

# QUALITY OF SERVICE INDICATORS ESTIMATION IN INTERDEPENDENT CRITICAL INFRASTRUCTURES USING INTELLIGENT RAO SIMULATOR

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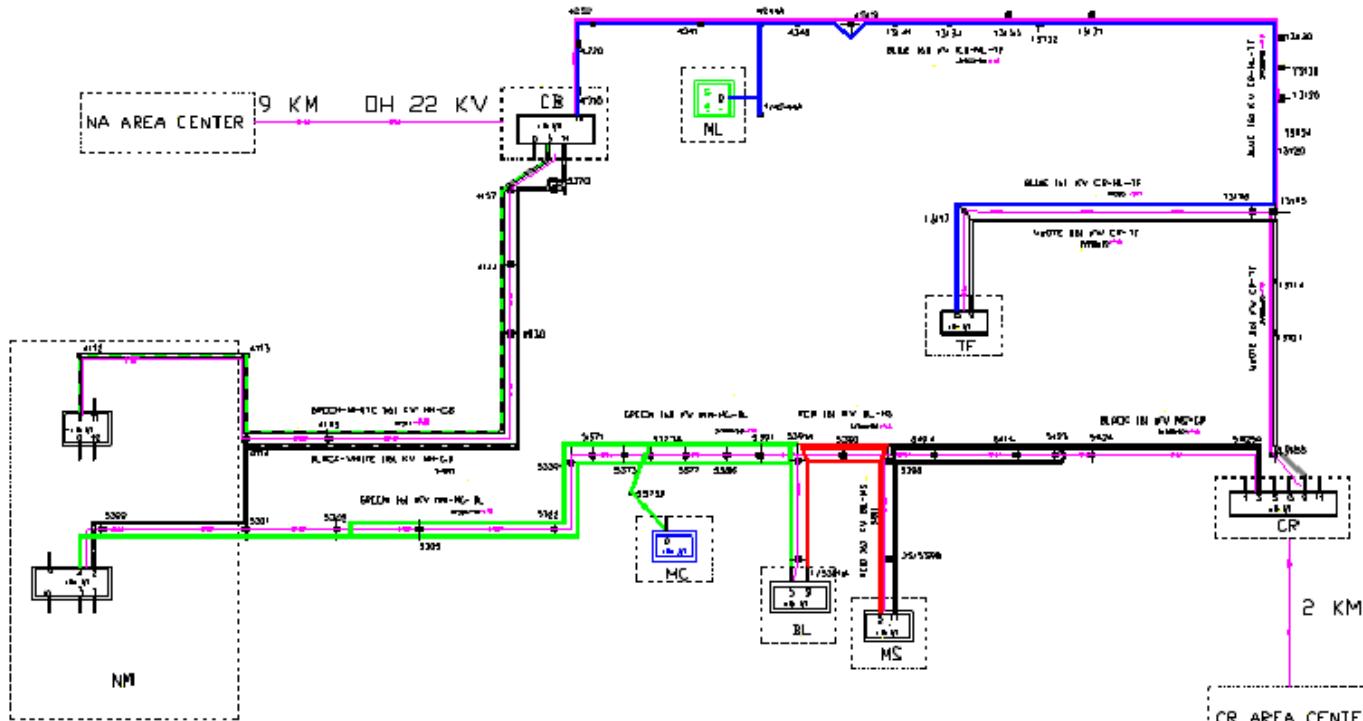
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# Interdependent infrastructures

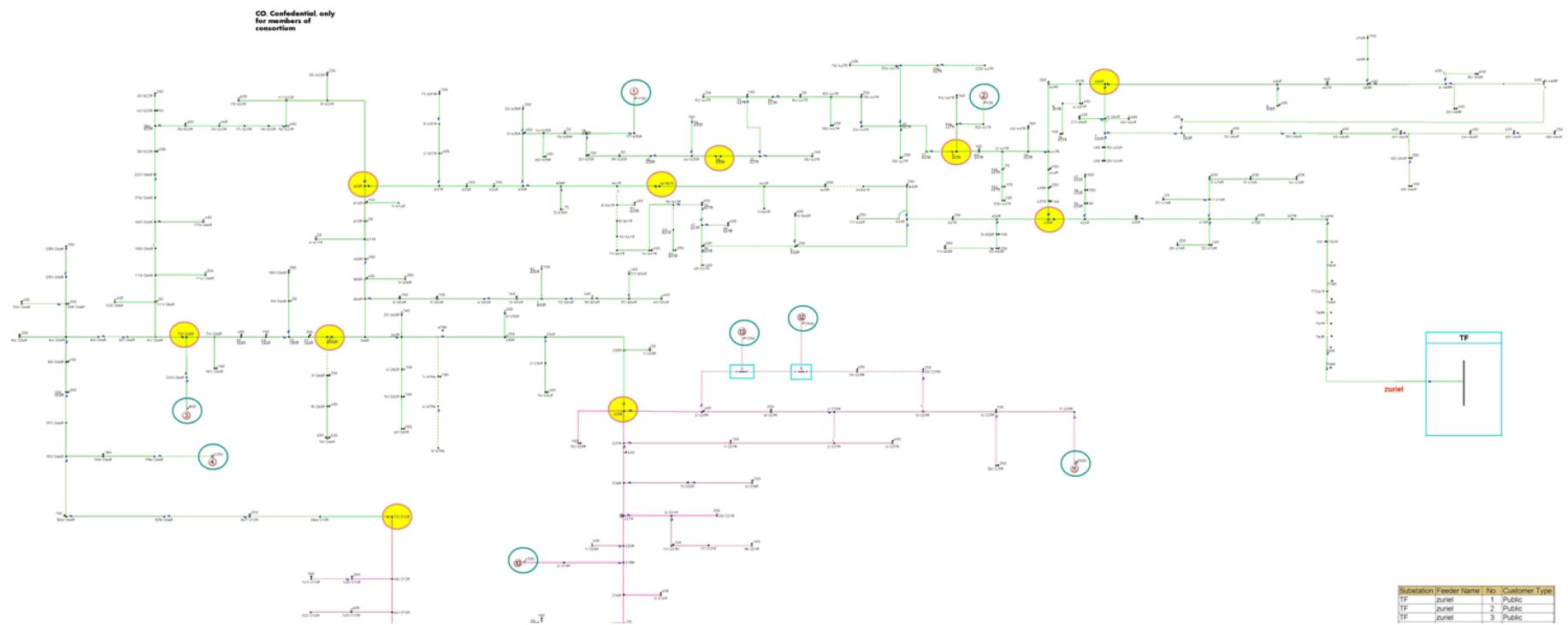
- Electrical infrastructure
  - Level 1: high-voltage transmission lines
  - Level 2: medium voltage
- Telecommunication infrastructure
- Control infrastructure (SCADA)

## HV 161 KV TRANSMISSION LINES

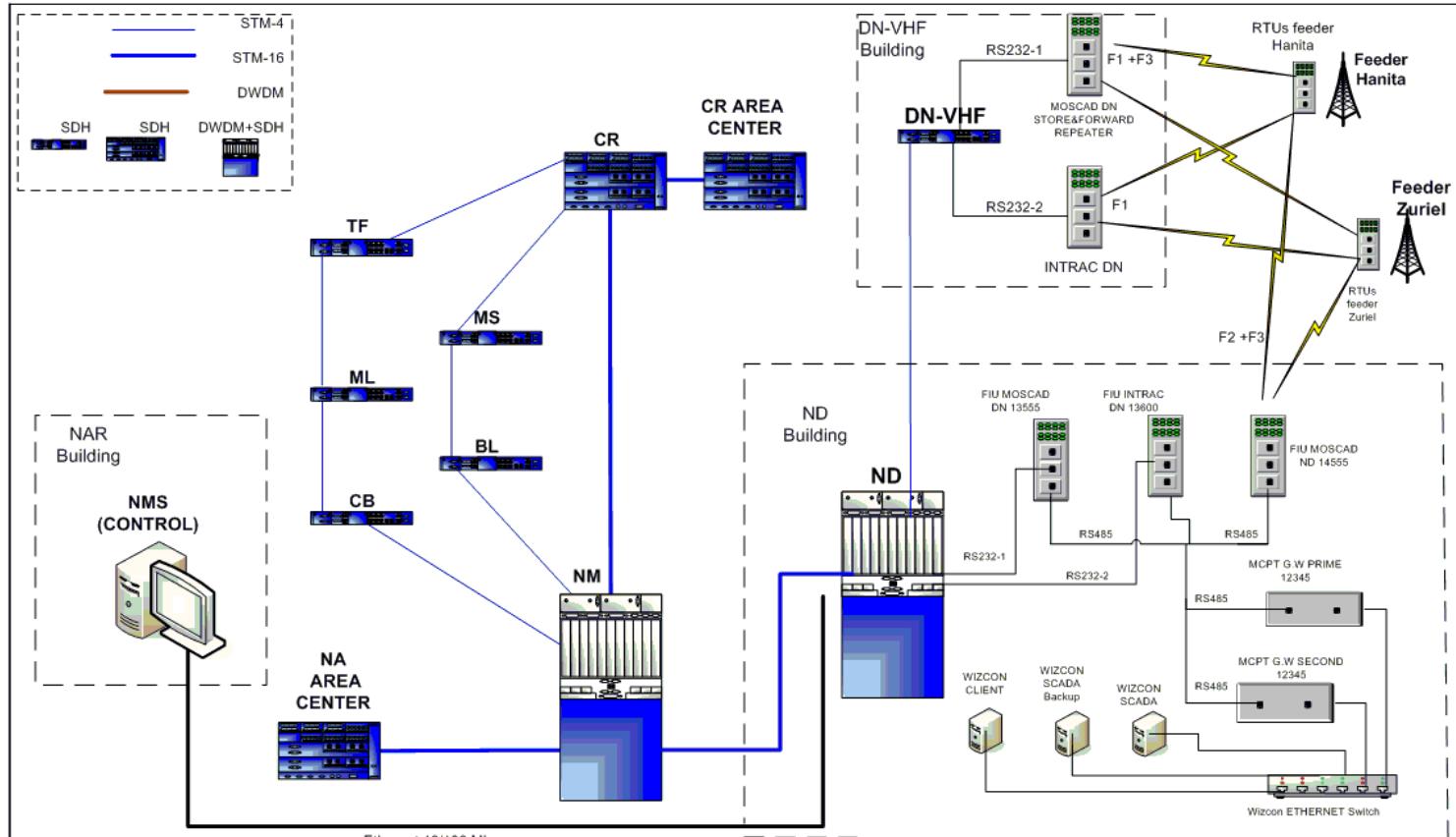


# ECI Level 2: Reference scenario fragment

- Zuriel feeder of TF substation



# Information and telecommunication CI



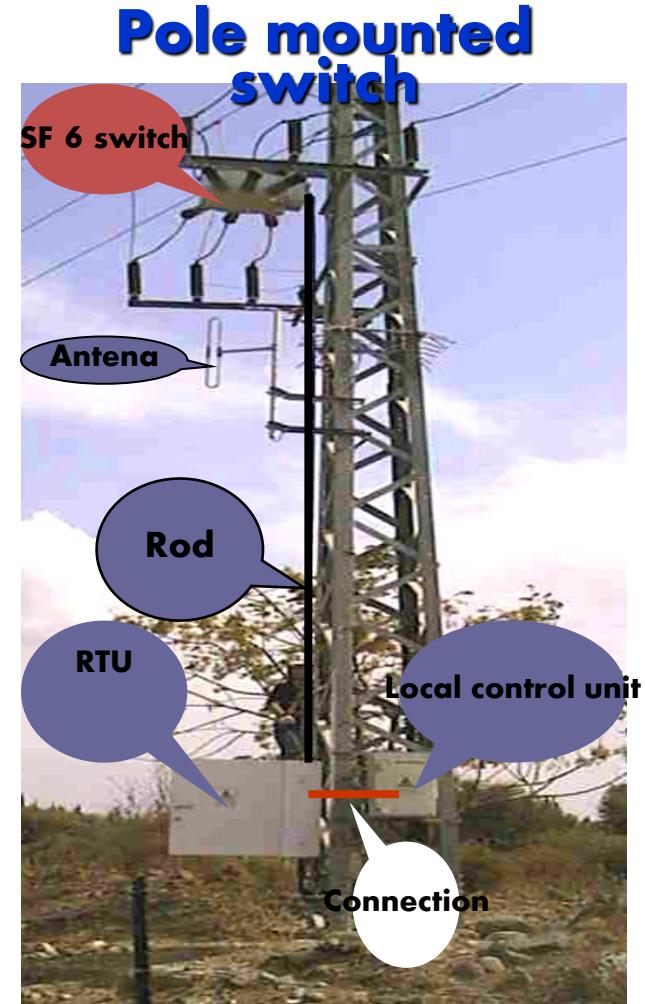
		THE ISRAEL ELECTRIC CORP. LTD. ELECTRONICS & COMMUNICATION UNIT REMOTE COMMAND & CONTROL DEPT.						
			NAME	DATE	SIGN	SCALE		
DRAWN	Vaisler	05.05.09						
DESIGN	Holzer	03.05.09						
CHECK	Hunovich	05.05.09						
APPROV	Lev	05.05.09						
REV.	DATE	DESIGNED	CHECKED	APPROVED	DESCRIPTION		CO, Confidential, only for members of the Consortium (including the Commission services)	
							REV	3.0

# IEC control center



# CI Interdependency

- Telecommunication infrastructure doesn't work without power supply
- Automatic fault localization and isolation on the ECI is not possible without telecommunication and SCADA running
- This interdependency affects the level of risk
- State of the art: a lot of works, models, tools on separate CIs, almost nothing on interdependency
- Need a modeling tool capable to model and simulate different CIs and interdependency



# Interdependency scenarios

- High voltage (HV) (161 KV) poles, on which a F.O. line is installed, fell
- Power supply failure at the telecommunication room located at the substation
- Destruction of Telecommunication Room at Substation
- Destruction of the Technical Center (Maintenance) of the SCADA system for MV grid
- Failure of the Communication Backbone equipment located at the MV SCADA Control Center (CC)
- Failure in power supply to WIZCON Control Center
- Failure in Power Supply to Base Station (BS)
- Failure in power supply to FIU (Field Interface Unit)
- Failure in Power supply to RTU
- Failure in Local Area VHF Communication
- Earthquake Caused the Collapse of the Maintenance Center Building
- External Cyber attack cause the WIZCON Software to Crash
- Short circuit on a line

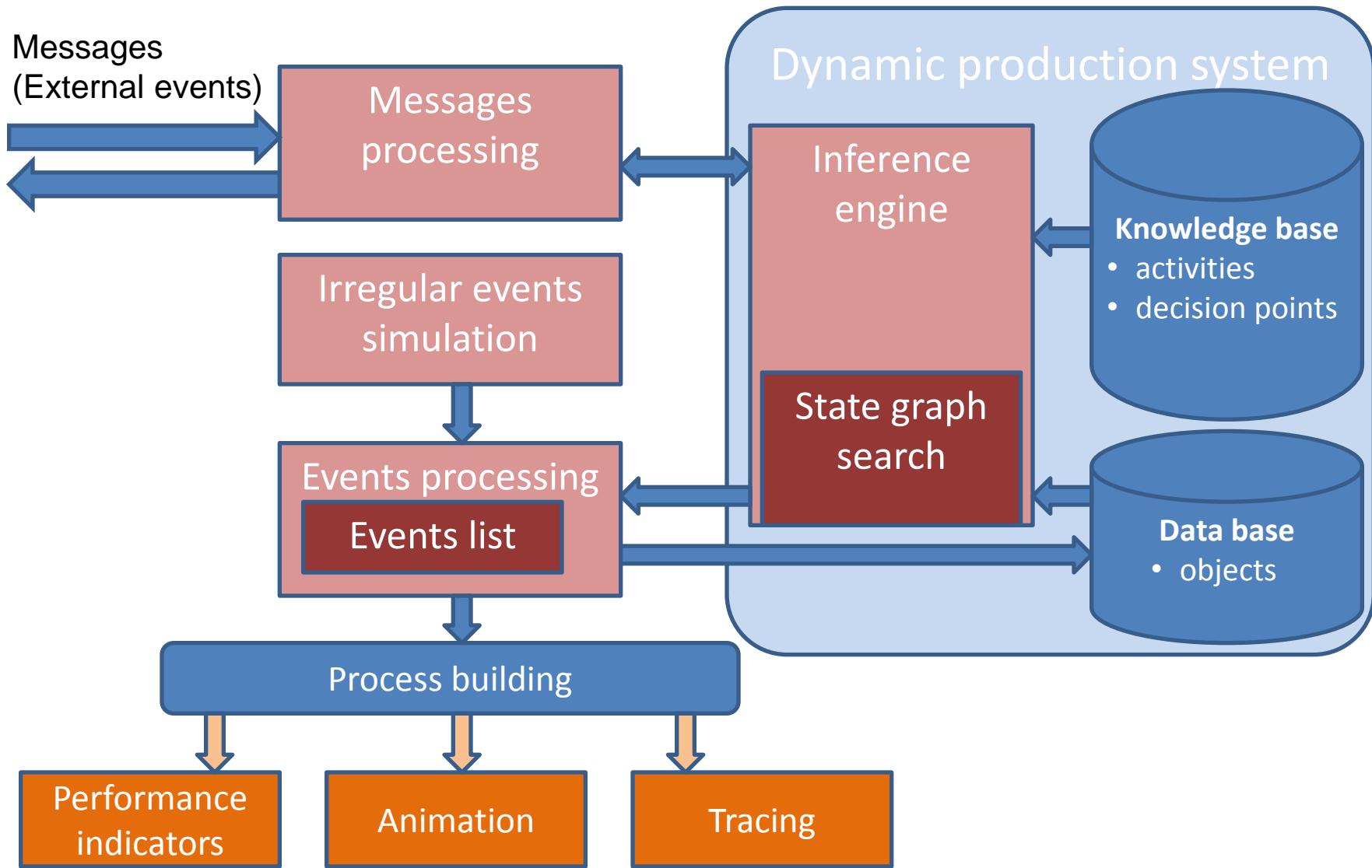
# Simulation for Interdependency Analysis: RAO tool

- To study and to validate the infrastructure interdependency model, we will use the **discrete-event simulation** and **Intelligent RAO simulator**
- In this approach, one need to represent:
  - objects of a real complex system and
  - the way they are interacting
- Once the simulation model is developed, we can run numerous simulations to study system behaviour on various scenarios and to calculate necessary performance indicators
- It does not matter in this approach whether we study a homogeneous system or a multi-layer and interdependent one

# Intelligent RAO simulator

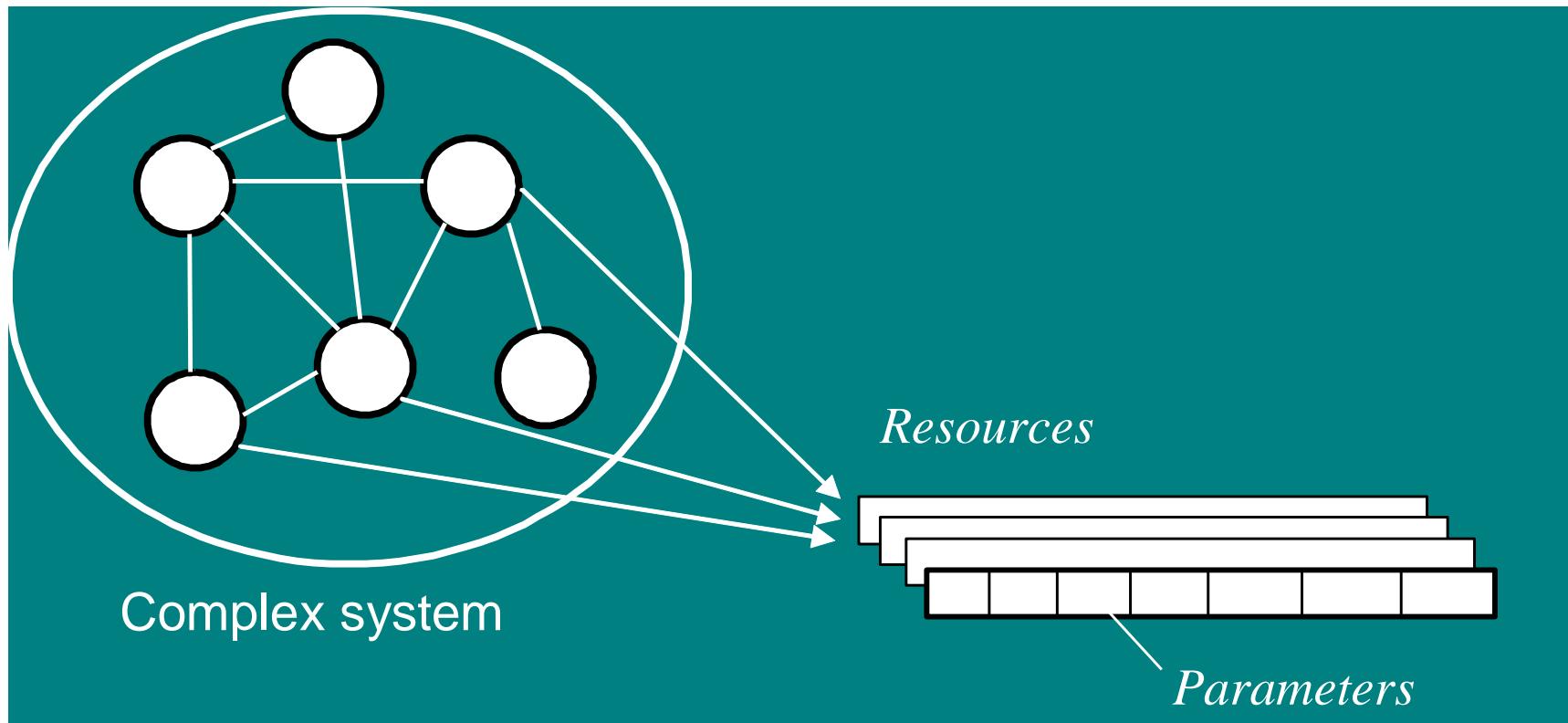
- A hybrid tool based on artificial intelligence for on line and off line optimisation and decision making
  - A discrete-event simulator
  - An expert system engine
  - An optimization tool (state graph search)
  - A data driven programming tool

# RAO: structure



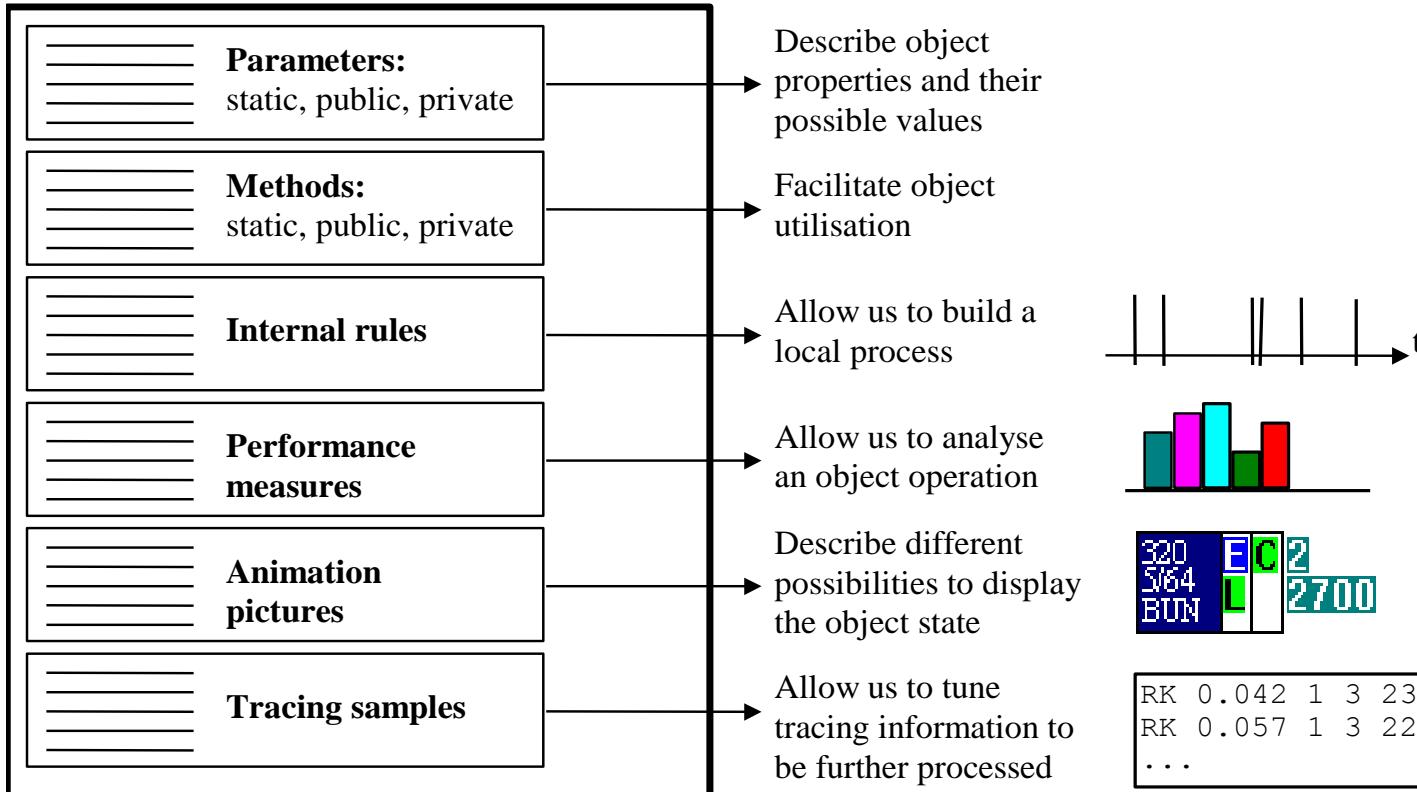
# RAO: resources (objects)

- Complex discrete system (CDS) = set of interacting resources
  - Permanents
  - Temporaries
- Characterized by a set of *parameters*



# RAO: Object class

## Object class

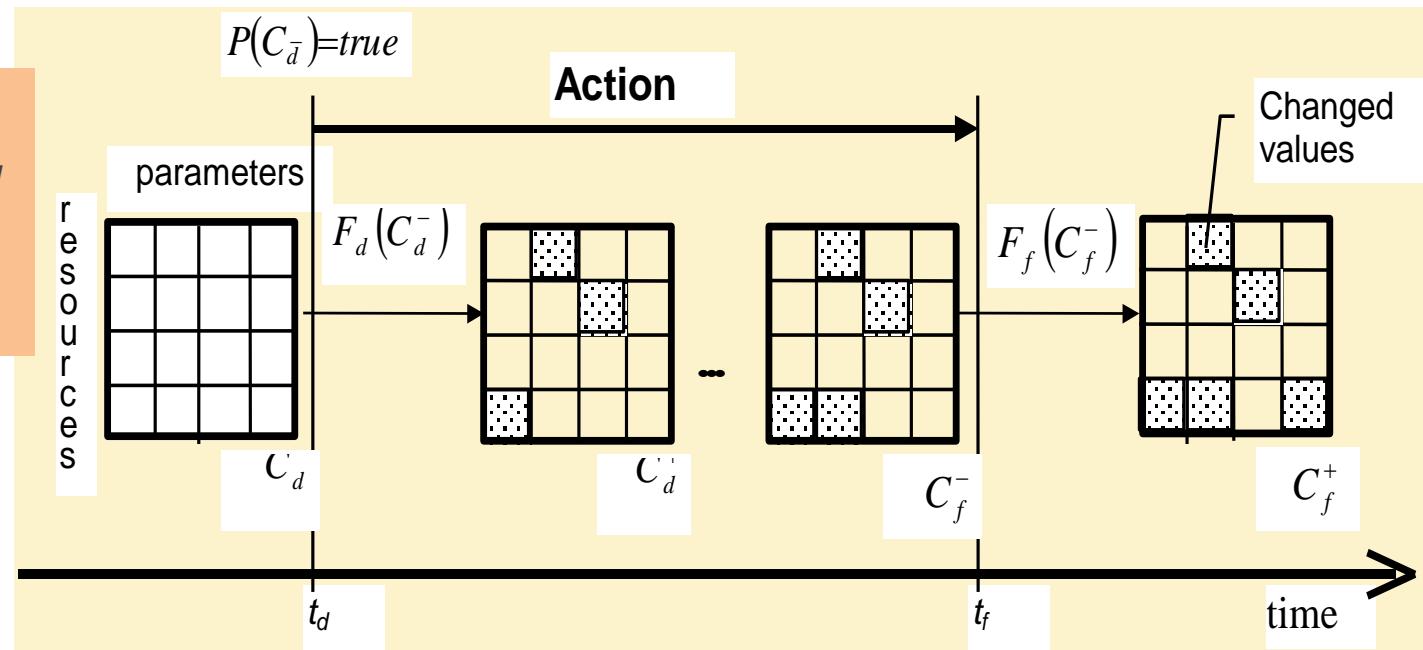


# RAO: actions

- Limited by two events which change the system state
  - Beginning
  - End
- Characterized by :
  - a precondition
  - the rules of system state change at the beginning and at the end
  - a duration

If **condition** then

- **event of beginning**
- **wait  $\Delta T$**
- **event of end**



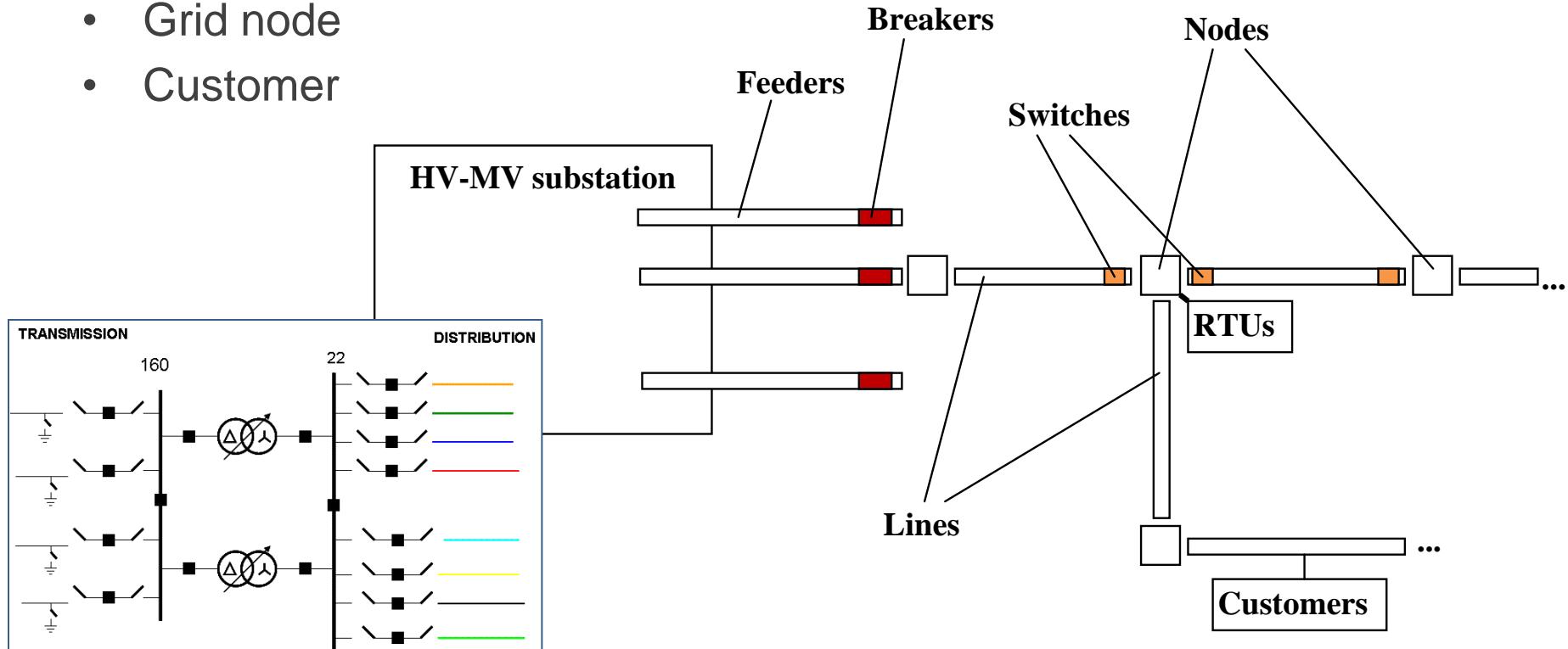
# The interdependent infrastructure simulation model

- Consists of:
- Data base: a set of objects describing system composition and state
  - 149 permanent objects + temporary objects created while simulating)
  - belonging to 14 object types (substation, breaker, line, FIU, gateway, SCADA, etc.)
- Knowledge base: a set of activities describing system behaviour
  - 151 activities of 70 types (toggle breaker state, send a command, repair a line, etc.)
- Animation description to illustrate system state
  - 6 main screens
- Quality of service indicators and specific technical indicators definition
  - Tn, SAIDI, SAIFI, CAIDI
  - About 1000 specific technical indicators for different elements of the system

# ECI elements and structure modeling

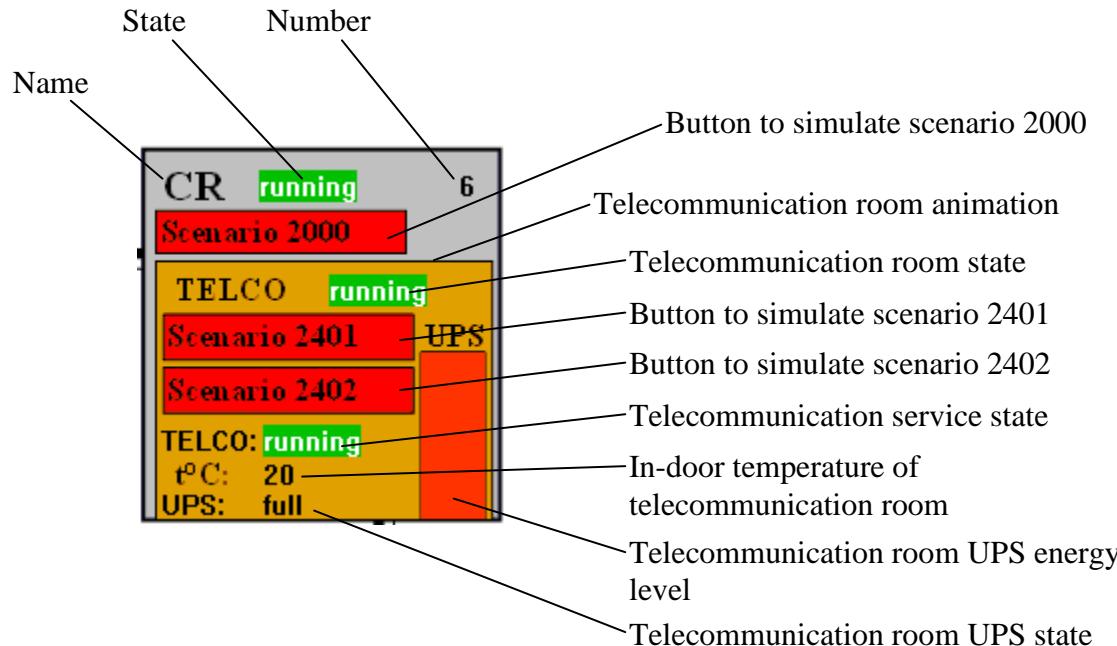
Object types of the model:

- HV\_MV substation with Telco room
- Feeder
- Line
- Grid node
- Customer



# Animation of the objects state and user interaction with the model (1)

- HV-MV substation



RAO-editor - model3

```

File Edit Search RAO View Insert Help
PAT RTP RSS OPR FRM FUN DPT SMR PMD PM

$Resource_type an_HV_MV_substation : permanent
{ 1 Scenario 2000: High voltage (HV) (161 KV)
{ 2 Scenario 2401: Power supply failure at the
{ 3 Scenario 2402: Destruction of Telecommunicat
$Parameters
    Number           : integer
    Name             : (na, zuriel, hanita) : integer
    Connected_Telco_1 : integer
    Connected_Telco_2 : integer
    State            : (running, down) = runi
    TR_State         : (running, power_down, :
    TR_temperature   : real {TELCO room tempera
    TR_Power_consumption : real {KW/h}
    TR_UPS_State    : (full, charging, provi
    TR_UPS_Capacity : real {KW/h}
    TR_UPS_Cur_energy : real {KW/h}
    TR_UPS_Charging_rate : real {KW/h/h}
    TELCO_State     : (running, limited, do
    Last_step        : longint = -1
$End

```

Scenario 2000: High voltage (HV) (161 KV) poles, on which a F.O. line is installed, fell  
 Scenario 2401: Power supply failure at the telecommunication room located at the substation  
 Scenario 2402: Destruction of Telecommunication Room at Substation

# Level 1: HV-MV substations with FO and Telco rooms

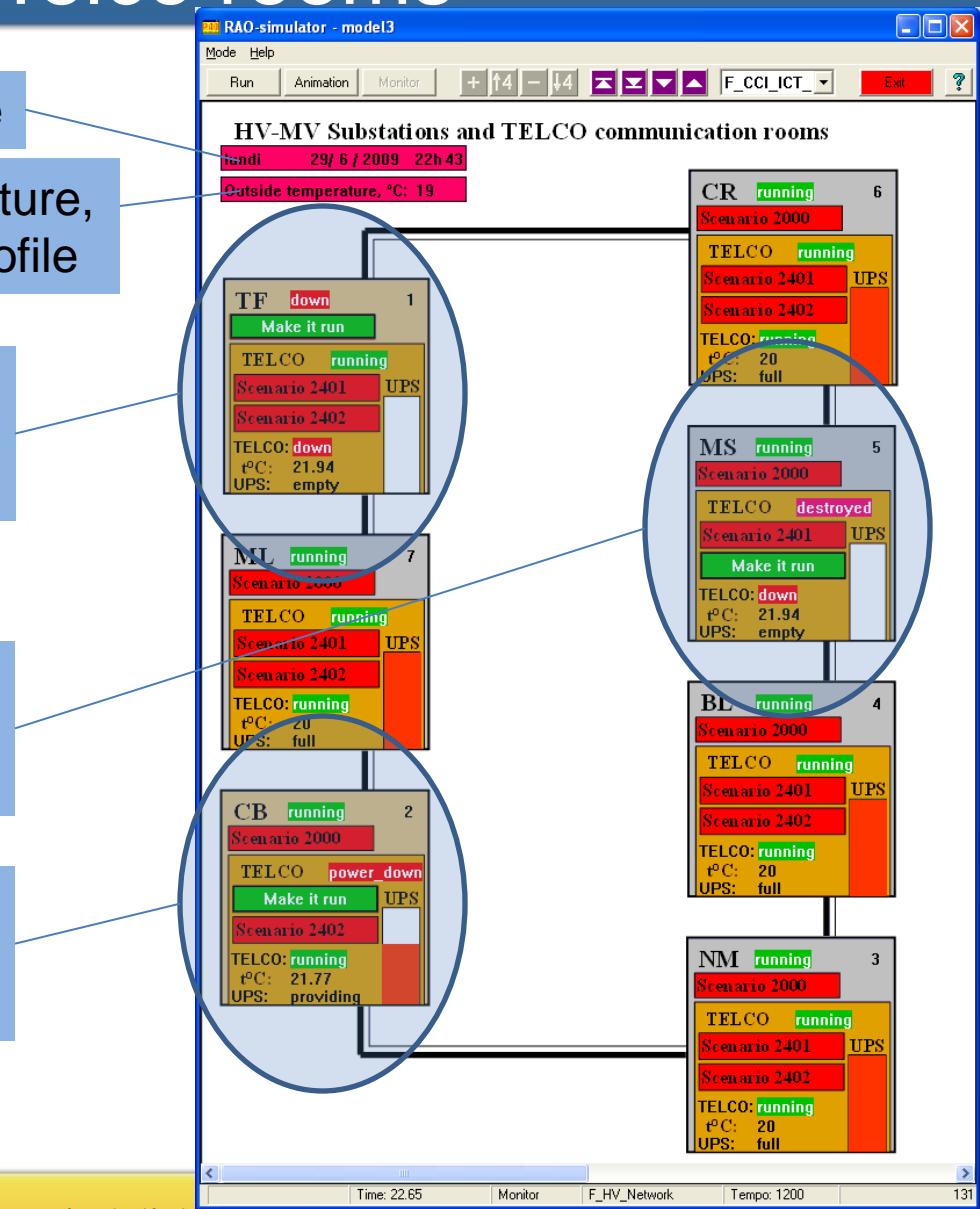
Date and time

Outside temperature,  
given by daily profile

Scenario 2000 applied to TF: High voltage (HV) (161 KV) poles, on which a F.O. line is installed, fell

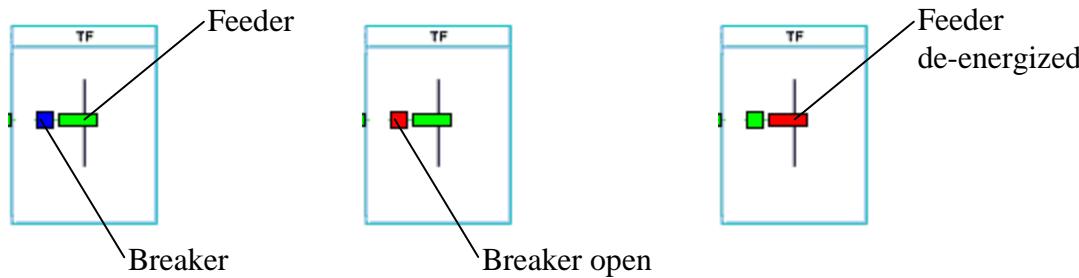
Scenario 2402 applied to MS:  
Destruction of Telecommunication Room at Substation

Scenario 2401 applied to CB: Power supply failure at the telecommunication room located at the substation

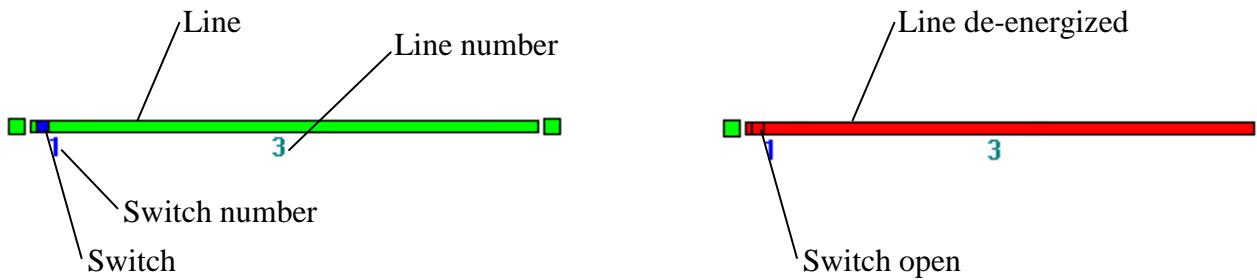


# Animation of the objects state and user interaction with the model (2)

- Feeder + breaker

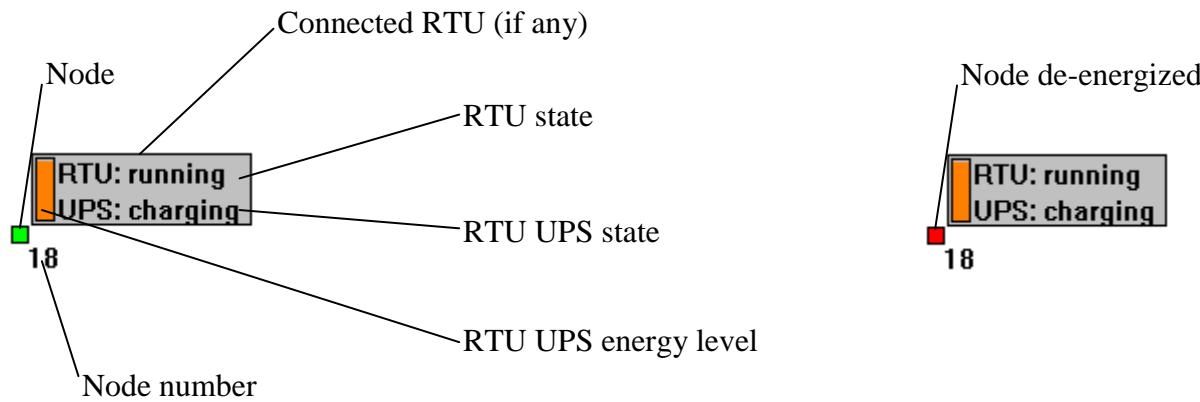


- Transmission line with switch



# Animation of the objects state and user interaction with the model (3)

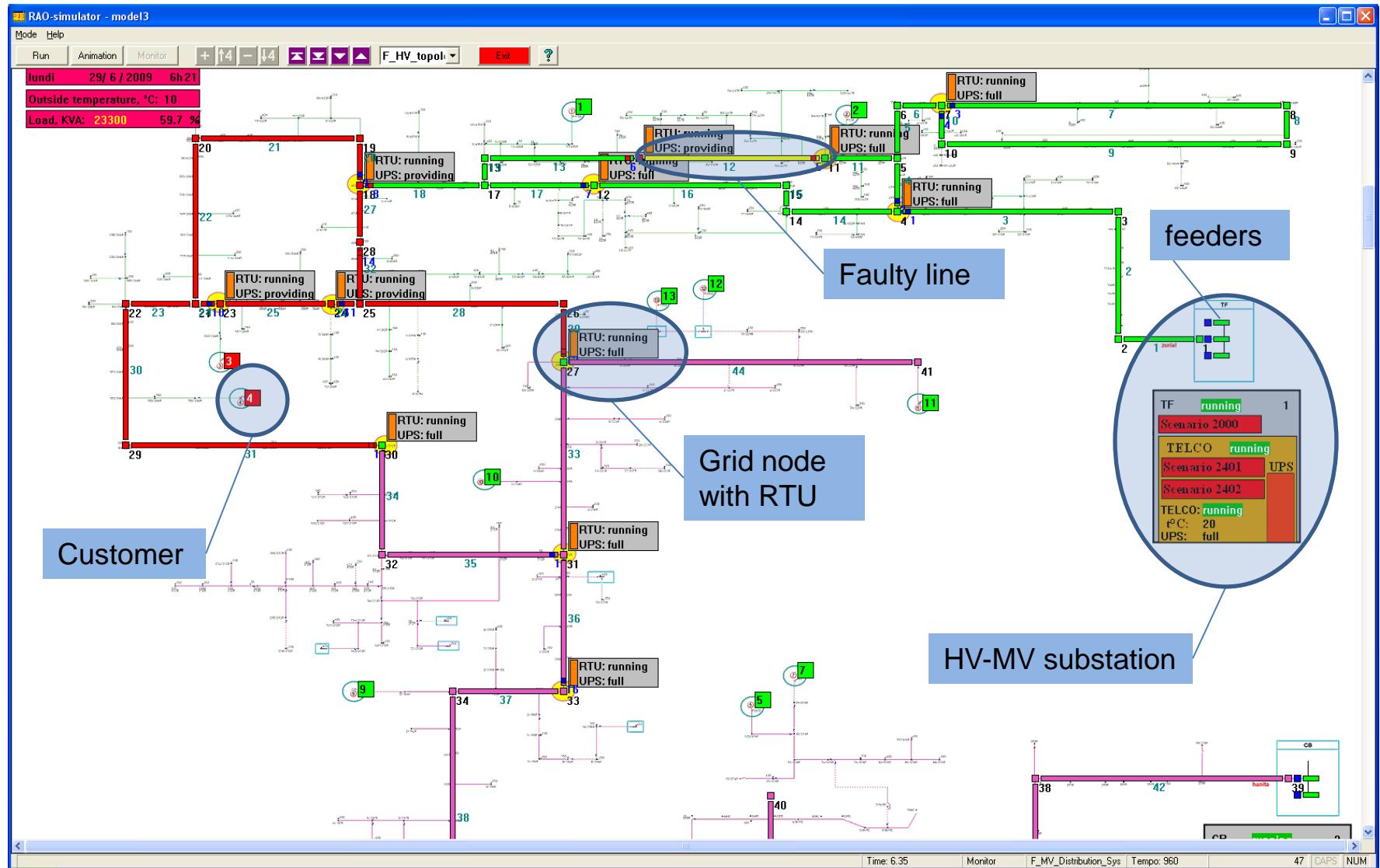
- Grid node with an RTU



- Customer



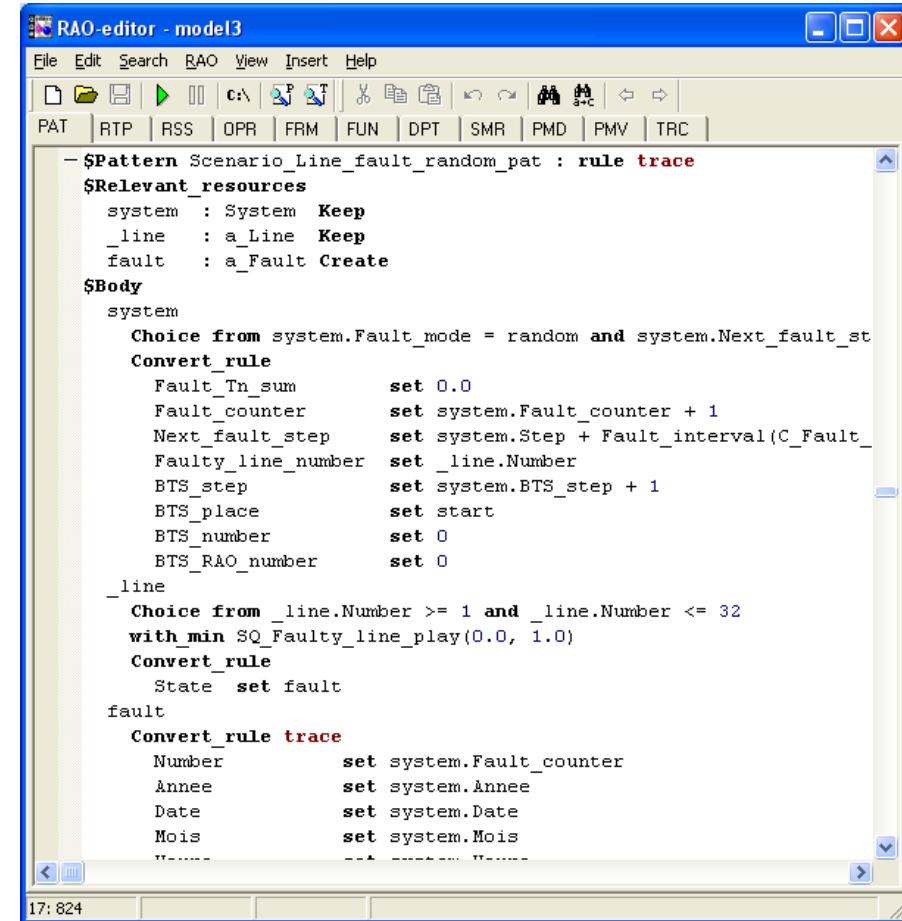
# Level 2: ECI distribution greed (reference FISR scenario)



# Faults (short circuits) simulation

Three ways to initiate a fault:

- Manually by mouse click on a line
- Randomly with faulty line number and time interval randomly generated with given distributions
- Programmed scenario with time of arrival and faulty line number defined by user at the beginning of simulation



The screenshot shows the RAO-editor software interface with a window titled "RAO-editor - model3". The menu bar includes File, Edit, Search, RAO, View, Insert, and Help. The toolbar contains various icons for file operations. The bottom navigation bar includes buttons for PAT, RTP, RSS, OPR, FRM, FUN, DPT, SMR, PMD, PMV, and TRC. The main area displays a script for a fault pattern:

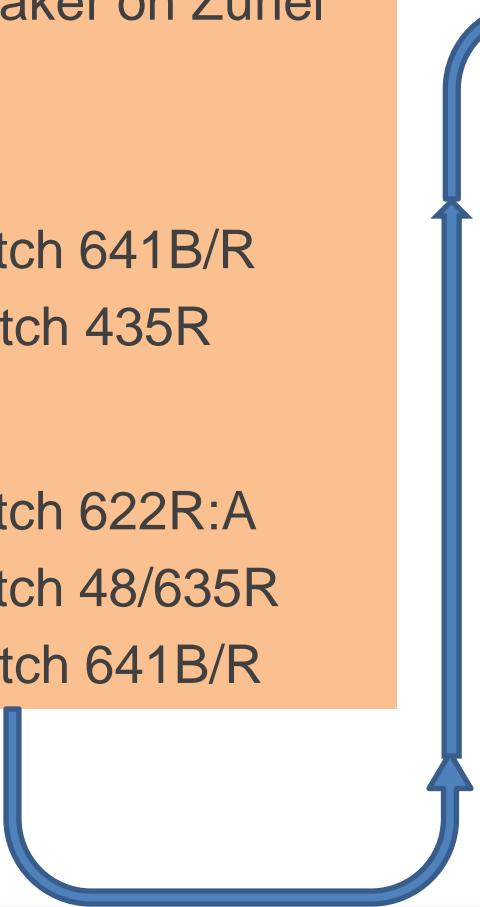
```

$Pattern Scenario_Line_fault_random_pat : rule trace
$Relevant_resources
    system : System Keep
    _line  : a_Line Keep
    fault   : a_Fault Create
$Body
    system
        Choice from system.Fault_mode = random and system.Next_fault_st
        Convert_rule
            Fault_Tn_sum      set 0.0
            Fault_counter     set system.Fault_counter + 1
            Next_fault_step   set system.Step + Fault_interval(C_Fault_
            Faulty_line_number set _line.Number
            BTS_step           set system.BTS_step + 1
            BTS_place          set start
            BTS_number         set 0
            BTS_RAO_number    set 0
        _line
            Choice from _line.Number >= 1 and _line.Number <= 32
            with_min SQ_Faulty_line_play(0.0, 1.0)
            Convert_rule
                State set fault
            fault
                Convert_rule trace
                    Number      set system.Fault_counter
                    Annee       set system.Annee
                    Date        set system.Date
                    Mois        set system.Mois
                    -----

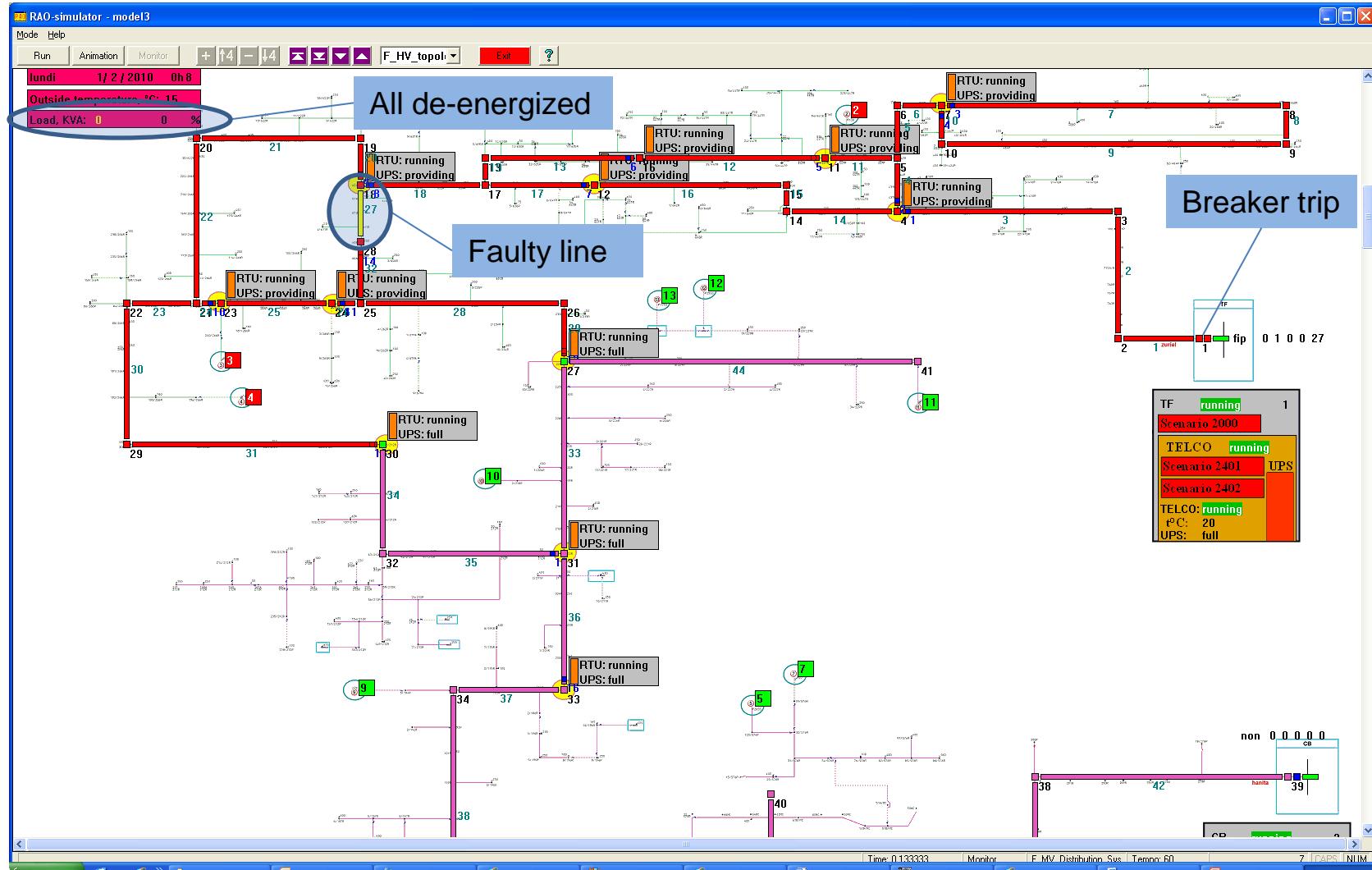
```

# Fault localization process

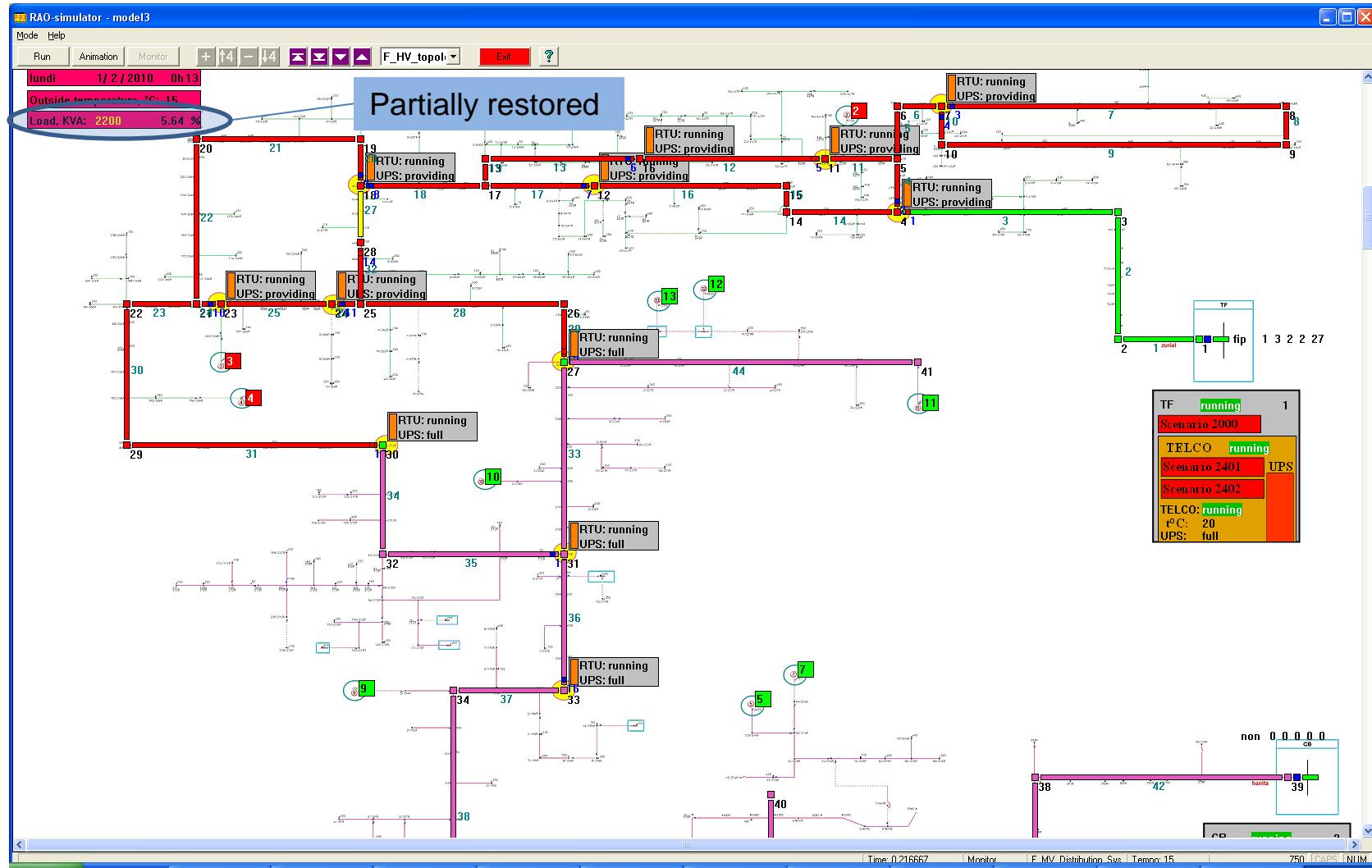
- Step1
  - open switch 435R
  - close breaker on Zuriel feeder
- Step 2
  - open switch 641B/R
  - close switch 435R
- Step 3
  - open switch 622R:A
  - open switch 48/635R
  - close switch 641B/R

- 
- Step 4
    - close switch 48/635R
  - Step 5
    - open switch 622R:B
    - close switch 622R:A
  - Step 6
    - open switch 78/266R
    - close switch 622R:B

# Manual fault simulation on line 27 (5<sup>th</sup> segment)



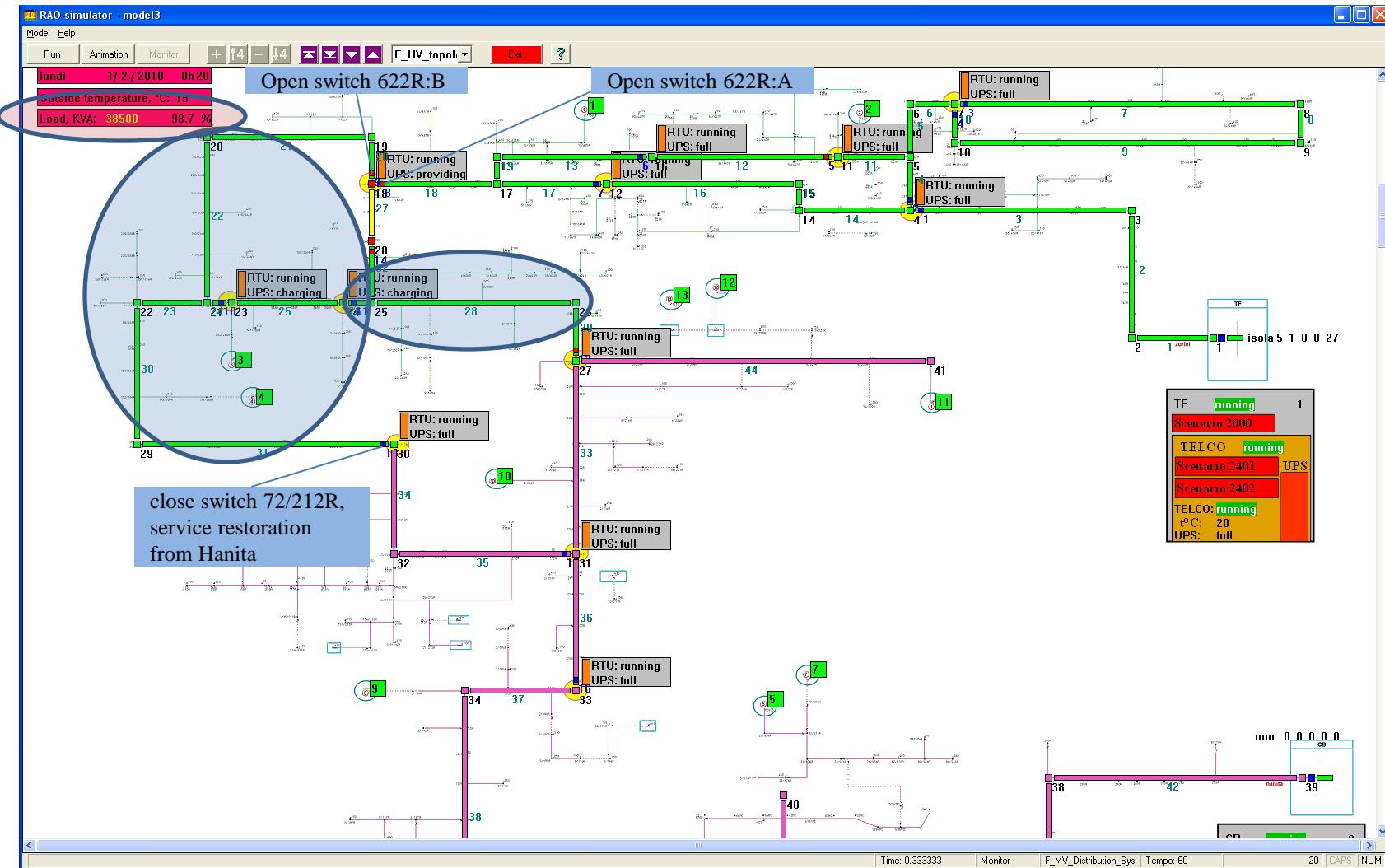
# Fault localization, step 1



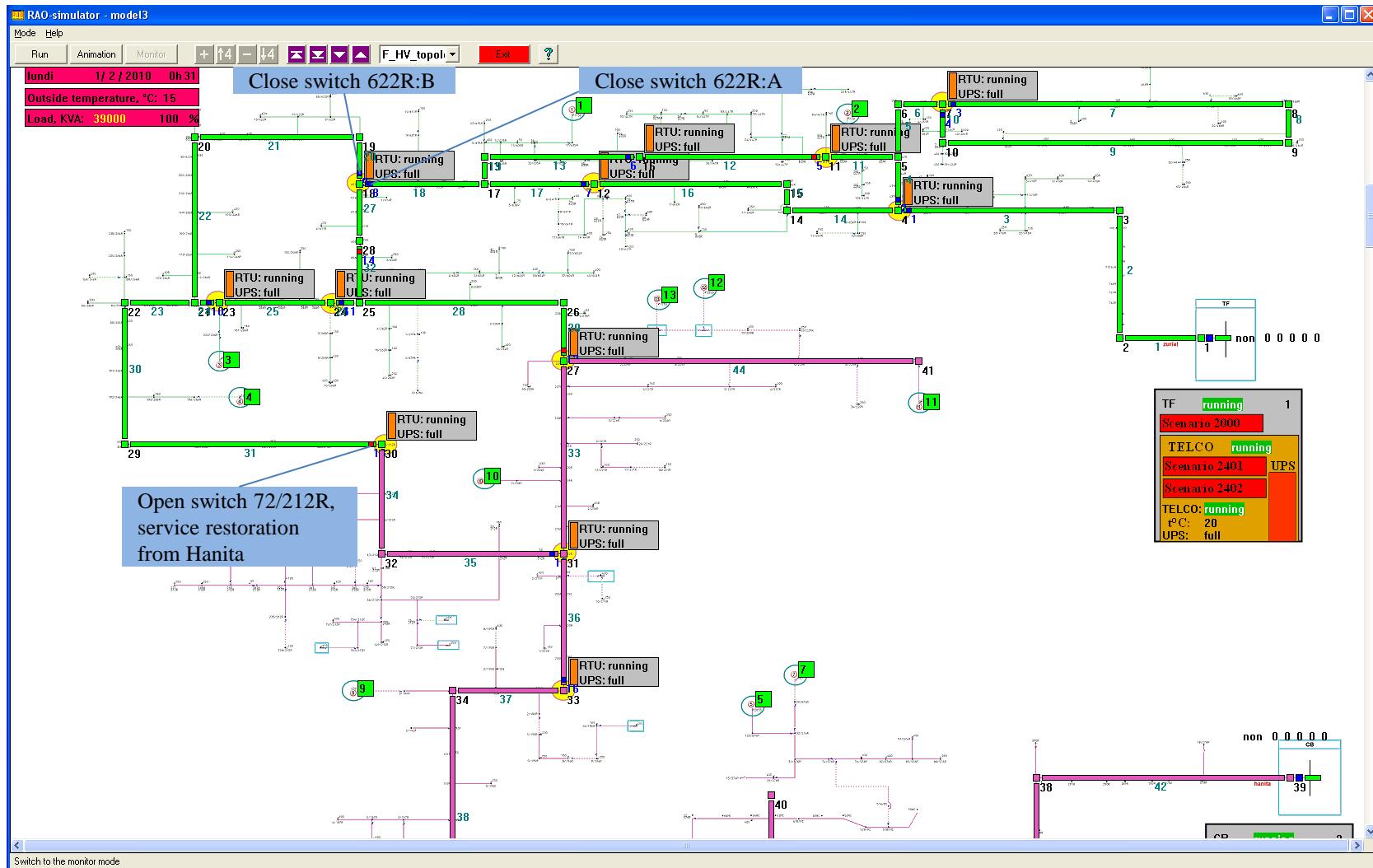
# Fault isolation process

Faulty segment number	Isolation procedure
1	1. close switch 72/212R
2	1. open switch 435R 2. close breaker on Zuriel feeder 3. close switch 72/212R
3	1. open switch 641B/R 2. close switch 5/447R 3. close breaker on Zuriel feeder 4. close switch 72/212R
4	1. open switch 48/635R 2. close switch 622R:A 3. close breaker on Zuriel feeder
5	1. open switch 622R:B 2. open switch 622R:A 3. close breaker on Zuriel feeder 4. close switch 72/212R
6	1. open switch 622R:B 2. open switch 78/266R 3. close breaker on Zuriel feeder 4. close switch 609R (the switch is only manually controlled)
7	Nothing to do, the segment is already isolated after localization

# Fault isolation for 5<sup>th</sup> segment



# Initial configuration restoration

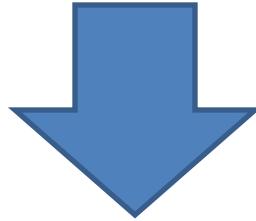


# SCADA modeling

- The fault localization and isolation processes are modeled step by step by giving explicitly all the actions to be done
- Each action is represented by an object of type a\_FIP\_step with the following parameters:
  - Substation number
  - Feeder number
  - Process (localization, isolation)
  - Step number
  - Sub step number
  - Time delay if any
  - ECI element to act on (breaker or switch)
  - Element number
  - Action (open or close)

# SCADA modeling: Fault localization process

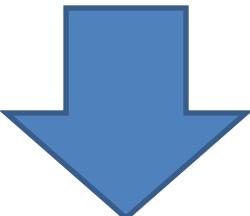
- Step 3
  - open switch 622R:A
  - open switch 48/635R
  - close switch 641B/R



```
1 1 localisation 3 1 0.0 switch 8 open {622R:A}
1 1 localisation 3 2 0.0 switch 6 open {48/635R}
1 1 localisation 3 3 0.0 switch 7 close {641B/R}
```

# SCADA modeling: Fault isolation process

Faulty segment number	Isolation procedure
5	<ol style="list-style-type: none"> <li>1. open switch 622R:B</li> <li>2. open switch 622R:A</li> <li>3. close breaker on Zuriel feeder</li> <li>4. close switch 72/212R</li> </ol>



1 1    isolation 5 1 0.0 switch 9 open {622R:B}
1 1    isolation 5 2 0.0 switch 8 open {622R:A}
1 1    isolation 5 3 0.0 breaker * close {Zuriel}
1 1    isolation 5 4 0.0 switch 13 close {72/212R}

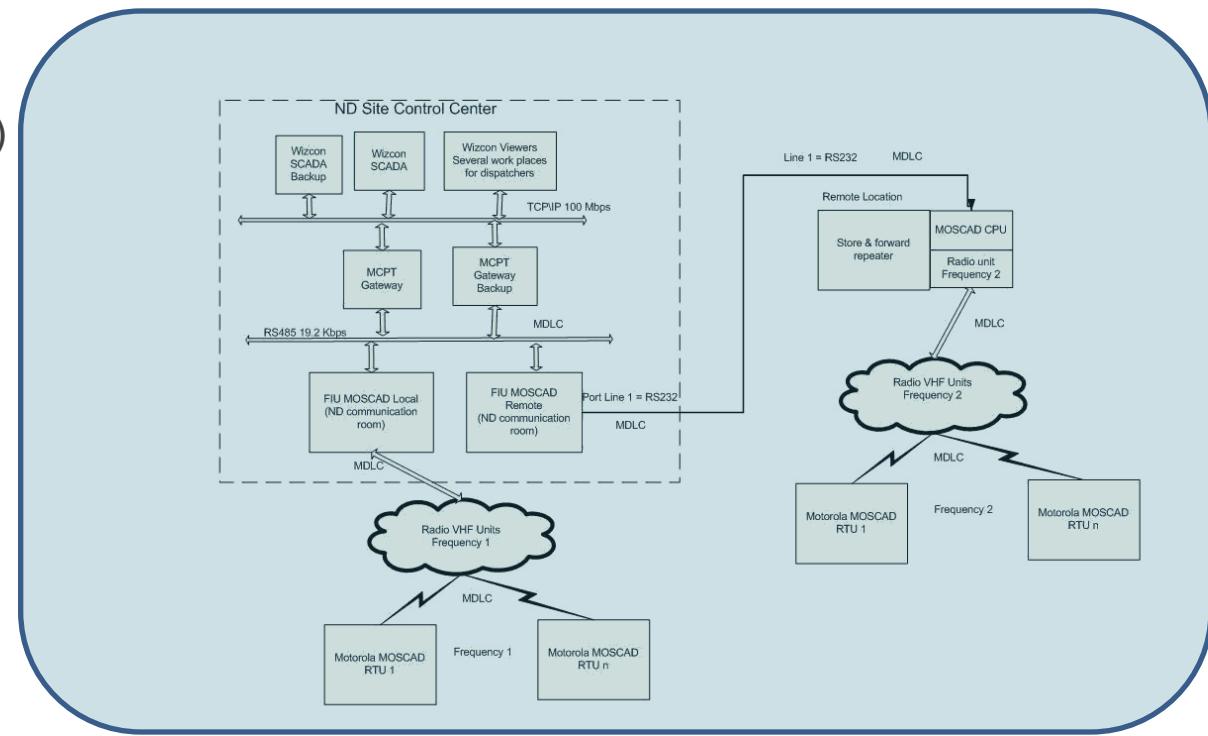
# SCADA modeling: Initial configuration restoration

- Procedure is automatically generated on the basis of normal switch states
- Normal switch states are defined by table (for Zuriel feeder):

Switch	Switch number	Normal state	Switch	Switch number	Normal state
435R	1	closed	622/R:A	8	closed
435R	2	closed	622/R:B	9	closed
464R	3	closed	78/266R	10	closed
464R	4	closed	2/266R	11	closed
5/447R	5	open	229R	12	open
48/635R	6	closed	72/212R	13	open
641B/R	7	closed	609R	14	open

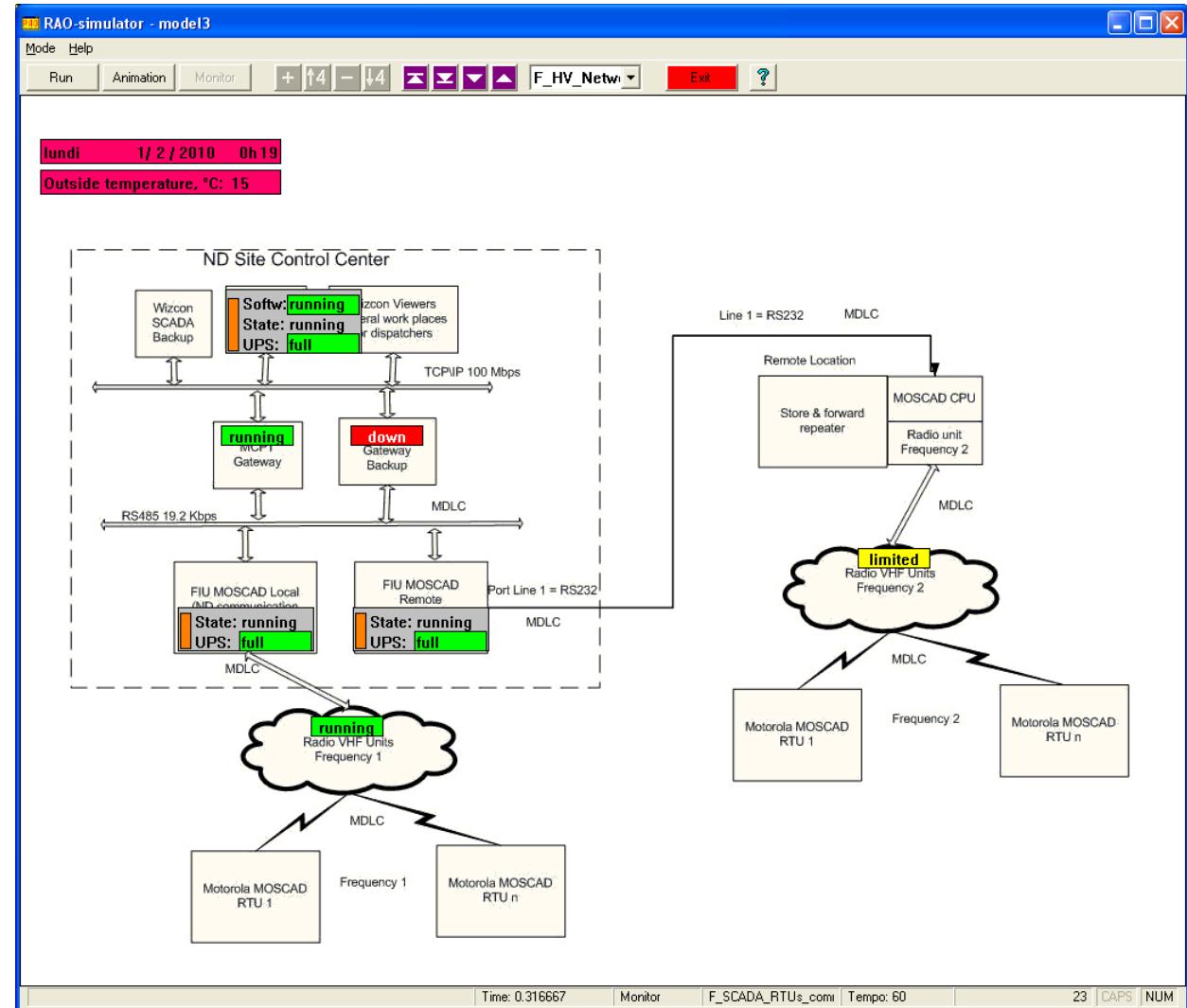
# CCI modeling

- Communication critical infrastructure delivers SCADA commands to RTUs
- Command objects have the following parameters:
  - Number
  - Creation time
  - Execution order
  - Substation number
  - Feeder number
  - Element (breaker, switch)
  - Element number
  - Action
  - State (issued, delivered)
  - Execution time



# CCI modelling

- Software
- Gateways
- Field Interface Units
- Radio VHF Stations
- Remote Terminal Units



# Quality of service indicators

- $T_n$  - equivalent de-energized time for fault n  
$$T_n = \sum(KVA * Duration) / Installed KVA$$
- SAIDI- System Average Interruption Duration  
$$SAIDI = \sum(\text{unsupplied KVA} * t_n) / \text{Installed KVA}$$
- SAIFI- System Average frequency Interruption  
$$SAIFI = \sum(\text{unsupplied KVA}) / \text{Installed KVA}$$
- CAIDI- Customer Average Interruption Duration  
$$CAIDI = SAIDI / SAIFI$$

CAIDI index is the most important index for power utilities. Annually reducing this value indicates an improvement of the overall distribution system performance and reliability.

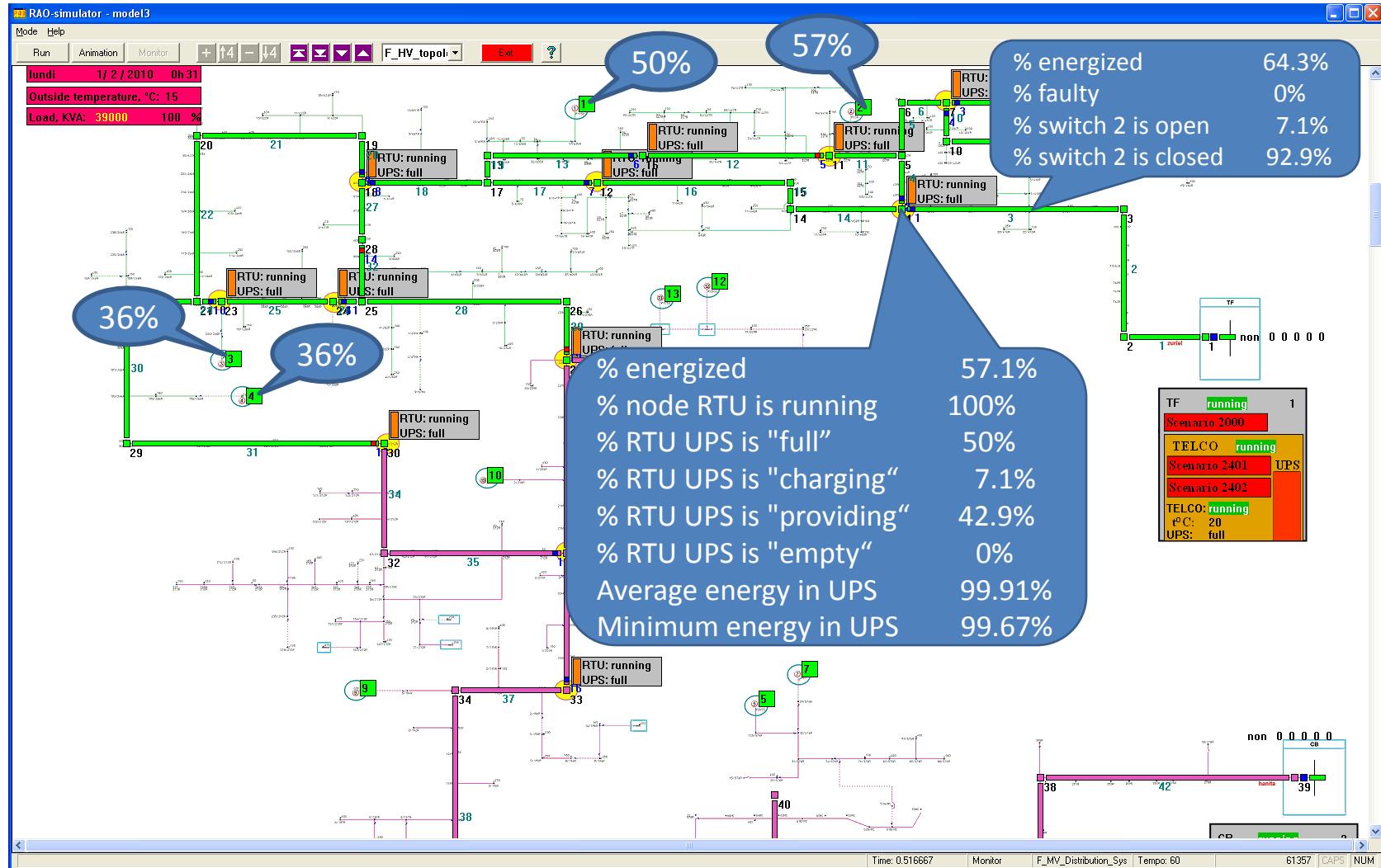
# Quality of service indicators for fault on segment 5

Totally the process lasts for 14 minutes:

- Five minutes for automatic reclosing cycle and for data gathering from customers before starting fault location process
- Four minutes for four additional steps of localization process
- **Five minutes for reparation**

<b>Indicator</b>	<b>Value</b>
Tn	7.26 min
SAIDI - System Average Interruption Duration	7.26 min
SAIFI - System Average Frequency Interruption	1
CAIDI - Customer Average Interruption Duration	7.26 min

# Quality of service indicators: detailed



# Fault simulation on different segments

Indicator	Segment number						
	1	2	3	4	5	6	7
Duration, min	10	11	12	13	14	15	16
Tn, min	5.28	8.19	6.9	7.1	7.26	8.35	8.58
SAIDI, min	5.28	8.19	6.9	7.1	7.26	8.35	8.58
SAIFI	1	1	1	1	1	1	1
CAIDI, min	5.28	8.19	6.9	7.1	7.26	8.35	8.58
Customer 1	50%	45.5%	0%	46.2%	50%	53.3%	56.3%
Customer 2	50%	0%	50%	53.8%	57%	60%	62.5%
Customer 3	50%	45.5%	41.7%	38.5%	36%	33.3%	0%
Customer 4	50%	45.5%	41.7%	38.5%	36%	0%	37.5%

# Fault simulation on different segments

- Tn values in case of reduced service level (increased delivery times) of one of base stations of CCI compared to normal (below).

Indicator	Segment number						
	1	2	3	4	5	6	7
Duration, min	14	15	18	20	20	59	20
Tn, min	7.28	10.07	9.06	10.59	9.0	24.25	10.13

Indicator	Segment number						
	1	2	3	4	5	6	7
Duration, min	10	11	12	13	14	15	16
Tn, min	5.28	8.19	6.9	7.1	7.26	8.35	8.58

# CCI failure, manual FISR

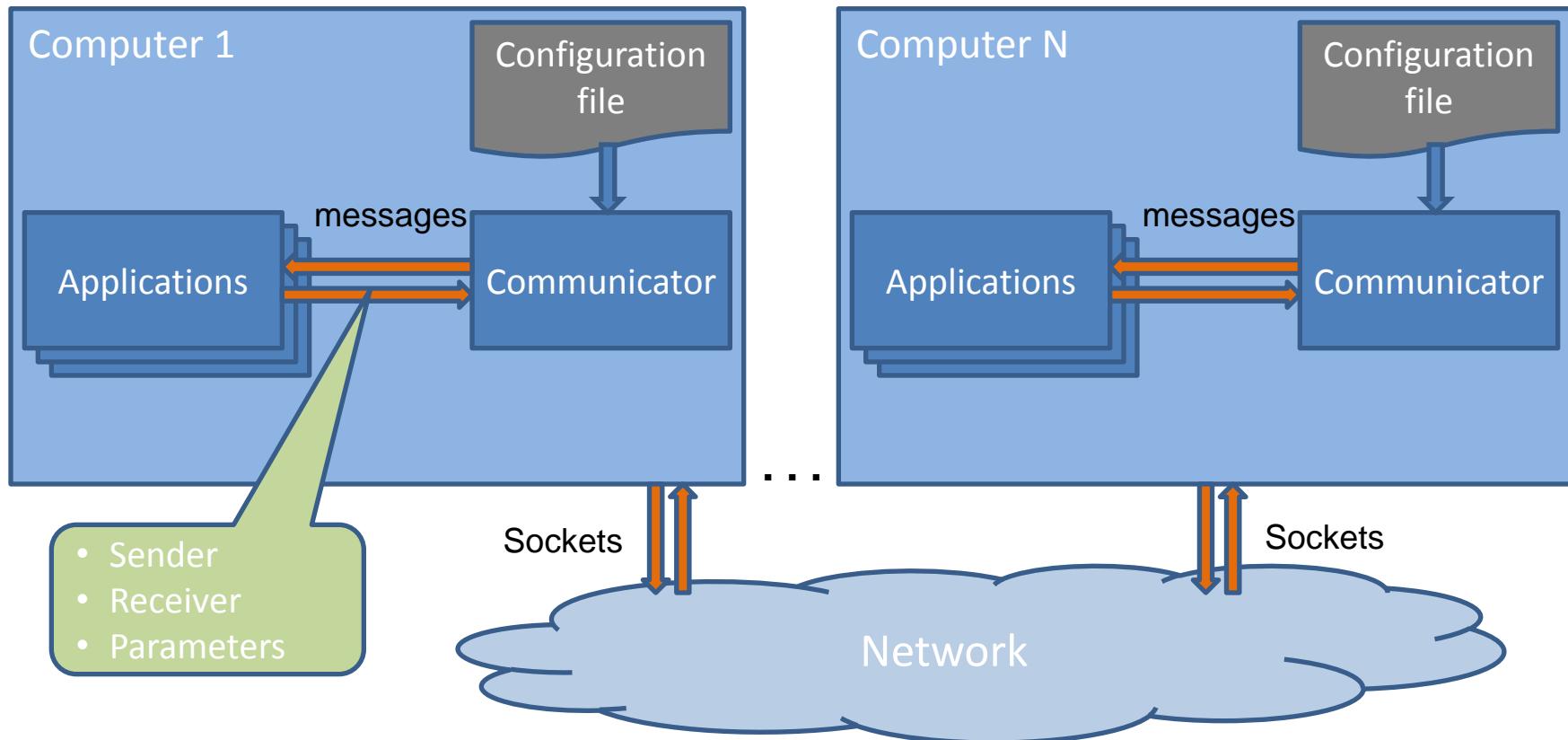
- Tn values in case of failure in Local Area VHF Communication (CCI failure) (radio VHF unit 1 is out of service) with one maintenance team.

radio VHF unit 1 is out of service							
Indicator	Segment number						
	1	2	3	4	5	6	7
Duration, min	46	47	78	38	52	59	50
Tn, min	41.3	42.2	27.1	19.6	24.3	25.2	24.2
Average team command delay, min	18	18	16.5	6.5	10	6.7	9.5

radio VHF unit 2 is out of service							
Indicator	Segment number						
	1	2	3	4	5	6	7
Duration, min	25	53	97	79	79	85	79
Tn, min	20.3	40.2	62.9	59.5	54.2	55.9	55.0
Average team command delay, min	7.5	7.17	8.7	11.5	6.27	6.25	8.63

# Possible extensions: on-line prediction model

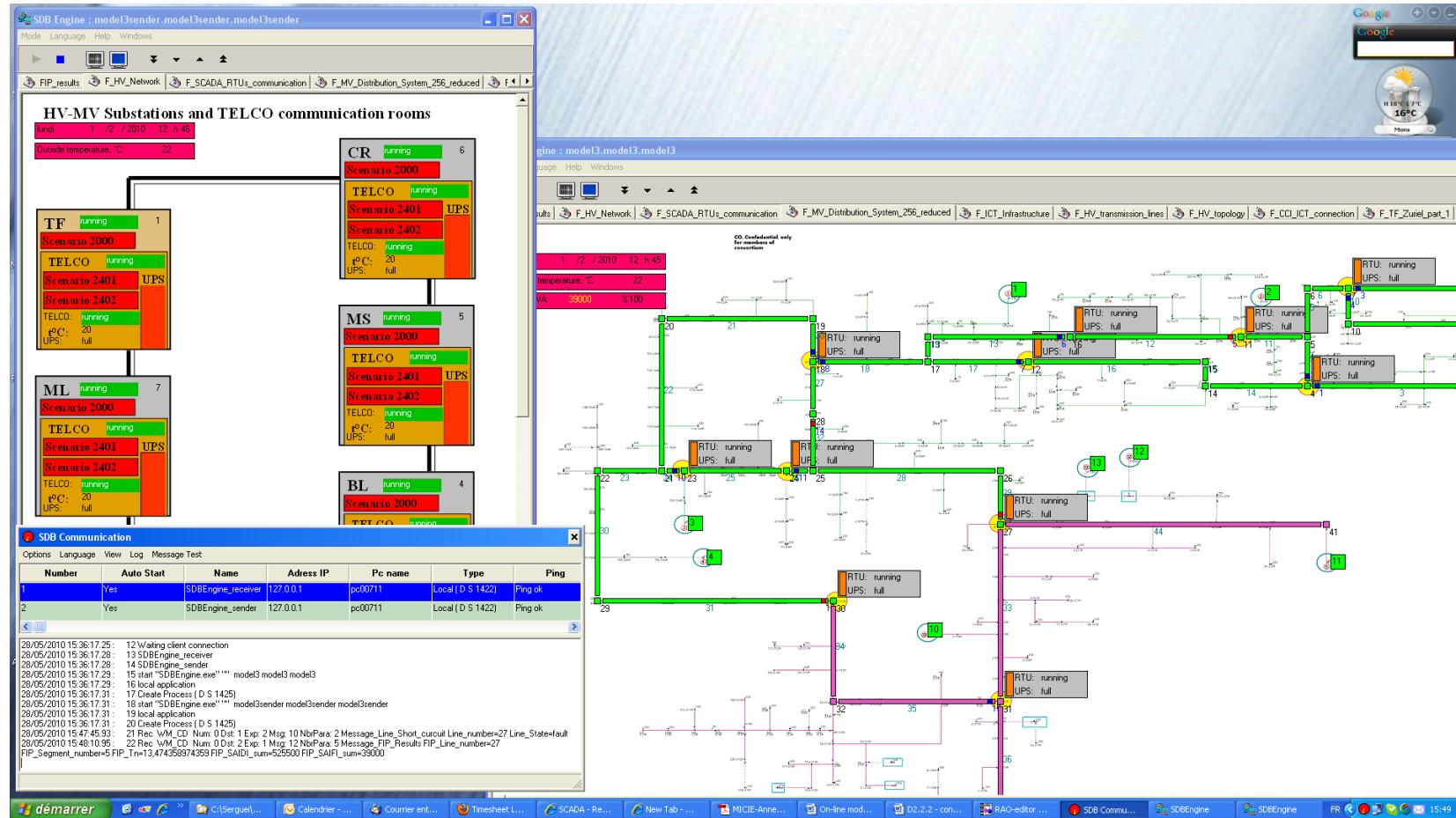
- Distributed architecture



# Communication protocol

- Message\_scenario\_2000 - High voltage (HV) (161 KV) poles, on which a F.O. line is installed, fell
- Message\_scenario\_2401 - Power supply failure at the telecommunication room located at the substation
- Message\_scenario\_2402 - Destruction of Telecommunication Room at Substation
- Message\_scenario\_Gateway - Failure of the Communication Backbone equipment located at the MV SCADA Control Center (CC)
- Message\_scenario\_power\_supply\_to\_SCADA - Failure in power supply to WIZCON Control Center
- Message\_scenario\_SCADA\_Software\_crash - External Cyber attack cause the WIZCON Software to Crash
- Message\_scenario\_S3004\_FIU\_state - Failure in power supply to FIU (Field Interface Unit)
- Message\_scenario\_VHF\_Communication\_failure - Failure in Local Area VHF Communication
- Message\_Breaker\_state\_change - current breaker state (open or closed)
- Message\_Line\_switch\_state\_change - current switch state (open or closed)

# On-line model running



# Conclusions

- The goal of modeling interdependencies of different critical infrastructure is reached
- The expressive power of RAO simulator allows one to simulate different CIs as well as their interdependencies
- Interdependency aspects are significant
- Simulation brings important elements to estimation of risk level, allowing quantitative estimation of QoS indicators in actual system state for possible scenarios