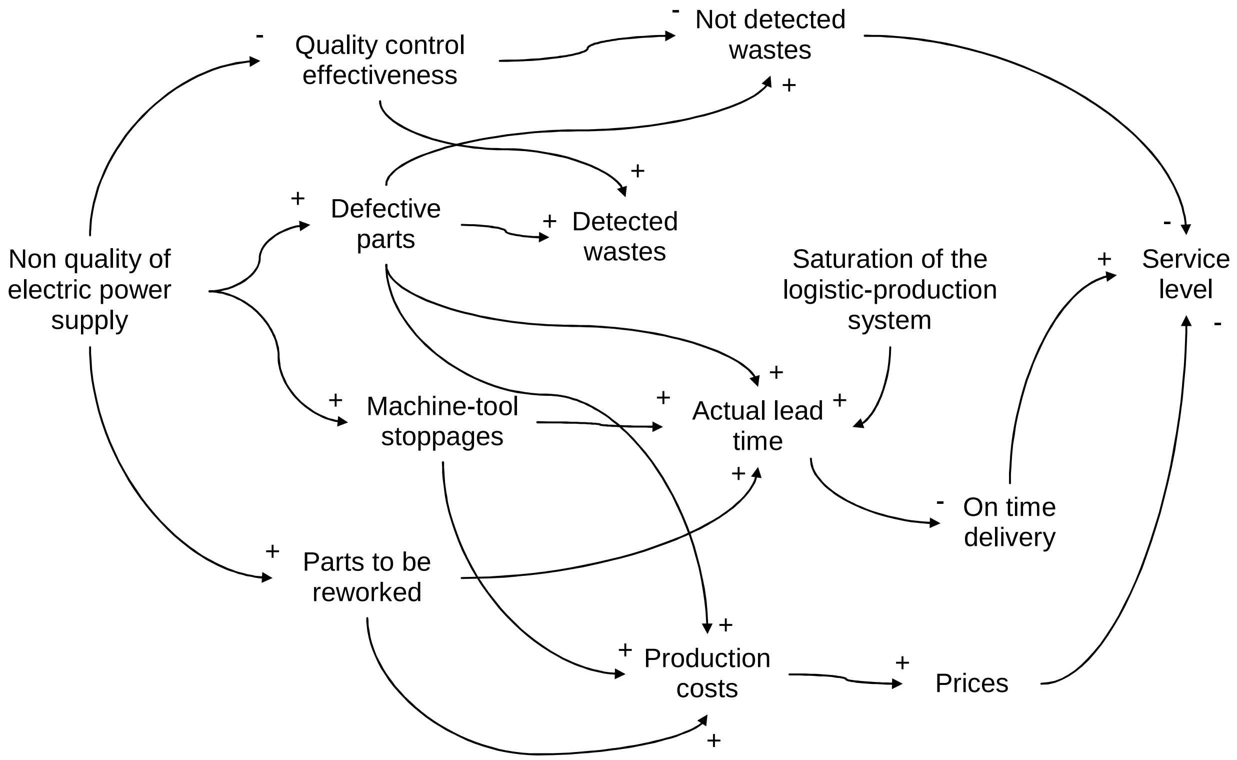

Figure 1 – Causal diagram representing the context and the relations among its variables

The rise of the defective parts has a positive effects on both detected wastes and not-detected wastes, whereas a higher quality control effectiveness increases the detected defective parts and decreases the not-detected ones. The growth of detected wastes as well as of parts to be re-worked and machine-tool stoppages cause delays in production plan that could generate rise in lead time if it is impossible to recover the lost time increasing the saturation rate of the system (the higher the current saturation of the system, the longer the actual lead time). When the actual lead time increases (in particular when it exceeds the planned lead time) the on-time delivery decreases. The growth of defective parts as well as of parts to be re-worked and machine-tool stoppages causes a raise of the production costs. Finally, the increase of not-detected wastes, of prices (through production costs) and a lower on-time delivery determine negative effects on the service level assured by the logistic-production system.

The attributed Petri net modelling the system

The Petri net which represents the logical model of how faults in electric power supply influence the performances of logistic-production systems can be divided into 2 sub-nets. The first one models the behaviour of a simplified logistic-production system, the second one models the faults occurrence.

The sub-net modelling the logistic-production system
With reference to the first sub-net (about right side of figure 2), places P4 and P3 allow the statuses of the machine depending on its seizing and on the electric power supply respectively to be represented. In particular, 3 cases corresponding to different machine statuses can be distinguished:

1. 1 token in P3 and 1 token in P4: the machine is available and idle, i.e. a new part can be processed on it;
2. 1 token in P3 and no-token in P4: the machine is available but is already occupied by a part to be worked;
3. no-token in P3 and no-token in P4: the machine is not available (the fourth case – no-token in P3 and 1 token in P4 – is not possible since the machine can not be made idle if not available).

Status 1 and 2 represent the normal functioning of the system, status 3 models the system behaviour when a fault in electric power supply is occurred.
With reference to the first case, if at least 1 token is present in place P5 (such a place models the inventory of parts to be worked), transition T5 becomes active and deletes 1 token from P5 and P4 (the latter removal allows the machine to be occupied and, as a consequence, the status 2 to be set preventing from a new firing of T5). After a time given by the T5 duration (equal to the cycle time of the part to be processed), the transition creates 1 token in P6 and records in the token attribute ‘goodness’ a value (0 or 1) drawn from a discrete probability distribution. Such a token models the finished part and its attribute ‘goodness’ allows for describing if the part is defective (goodness=0) or good (goodness=1). At this point transitions T6 fires; it deletes the token from P6 and creates 1 token in P4 and in P7 respectively (the token in P7 inherits the attribute ‘goodness’ of the one deleted from P6). The former creation makes the machine idle (and resets the machine status to 1), whereas the latter activates the quality control cycle. At this point different paths on the Petri sub-net can be followed depending on the value attribute ‘goodness’ of the token in P7. In particular:

- if the value of such attribute is equal to 1, i.e. if the part represented by the token is good, and a token is present in place P8, i.e. the quality control station is idle, transition T7 starts to fire. It deletes the token from P8, making occupied the control station and preventing from a new activation of itself as well as of transition T8, and after its duration, given by the time necessary to execute the quality control activities, creates 1 token in P9 and in P8 respectively. The former creation adds a part to the inventory from which the customers orders will be satisfied, whereas the latter creation makes the quality control station idle;
- if the value of the token attribute ‘goodness’ is equal to 0, i.e. if the part represented by the token is defective, and a token is present in place P8, i.e. the quality control station is idle, transition T8 starts to fire. It deletes the token from P8, making occupied the control station and preventing from a new activation of itself as well as of transition T7, and after its duration, given by the time necessary to execute the quality control activities, creates 1 token in P8, which makes the control station idle, and 1 token in P10. To the attribute ‘perceived goodness’ of this token transition T8 assigns a value (0 or 1) drawn from a discrete probability distribution which models the test efficiency of the quality control station. At this point, 2 different paths can be followed depending on the value of the token attribute ‘perceived goodness’. In particular:

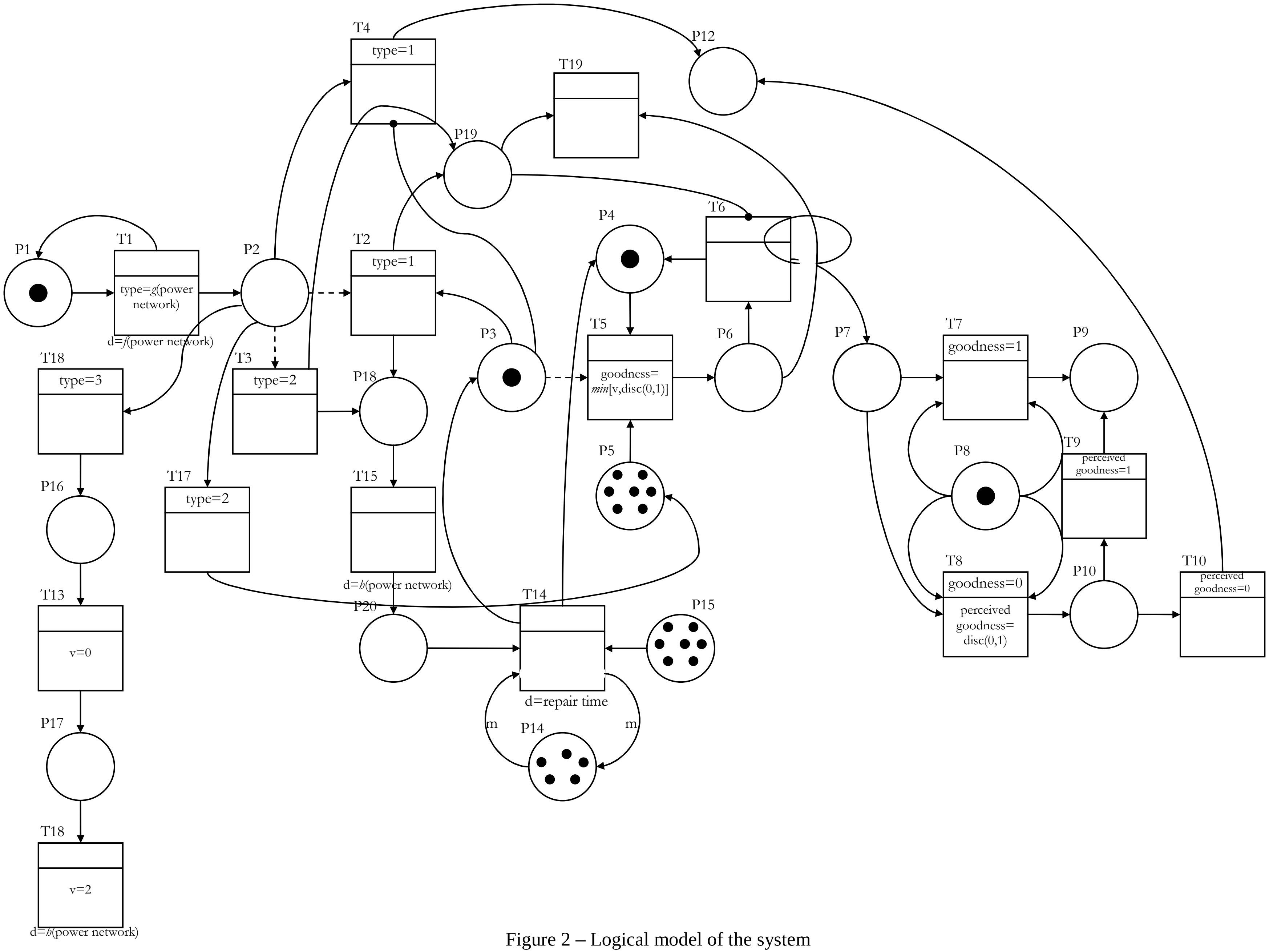

Figure 2 – Logical model of the system

    - if the value of such a attribute is equal to 1, i.e. if the defective part has been accepted as good by the quality control station, transition T9 becomes active; it deletes the token from P10 and creates 1 token in P9, i.e. a defective part is added to the inventory available for satisfying customers' requests;
    - if the value of the token attribute 'perceived goodness' is equal to 0, i.e. if the defective part has been refused as defective by the quality control station, transition T10 fires and deletes the token from P10 and creates 1 token in P12, i.e. in the place of the Petri net which records the defective parts produced by the considered logistic-production system.

The sub-net modelling the occurrence and the effects of faults in electric power supply

With reference to the second sub-net (about left side of figure 2), place P1 and transition T1 allow the inter-arrival time among two subsequent faults in electric power supply as well as the kind of the current fault to be drawn from the empirical probability distributions defined by the simulation model of electric power network. The fault kinds can be grouped into three classes according to their effects on the logistic-production system. The three classes are:

1. fault generating machine-tool stoppage and defective part;
2. fault generating machine-tool stoppage but not defective part because of the part can be reworked or the fault occurs while part and tool are not in contact;
3. fault not generating machine-tool stoppage but defective parts.

In particular, when a token is in P1, transition T1 is active. It fires by cancelling the token in P1 and creating after its duration a token in P2. This token is characterized by the attribute ('type') whose value describes the kind of fault (the values 1, 2 and 3 correspond to 'class 1', 'class 2' and 'class 3' faults respectively). At this point, different transitions can fire depending on the value of the 'type' attribute characterizing the token in P2. In particular:

- if the value of such an attribute is equal to 1, i.e. if a 'class 1' fault is occurred, transition T2 becomes active. It deletes the token from P3 and creates 1 token in P18 and in P19 respectively.
    - The removal of the token from P3, which represents the machine availability (see the previous paragraph), has several effects:
        - first of all, it allows status 3 to be set;
        - secondly, it makes active transition T4 (as a matter of fact place P3 is connected to transition T4 by means of an inhibitor arc with weight equal to 1). Such transition deletes the token in P2 and creates 1 token, representing a defective part, in P12 (in this way it is possible to record the defective parts generated by 'class 1' faults in electric power supply);
        - finally, it prevents, by means of the token in place P19, from the activation of transition T6, i.e. the transition responsible for making idle the machine which the simplified logistic-production systems is composed of (see the previous paragraph).
    - The creation of 1 token in P18 allows transition T15 to be activated; it deletes the token from P18 and, after its duration (given by the duration of the fault drawn from the empirical probability distribution defined by the simulation model of the electric power network), it creates 1 token in P20. The latter, together with the tokens in P14 and in P15 which represent the availability of operators and spare parts respectively, concurs to activate transition T14. Such transition, which models the activities necessary to re-start the machine after its stoppage due to a fault, deletes 'm' tokens from place P14, i.e. occupies 'm' operators, and deletes 1 token from P15, i.e. consumes 1 spare part. After its duration, given by the time necessary to repair the machine, transition T14 creates 1

    token in P3 and 1 token in P4 which make the machine available and idle respectively and, as a consequence, set the machine status to 1.
  - The creation of 1 token in P19 inhibits transition T6 and allows the token created by T5 in P6 after the fault occurrence to be deleted by means of transition T19.
- If the value of the ‘type’ attribute characterizing the token in P2 is equal to 2, i.e. if a ‘class 2’ fault is occurred, transition T3 becomes active; it deletes the token from P3 and creates 1 token in P18 and in P19 respectively.
  - The first and the third effects of the removal of the token from P3 are the same of the ones depicted above, whereas the second is different. As a matter of fact, since the attribute ‘type’ of the token in P2 is equal to 2, transition T17 instead of transition T4 becomes active. It deletes the token from P2 and creates 1 token in P5 (actually, a ‘class 2’ fault does not cause the production of defective parts or causes the production of defective parts which can be reworked).
- If the value of the ‘type’ attribute characterizing the token in P2 is equal to 3, i.e. if a ‘class 3’ fault is occurred, transition T18 becomes active; it deletes the token from P2, preventing from a new firing of itself, and creates 1 token in P16. The latter allows transition T13 to be activated: it deletes the token from P16, assigns to variable ‘v’ the value 0 (in this way all the parts produced by the machine are defective parts) and creates 1 token in place P17. Due to the presence of such a token, transition T18 starts to fire: it deletes the token from P17 and, after its duration (given by the duration of the fault drawn from the empirical probability distribution defined by the simulation model of the electric power network), it assigns to variable ‘v’ its original value (2).

Introduction to the quality of electric power supply

In the recent years a large interest has been dedicated to the quality of supply, with particular reference to the voltage dips and interruptions both in industrial and in domestic applications. The problems associated to interruptions are well known: a sudden lack of power blocks industrial processes, causing delay in production and loss of money for investors; moreover it affects domestic costumers too, especially with reference to personal computers, refrigerators and air conditioning systems. Voltage dips are as disturbing: a supply voltage reduction may interrupt production processes or may induce undesired reset in personal computer and other electronic devices, with consequences comparable to those induced by an interruption. Since customers are becoming more and more sensible to these and other similar problems, the evaluation of the expected number and duration of interruptions, along with the expected depth and duration of voltage dips is turning out to be a key issue for a Distribution System Operator (DSO), especially in order to increase the overall performances of its electrical network.

Focusing the attention on the Italian environment, the Italian Regulator has been monitoring quality of supply for years, supporting the reduction of interruption duration and penalizing DSO not achieving the expected reduction target. In 2007, in correspondence with the new regulatory period 2008- 2011, a significant turn was made: besides the interruption duration, in 2008 the monitoring of interruption number will be commenced too, in order to limit not only the energy not supplied (related to the duration of interruption) but also the frequency of disconnections (related to the restarting of industrial processes). Moreover in 2007 the Italian Regulator and the Italian Committee held a public consultation regarding the electrical schemes to be adopted by DSO to connect users to the distribution grid. For the final customers connected in Medium Voltage (MV) two possible protection devices are allowed: a traditional circuit breaker equipped with current relay or a switcher coupled with fuses. The former solution corresponds to the standard usually adopted by DSOs, while the latter one is introduced to ensure energetic selectivity and to limit dips duration and depth, as clearly highlighted in.

This work is aimed to develop a model suitable to simulate the behaviour of a MV distribution system in presence of fault and restoration events: a Monte Carlo simulation is run to sample the story of the systems, while power flow and short circuit calculations are performed to evaluate the impact of a fault in terms of currents and voltages; the tool is completed by a procedure aimed to simulate the protection devices intervention and, whenever necessary, the reconfiguration of the systems due, for example, to back feed activation. The model presented in this relation can be used for many different purposes: here the attention is focused on analyzing the interruptions and voltage dips associated to faulty events.

Monte Carlo model

A graph structure is introduced to represent the topology of the electric system: every component whose stochastic behaviour is characterized by a failure and a repair rate is represented by a node: feeders, busses, circuit breakers, transformers and loads are nodes (it shall be noted that the term load here denotes the set of all components connected to a MV/LV[1] transformer). Every node is described by its type, its connections with other nodes, its functional states and the corresponding transition rates, its initial functional state and its current functional state. For simplicity, but without loss of generality, the transition rates between the states of each node are assumed constant.

The theory of the “transport of the states of a system” is embraced to describe the stochastic life of an electric system. The system state at a given time t is represented by an integer variable k. Thus $\Omega \equiv (k, t)$ represents the system stochastic evolution in time as a random walk trajectory (figure 3).

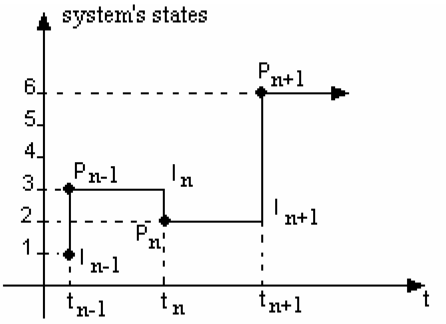

Figure 3 – Random walk trajectory

The realisation of a trajectory of the electric system is simulated through the indirect Monte Carlo approach. In general, one trial (history) of a Monte Carlo simulation based on the theory of the transport of the system states consists in generating a random walk which guides the system from one configuration to another, at different times. Starting from a given system configuration k' at t', the Monte Carlo simulation determines when the next transition occurs and which is the new configuration got by the system as a consequence of the transition.

This process has been widely described in worldwide literature: among the different solutions that have been proposed, in this work the so called “indirect” procedure is adopted. let k_n be the state entered by the system at time t_n; for each time $t>t_n$ it is possible to define the conditional probability $T(t|t_n,k_n)$ that a transition occurs at time t, starting from the state k_n. The time t_{n+1} of a system transition is thus sampled basing on the distribution of this conditional probability with reference to the time t. Then, the new configuration k_{n+1} is again sampled from the distribution of the conditional probability $T(k|t_{n+1},k_n)$ that the system already in state k_n enters the state k given a transition occurred at time t_{n+1} . The above described procedure is repeated starting from the new state k_{n+1}. The trial simulation proceeds through the various transitions till the mission time T_M is reached. Figure 4 summarizes the main process of the tool.

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[1] A transformer, connected to a distribution Medium Voltage system, feeding the low voltage network into analysis.

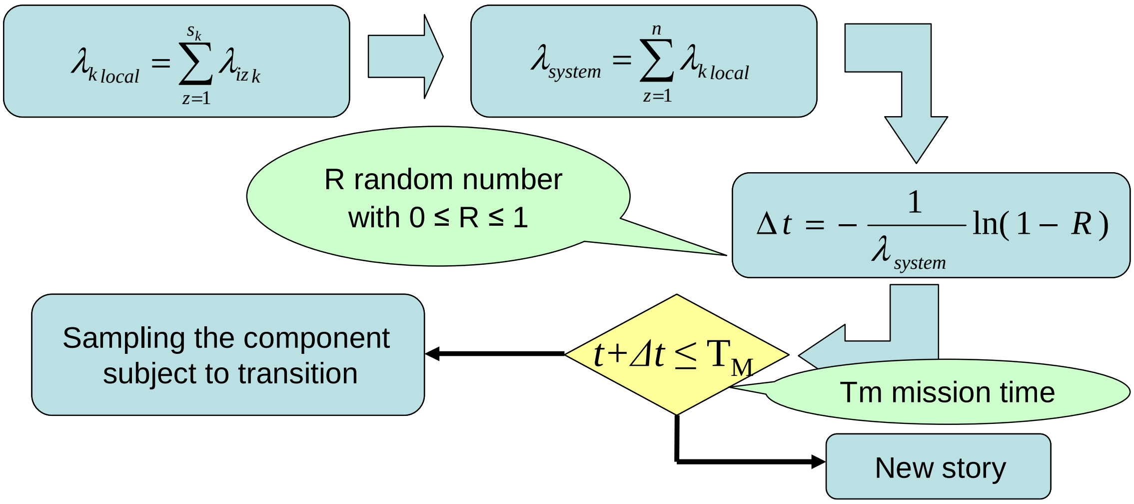


Figure 4 – Monte Carlo flow chart.

Functional states and short circuit evaluation

The system state at time *t* is defined on the basis of the different functional conditions assumed by each device at time *t* itself.

From a general point of view, each network component is assigned both faulty and operational states, linked by the corresponding transition rate: therefore all the components may be subject to a transition. In this work, for sake of simplicity, the main target being to evaluate interruptions and voltage dips, the attention is focused only on those transitions effectively causing a fault or a restoration as perceived by final customers. As a consequence, all the logical components (circuit breakers and switchers) are simulated to be fully reliable and only lines and transformers are allowed to transit in a faulty state.

Regarding faults, only 3 phase short circuit are taken into account: in fact, in a MV distribution network the neutral grounding scheme usually limits the single phase short circuit current such that its value is not able neither to trigger protection devices to open and, consequently, to cause an interruption nor to significantly affects the supply voltage for loads.

In conclusion only the following states are introduced for each component:

- normal operating state (NOS), i.e. the component is normally working;
- standby state (SBS), i.e. the component is inactive but can be switched on if required (it is the case of an open circuit breaker)
- permanent 3 phase fault (P3F), i.e. a permanent 3 phase fault occurs and the component has to be isolated immediately from the system;
- temporary 3 phase fault (T3F), i.e. a temporary 3 phase fault occurs.

Whenever a fault occurs, different procedures have to be put in operation in order to evaluate the behaviour of the electrical system. First of all, since both currents and voltages in the faulty condition are strongly dependent on the fault position, it is necessary to identify the effective point (within the damaged line or transformer) where the short circuit occurs: this is achieved through a random selection.

Given the fault position, the short circuit tool is started: it consists of a steady state computation based on nodal impedance matrix. Since the chosen approach allows to calculate short circuit only in busses, it is necessary to introduce the auxiliary bus AUX coincident with the fault position. The series impedance of the faulty component is therefore divided in two sections, one before and one after the fault, as represented in figure 8.

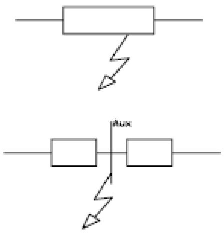


Figure 5 – Series impedance management after fault

With the modified network a load flow is used to compute the vector $\mathbf{V_{pf}}$ of the voltage at each node in the pre-fault situation. Let $\overline{V_{aux}}$ be the voltage at the bus AUX in that situation; the 3 phase symmetrical component $\overline{I_{3f}}$ of short circuit current can be computed as follows

$$\overline{I_{3f}} = \frac{\overline{V_{aux}}}{\overline{Z_{aux}} + \overline{Z_f}}$$

where

- $\overline{Z_{aux}}$ is the nodal impedance seen from the bus AUX

- $\overline{Z_f}$ is the randomly generated fault impedance.

$\overline{Z_{aux}}$ is the diagonal element of the nodal impedance matrix **Z** associated to the bus AUX. The matrix **Z** is computed inverting the modified admittance matrix $\mathbf{Y_{cc}}$, appositely build from the network nodal admittance matrix **Y** through the following procedure:
a) each diagonal element $\overline{Y_{ii}}$ is substituted by $\overline{Y_{ii}} + \overline{Y_{iadd}}$ being $\overline{Y_{iadd}}$ the sum of the admittances of generators and load connected to the bus *i*;
Given the current $\overline{I_{3f}}$, the vector **V** of the voltage at each bus is computed as $\mathbf{V} = \mathbf{V_{pf}} + \mathbf{Z} \cdot \mathbf{I_{cc}}$ where $\mathbf{I_{cc}}$ is the vector of the current injection due to the fault: all the element are equal to zero, but the one associated to the bus AUX equal to $-\overline{I_{3f}}$.

It is worth noticing that the vector **V** contains the symmetrical component of the voltage at each bus; these values represent the steady state situation got by the network after the dynamic consequent to the fault. They can be used to compute the symmetrical component of the current circulating in each branch, along with the depth of voltage dips at each bus.

Protection devices intervention and network reconfiguration

Two types of protection devices are considered in this work: circuit breaker equipped with current relay and fuses coupled with switchers.

The short circuit tool described in Section 3 provides the current circulating in each branch after the fault. These values can be used to verify the intervention of the protection devices installed on lines and transformers.

Let I_b be the symmetrical component of the current circulating in the branch b and let this branch be protected by a circuit breaker, equipped with a current relay. This protection device is simulated to have a two step intervention curve, characterized by two current thresholds I_{temp} and I_{ist}:

- if $I_b \geq I_{ist}$ the relay immediately activates the circuit breaker and the fault is cleared in a very short time (usually 120 ms, associated to the opening time of the circuit breaker itself);
- if $I_{temp} \leq I_b < I_{ist}$ an intentional delay t_d is introduced;
- if $I_b < I_{ist}$ no intervention occurs.

In case branch b is protected with a fuse, the situation is quite different: with respect to the prospective wave associated to the fundamental current I_b, the current effectively circulating in the branch is limited, as depicted in figure 9.

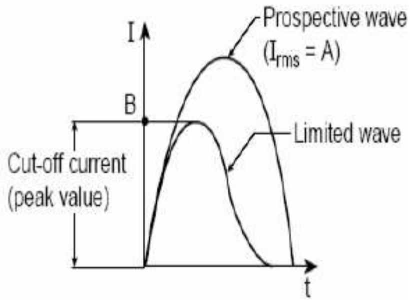


Figure 6 – Fuse limiting power

As a result, all the current circulating in the network due to the fault are reduced, thus resulting a in higher voltage at each bus and in a reduced dip depth.

In particular, given the peak value I_{pc} of the cut-off current, it is possible to evaluate the fundamental component associated to the limited current wave, from which the currents circulating in the other branches and the voltages at each node can be easily computed by the mean of the matrix **Z**.

Regarding the intervention time, the fuses are characterized by a pre-arching time t_a after which the device opens and does not conduct anymore. As a consequence t_a can be considered as the time required by this device to clear the fault.

Both I_{pc} and t_a are dependent on the prospective fundamental current I_b: the relevant curves are annexed to the documentation accompanying the device.

In real distribution systems the intervention of protection devices is aimed to avoid the propagation of the disturbance to the whole network; when the situation is stabilized (i.e. the protection device correctly intervened), the DSO proceeds to reconfigure the network in such a way to identify and isolate the faulty components and to repower as many loads as possible to contain the duration of interruptions.

In the model here proposed, the reconfiguration is obtained by modifying the state of some logical components (circuit breakers, switchers and so on) from NOS to SBS (isolation of faulty components) or from SBS to NOS (repower of loads). Let be I the group of all the components affected by trhge reconfiguration process: their functional state is blocked until the faulty component is restored on the basis of the Monte Carlo simulation; eventually, when this component is brought to a NOS, the state of all the I components is restored to its nominal condition.

Quality of supply evaluation

The quality of supply at each bus of the distribution system is evaluated in terms of interruptions and voltage dips.

At each customer bus, the dip depth (in term of supply voltage magnitude in the steady state situation after a fault) is by applying the short circuit tool described in Section 3 (as opportunely modified to take into account the fuse limiting power as described in Section 4). The dips usually lasts until the fault is cleared by the intervention of a protection device. After this event two different situations may occur:

a) the customer results disconnected by the network: the dip evolves in a permanent interruption;

b) the customer remains connected to the network: the dip ends and the supply voltage is fully recovered within its operating limits.

In the model here proposed voltage dips are counted independent if they are related to case a) or case b): their duration is always assumed equal to the protection device intervention time even if they evolves in a permanent interruption. The dips occurring at each bus are recorded in different classes on the basis of their depth and duration. The classification illustrated in Table I, derived from UNIPEDE, is adopted. No class with duration greater than 1 s is considered since all the simulated protection devices are able to act within 1 s. Moreover the interruption at each bus is memorized in an apposite counter.

Table 1 – UNIPEDE voltage dips classification

	Duration				
Residual Voltage	**<20ms**	**20 -100 ms**	**100 -150 ms**	**150 -500 ms**	**0.5- 1 s**
85-90%					
70-85%					
40-70%					
10-40%					
<10%					

Since the model is based on stochastic analysis many different trials (histories) are required to get significant results. When all the trials are executed, table 1 contains the total number of dips belonging to each class that occurred in the distribution network during all the trials. The mean number D_c of dips belonging to class c that may be expected at each bus is computed by dividing the number n_c of dips of class c occurring in all the histories by the number n of busses in the considered network.

An analogue method is applied to the interruption occurring in the network in all the considered trials.

Simulations

The model is applied to a real distribution network, whose topology and parameters are derived from the survey performed by AEEG and Politecnico di Milano in 2006.

The results regarding quality of supply both in terms of dips and interruptions are used to sample a standard history of events for a customer connected to a MV grid. The time t of each event is randomly sampled on the basis of the total number of events E_b occurring at each bus: E_b includes both dips (of all the classes of table I) and interruptions and is equal to the total number of events E occurring in the network, divided by the number n of busses in the network itself. For each event time, the associated type (class of dip or interruption) is randomly chosen according to the probability distribution of all the events occurring in the considered network in all the Monte Carlo histories.

References

AEEG: *Testo integrato della regolazione della qualità dei servizi di distribuzione, misura e vendita dell'energia elettrica per il periodo di regolazione 2008-2011*, Delibera 333/07, available on http://www.autorita.energia.it

AEEG, CEI: *Regole tecniche per la connessione alle reti di distribuzione dell'energia elettrica in alta e media tensione*, Atto 34/06,. available on http://www.autorita.energia.it

AEEG, CEI: *Condizioni tecniche per la connessione alle reti di distribuzione dell'energia elettrica con tensione nominale superiore a 1 kV*, Atto 45/07, available on http://www.autorita.energia.it.

R. Billinton, P. Wang: *Teaching Distribution System Reliability Evaluation Using Monte Carlo Simulation*, IEEE Trans, on Power Systems, Vol.14, Issue 2, May 1999.

N. Bombieri, C. Bovo, M. Delfanti, M.S. Pasquadibisceglie, M. Pozzi: *Voltage dips analysis by Monte Carlo approach*, Proceedings of Cired 2007, Wien, May 2007.

C. Bovo, M. Delfanti, M. S. Pasquadibisceglie, M. Pozzi, E. Zio: *Indirect Monte Carlo approach to evaluate reliability and availability indices of distribution networks*, Proceedings of Cired 2005, Turin, May 2005.

C. Bovo, M. Delfanti, M. S. Pasquadibisceglie, M. Pozzi, E. Zio: *Indirect Monte Carlo approach to test the distribution supply quality*, Proceedings of Cidel 2006, Buenos Aires, November 2006.

CEI 44-5: *Sicurezza del macchinario - Equipaggiamento elettrico delle macchine - Parte 1: Regole generali.*

R. David, H. Alla: *Petri nets for modelling of dynamical systems: a survey*, Automatica, vol. 30, n. 2, 175-202, 1994.

A. Dubi: *Monte Carlo applications in system engineering*, Wiley &Sons, 2000.

J.W. Forrester: *Industrial Dynamics*, Pegasus Communicatons, Waltham, Massachussets, 1961.

E. Grassani: *Equipaggiamento elettrico delle macchine*, Editoriale Delfino 2007.

L. Lo Schiavo, M. Delfanti, M. Merlo, M. S. Pasquadibisceglie, M. Pozzi: *Relating power quality and short circuit power: a detailed analysis of Italian MV networks*, Proceedings of Cired 2007, Wien, May 2007.

M. Marseguerra, E.Zio: *Basics of Monte Carlo Method with Application to System Reliability*, LiLoLe-Verlag GmbH, Hagen, Germany, 2002.

T. Murata: *Petri nets: properties, analysis and applications*, Proceedings of IEEE, vol. 77, 541, 580, 1989.

M. Pero, T. Rossi, C. Noè, A Sianesi: *An exploratory study of the relation between supply chain topological features and the need for collaboration*, International Journal of Production Economics, accepted for publication, 2008.

S. Rinaldi: *Systems Theory*, in Italian, CLUP, Milan, Italy, 1993

C.M. Rocco, J.A. Moreno: *System Reliability Evaluation Using Monte Carlo & Support Vector Machine*, Proceedings Annual Reliability and Maintainability Symposium 2003.

T. Rossi, C. Noè, F. Dallari: *A formal method for analyzing and assessing operational risk in supplì chains*, Proceedings of the 23rd International Conference of the System Dynamics Society, Boston, July 2005. Available on line: http://www.systemdynamics.org/conferences/2005/proceed/index.htm.

J. Sterman: *Business Dynamics: systems thinking and modeling for a complex world*, McGraw Hill, Homewood, Illinois, 2000.

Appendix: Petri nets

Broadly speaking, Petri net is a graphical and mathematical formalism for the logical modeling of dynamical systems. Such net, which allow not only a particular status but also the evolution of the system under study to be represented, is characterized by 2 types of elements, i.e. places and transitions, interacting with each other by means of arcs (the graphical representation of the above mentioned elements is given in figure 7). Places and transitions manage tokens that allow the instantaneous status of the system to be described and the transitions to be activated or deactivated.

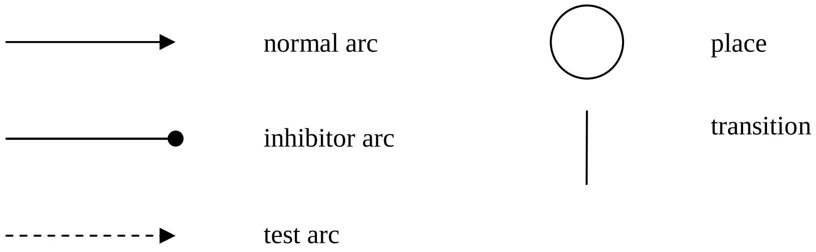


Figure 7 – Petri net elements

In more formal terms a Petri net can be defined as a tuple $R = <P, T, Pre, Post, M_0>$, where P is the finite set of places (with $|P|= n$); T is the finite set of transitions (with $|T|= m$); $P \cap T = \varnothing$ and $P \cup T \neq \varnothing$; $Pre(P_i, T_j)$ is a function that defines arcs from a place to a transition; $Post(P_i, T_j)$ is a function that defines arcs from a transition to a place; M_0 is the initial mark of the net (for possible combination among Petri net elements see the input and output arc in figure 8).

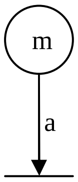
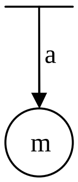
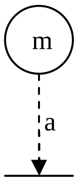
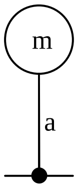
Input arcs	Output arcs
 classical relation among place and transition; transition fires if $m \geq a$	 classical relation among place and transition; token created in the discrete place are equal to a
 control relation; transition fires if $m \geq a$ (no token flow)	
 control relation; transition fires if $m < a$ (no token flow)	

Figure 8 – Possible combination among Petri net elements

The first input arc describes the classical relation among place and transition; the transition fires the number m of tokens is higher or equal to a and a token is deleted in the input place and created in the output place. The second input arc illustrates a control relation; the transition fires if m is higher or equal to a, but no token flows. The third input arc depicts another control relation; the transition fires if m < a, the tokens still do not flow. Finally, the output arc describes the classical relation among transition and place; token created in the discrete place are equal to a.

A special type of Petri net is represented by attributed Petri net. It is, substantially, a Petri net with attributed tokens. This means that each token could have one or more attribute whose values condition firing of transitions. The graphical representation differs for the transition element represented as in figure 9.

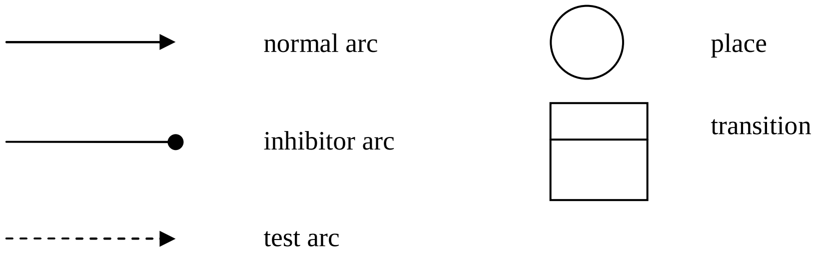


Figure 9 – Attributed Petri net transition element