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INTERNATIONAL SMART GRID ACTION NETWORK

ISGAN – WEBINAR
Planning of Distribution Systems in the Era of Smart Grids

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February 2018

iea Energy Technology Network

CLEAN ENERGY MINISTERIAL

Outline

- **About ISGAN**
- Context and motivation
- Distribution planning
- Deterministic distribution planning
- Novel Distribution Planning
  - Input data - Examples
  - Managing uncertainties and risks - Examples
  - Planning with Smart Grids - Examples
- Future works
- Conclusions

ISGAN in a Nutshell

ISGAN
INTERNATIONAL SMART GRID ACTION NETWORK

'Strategic platform to support high-level government attention and action for the accelerated development and deployment of smarter, cleaner electricity grids around the world'

CLEAN ENERGY MINISTERIAL
Accelerating the Transition to Clean Energy Technologies

- An initiative of the Clean Energy Ministerial (CEM)

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- Organized as the Implementing Agreement for a Co-Operative Programme on Smart Grids (ISGAN)

The CEM is the only multilateral forum dedicated exclusively to the advancement of clean energy technologies and related policies.
ISGAN is the only global government-to-government forum on smart grids

Activities of ISGAN

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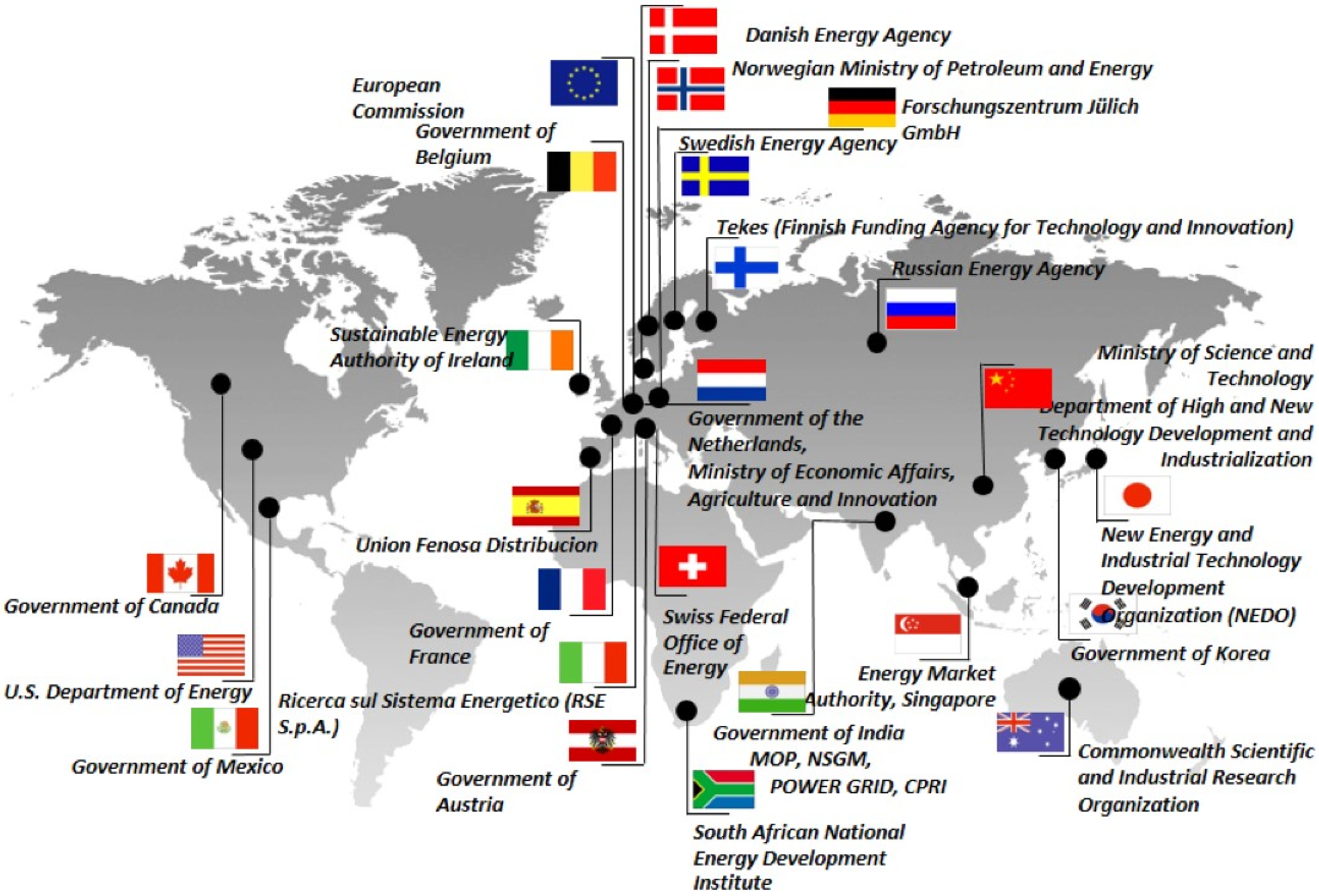
- **Annex 1:** Global smart grid inventory
- **Annex 2:** Smart grid case studies.
- **Annex 3:** Cost-benefits analysis and toolkits.
- **Annex 4:** Insights for decision makers
- **Annex 5:** Smart Grid International Research Facility Network (SIRFN)
- **Annex 6:** Power T&D systems.
- **Annex 7:** Smart grid transitions.
- **Annex 8:** ISGAN smart grid academy

Geography of ISGAN



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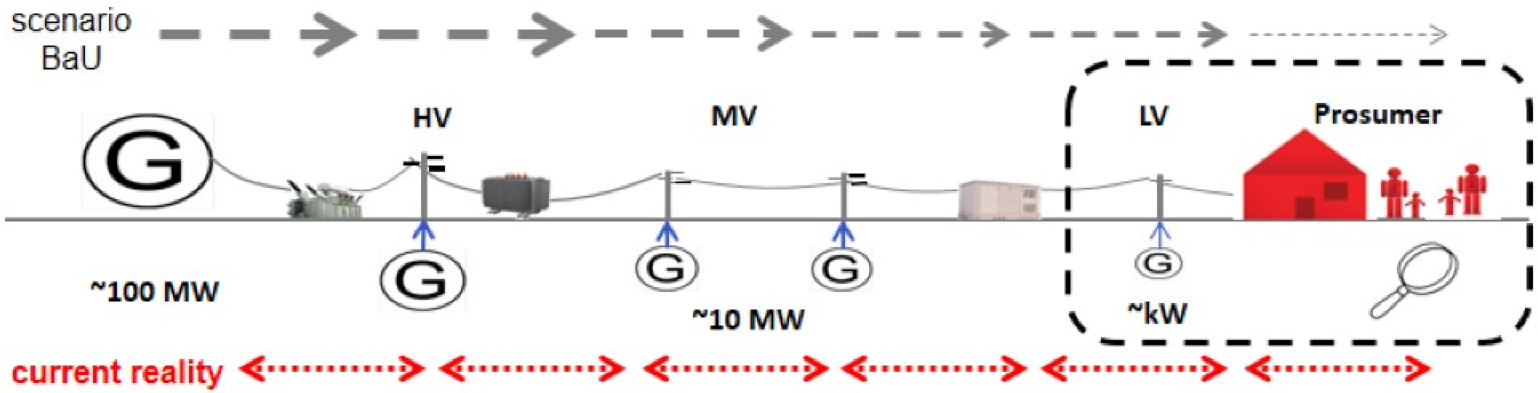
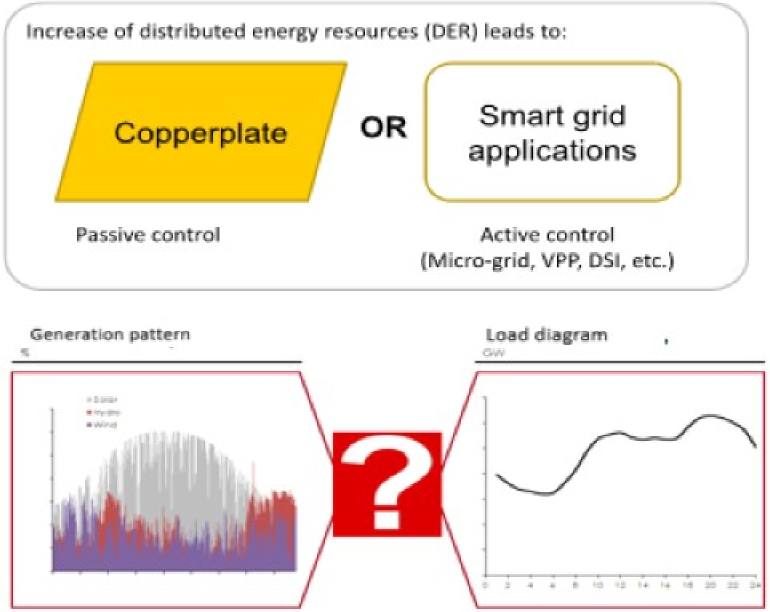
Key drivers



- environmental and regulatory pressure
- market liberalization and overall efficiency
- security of supply + increase quality of service
- "copper" investments postponement
- increasing dispersed renewable generation (DG)
- flexibility (storage, electric vehicle, active demand)



Decision making under volatility and uncertainty?

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Operations	Planning	Trend
real-time or near real-time decisions	"long-time" decision	shorten planning cycles
alternative scenario (contingency) is always "prepared"	alternative scenario is highly scrutinized	future is "foggy" and it is difficult to realize impacts
operational procedures are fundamental	analyses procedures are also fundamental	new variables to be incorporated
decisions evolve risk	risk highly mitigated	risk incorporation
decisions affect the present	decisions affect mostly the future	systems integration to improve decisions

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Planning	is still based on:	... but has to:
Demand forecast	macroeconomic and historical models	forecast for load and DG production(*)
Load data forecast	customer usage and territorial planning	incorporate information on DER development
Planning alternatives (scenarios)	compliance with standards based on traditional supply side options	considerate active network solutions and integrate risk variable
Approach	deterministic models	switch to probabilistic

(*) extreme scenarios considered

Smart Grid – the answer

A shared global definition of active distribution networks was developed by **CIGRE Working Group C6.11:**

"Active distribution networks have systems in place to control a combination of distributed energy resources (DERs), defined as generators, loads and storage with power electronics. Distribution system operators have the possibility of managing the electricity flows using a flexible network topology. DERs take some degree of responsibility for system support, which will depend on a suitable regulatory environment and connection agreement."

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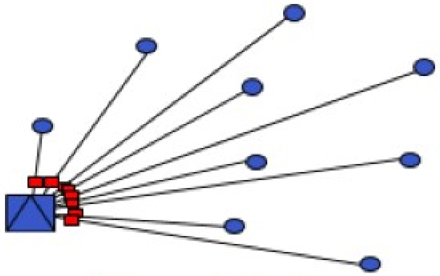
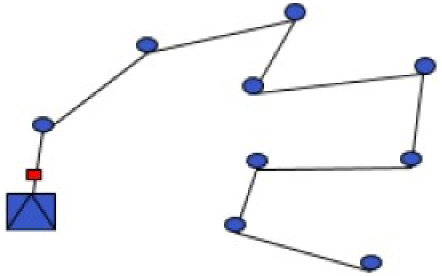
MV distribution network planning

Different choices …

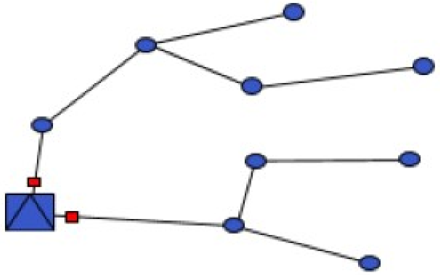
- ❑ Primary distribution voltages (1.1 kV ÷ 66 kV)
- ❑ Neutral earthing (solid, via impedance, unearthed)
- ❑ Network architecture (radial, meshed)
- ❑ Network path (contrasting requirements)



Star architecture
(extremely expensive)



Excessive long feeder
(bad continuity)



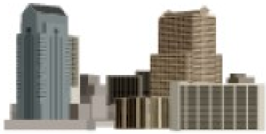
Good compromise

MV distribution network planning

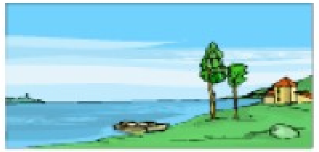
… motivated by different factors (Objective Functions)

- ❑ Minimum cost (*building, maintenance, losses*)

- ❑ Load density (*urban, semi-urban, rural areas*)



- ❑ Environmental constraints (*lakes, forest, historical buildings*)



- ❑ Continuity of supply (*penalties/rewards from regulators, network automation*)

Optimal Distribution Planning is an NP-Hard problem

MV distribution network planning

Evaluation of the alternatives: feeder calculation.

Customer's demand is not a certain data, but at MV level the uncertainty is reduced, because it is typically the aggregation of several customers.

⬇

Traditionally, it was acceptable to represent loads in Load Flow calculation with a single yearly power demand (peak value) or a unique load profile (calculation repeated for each hour).

Traditional MV feeder calculation

Simplifications in the calculations derive from the typical radial configuration. Without Distributed Generation (DG), this means unidirectional power flows.

These considerations led in the past to the adoption of a deterministic approach for the network calculations.

Data known with certainty (uncertainties are neglected).

- ✓ annual power demand;
- ✓ annual power generation (negative load);
- ✓ power demand growth rate;
- ✓ ……

Typical planning process

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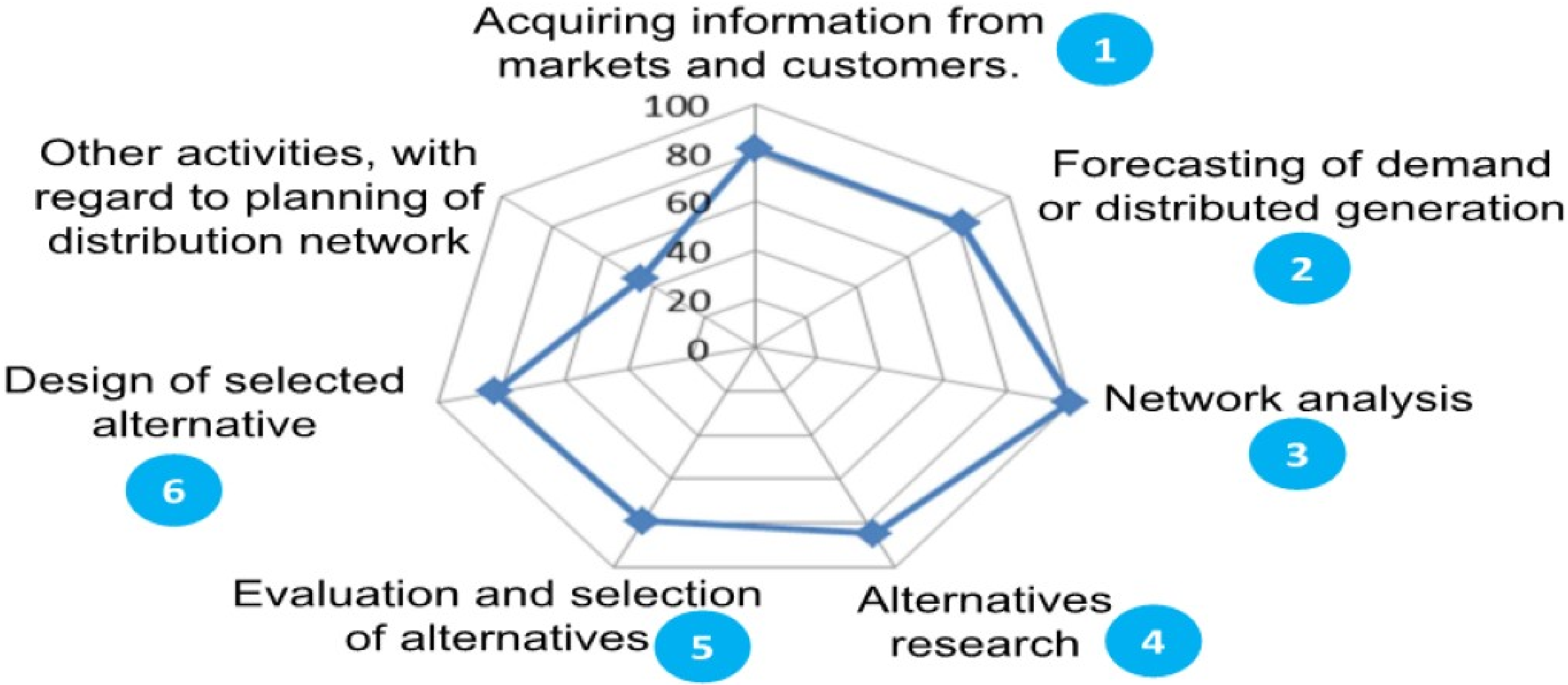
Acquiring information from markets and customers	1
Forecasting of demand or distributed generation	2
Network analysis	3
Alternatives research	4
Evaluation and selection of alternatives	5
Design of selected alternative	6

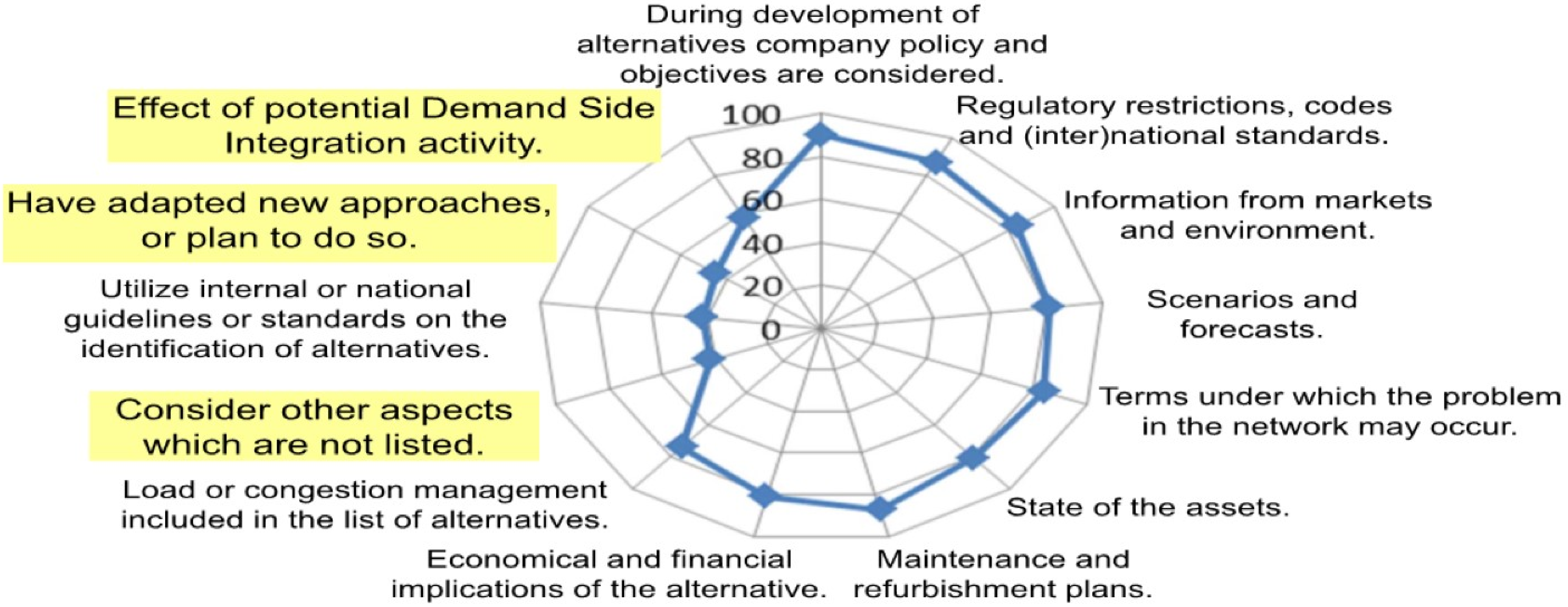
Alignment with typical planning process



More than 90% of respondents confirmed to perform the steps of the typical planning process

Source: CIGRE TB 591– Planning of active distribution networks

Research for planning alternatives



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Research for planning alternatives

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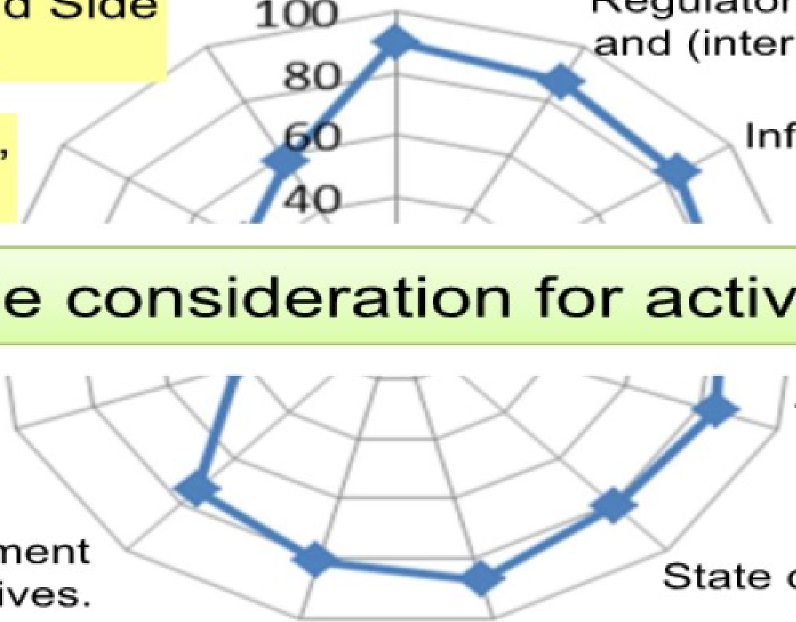

Most utilities make little consideration for active network solutions

Source: CIGRE TB 591 – Planning of active distribution networks

CIGRE WG C6.19 - SURVEY RESULTS

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Changing of planning objectives: mostly oriented to the **maximum exploitation of existing assets**, by working distribution networks much closer to their physical limits.

It is crucial that **modern planning tools** **integrate ADN solutions** in the set of feasible alternatives (CIGRE WG C6.11) in order to identify the best balance with traditional network expansion.

CIGRE WG C6.19
Survey on methods and tools for planning of ADN

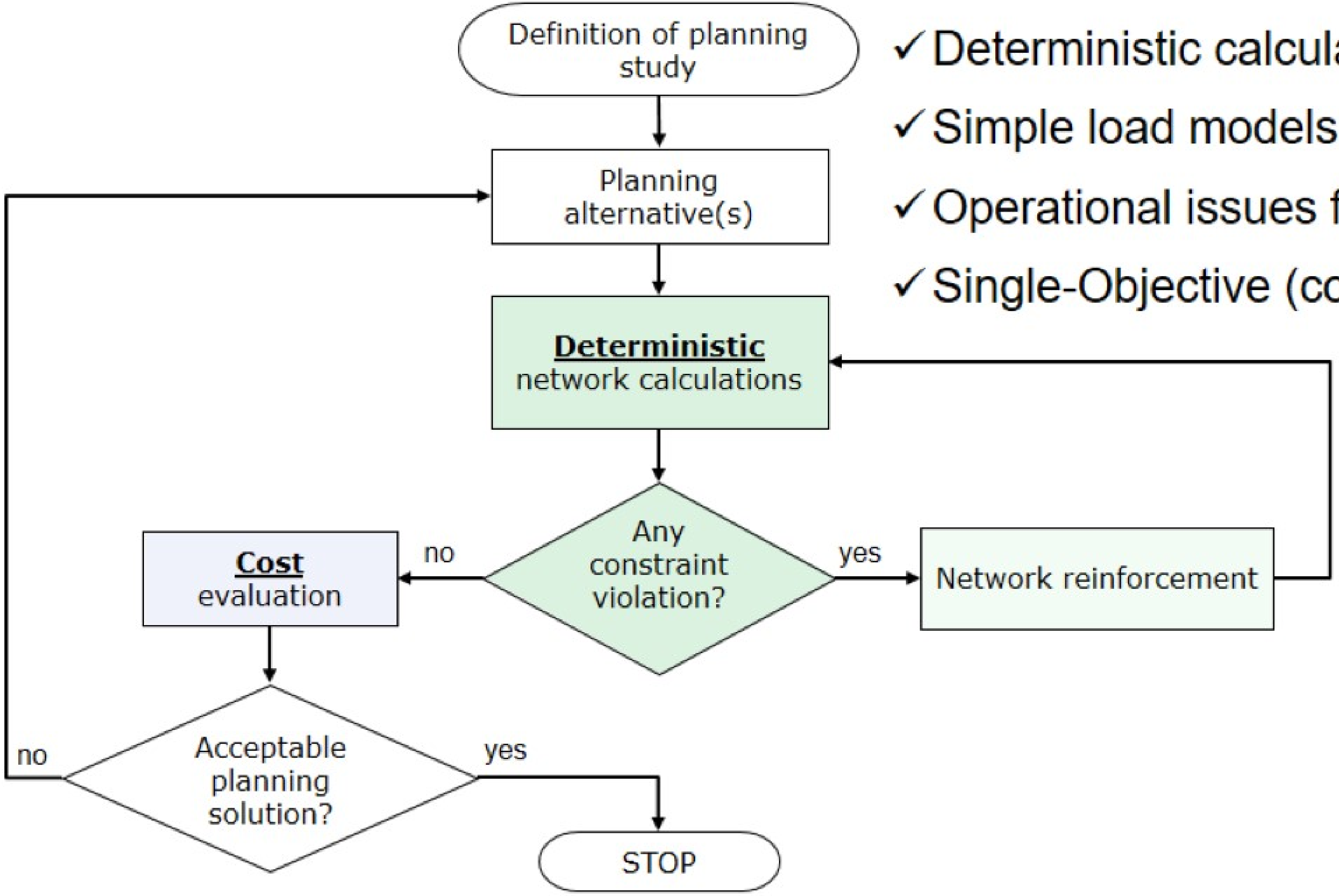
"Today, while of interest to many utilities, ADN concept fails to be taken seriously by utilities as viable alternatives in the planning process."

Main reasons:

1) lack of planning tools,

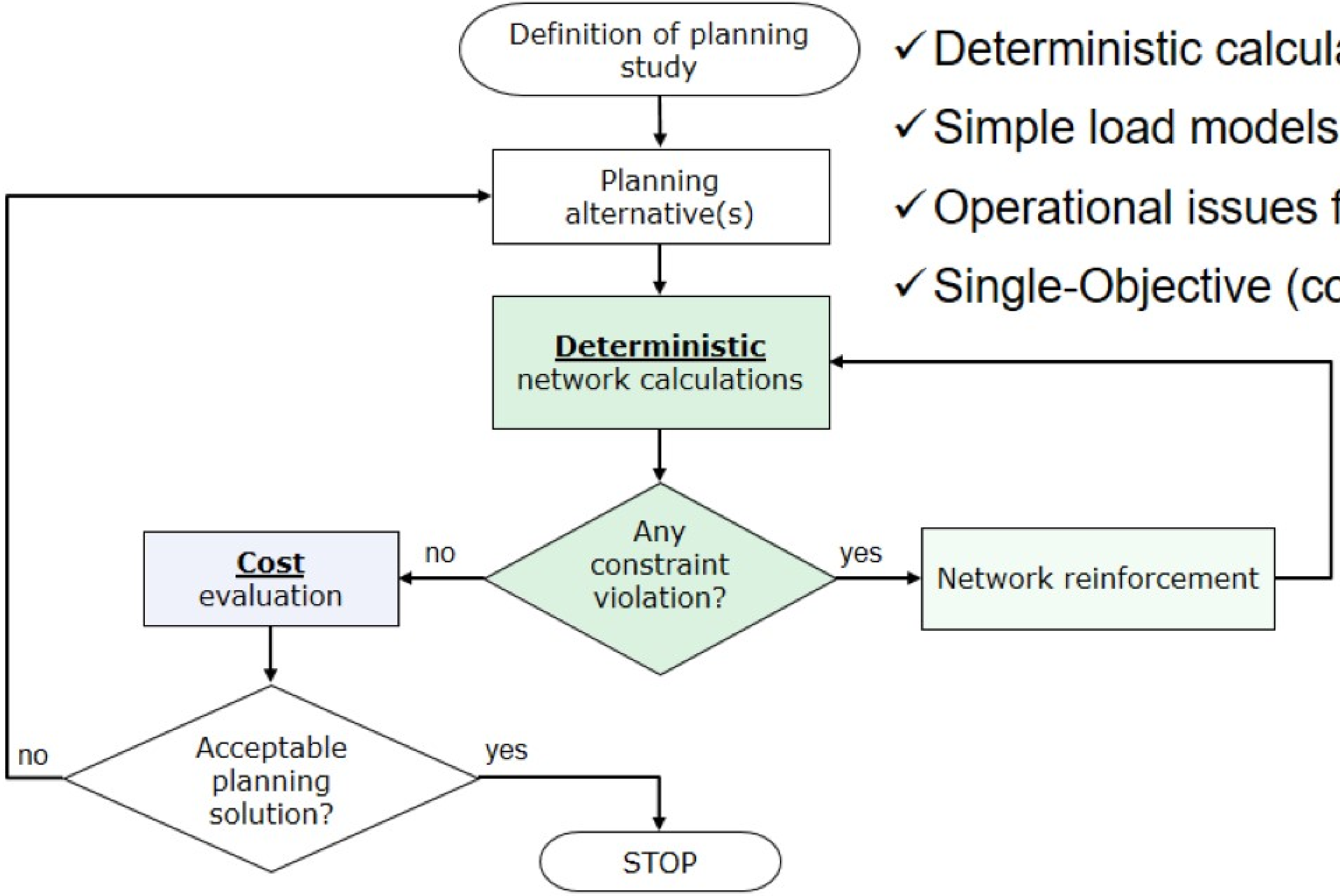
2) lack of ad hoc business cases.

Traditional distribution planning



- ✓ Deterministic calculations
- ✓ Simple load models
- ✓ Operational issues fixed at the planning/design stage
- ✓ Single-Objective (costs)

Traditional distribution planning



- ✓ Deterministic calculations
- ✓ Simple load models
- ✓ Operational issues fixed at the planning/design stage
- ✓ Single-Objective (costs)

- The occurrence of worst scenarios is rare.
- The assumptions for identifying the worst case are subjective
- No quantification of risk

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Need for new planning methodology

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- Electricity produced by Renewable Energy Sources
- Electricity increasingly produced by or closer to consumers/load centers
- Electrification of transport (plug-in EV);
- New markets
- Information and communication technologies
- Advanced metering infrastructure
- Energy Storage (electrical, mechanical, chemical, thermal, etc.)

Increase of distributed energy resources (DER) leads to:

Copperplate

OR

Smart grid applications

Passive control

Active control
(Micro-grid, VPP, DSI, etc.)

New philosophy for network planning

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Traditional network investments

cost-effective **Active Distribution Network** (ADN) solutions

Technical Issue	BAU Distribution Network	Active Distribution Network
Voltage rise/drop	Limits/bands for demand and generation connection/operation Generation tripping Capacitor banks	Coordinated volt-var control Static var compensators Coordinated dispatch of DER On-line reconfiguration
Hosting Capacity	Network reinforcement (e.g. lines, transformers)	Coordinated dispatch of DER On-line reconfiguration
Reactive Power Support	Dependency on transmission network Capacitor banks Limits/bands for demand and generation connection/operation	Coordinated volt-var control Static var compensators Coordinated reactive power dispatch of DER
Protection	Adjustment of protection settings New protection elements Limits for generation connection Fault ride through specifications for generation	On-line reconfiguration Dynamic protection settings

New philosophy for network planning

LESS traditional network investments

MORE cost-effective **Active Distribution Network** (ADN) solutions

Technical Issue	BAU Distribution Network	Active Distribution Network
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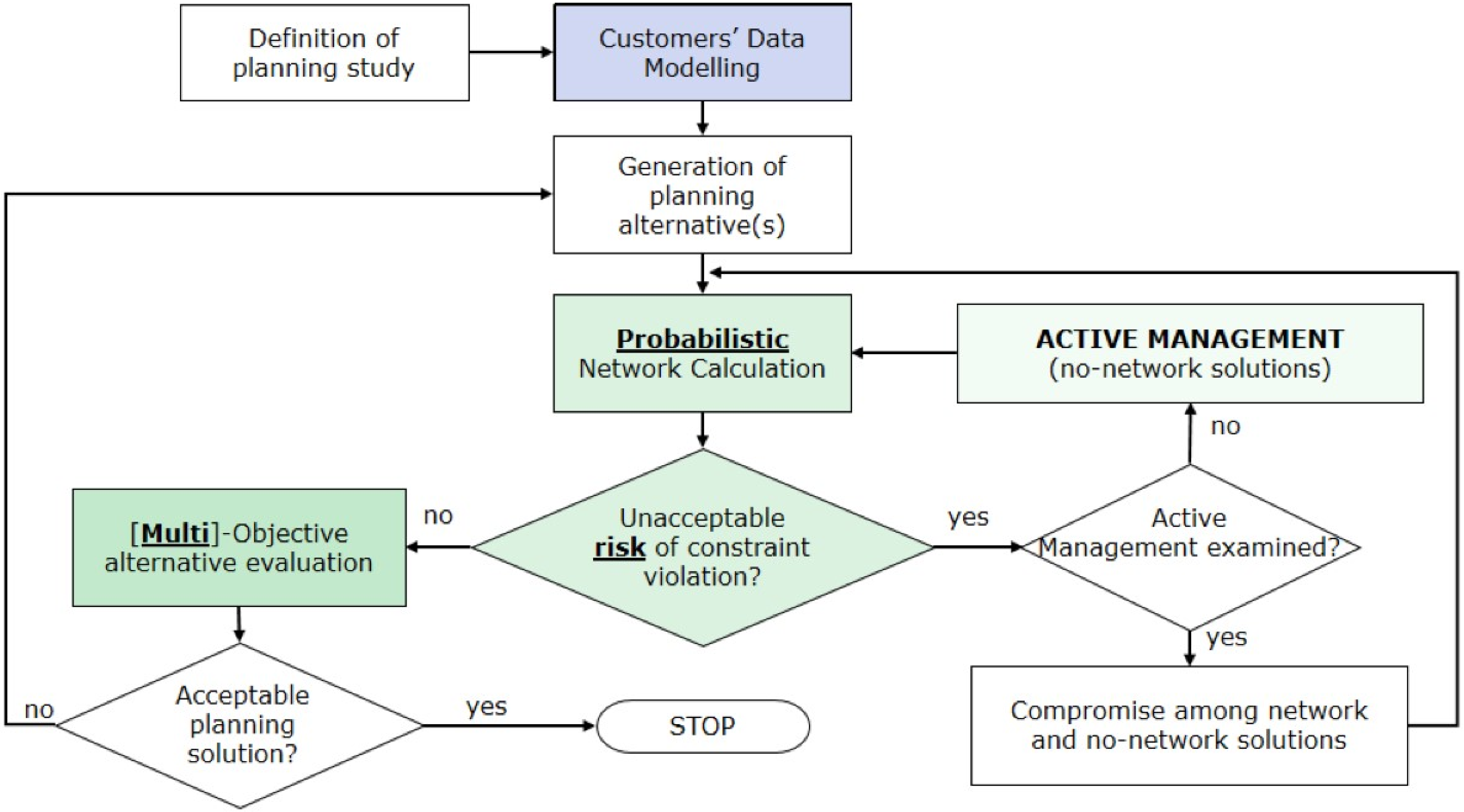
New distribution planning

- Enhanced load and generation representation
  - Load/generation profiles
  - Time series
- Detailed description of Smart Grid
  - Distribution State Estimation Measurement System
  - Information and Communication Technology
- Multi-objective, probabilistic, risk-oriented planning

- Operation actions are planning options
  - Volt/VAR regulation
  - Power congestion management
  - Generation curtailment
  - Demand response and flexibility
  - Storage and EV
  - ….

New distribution planning



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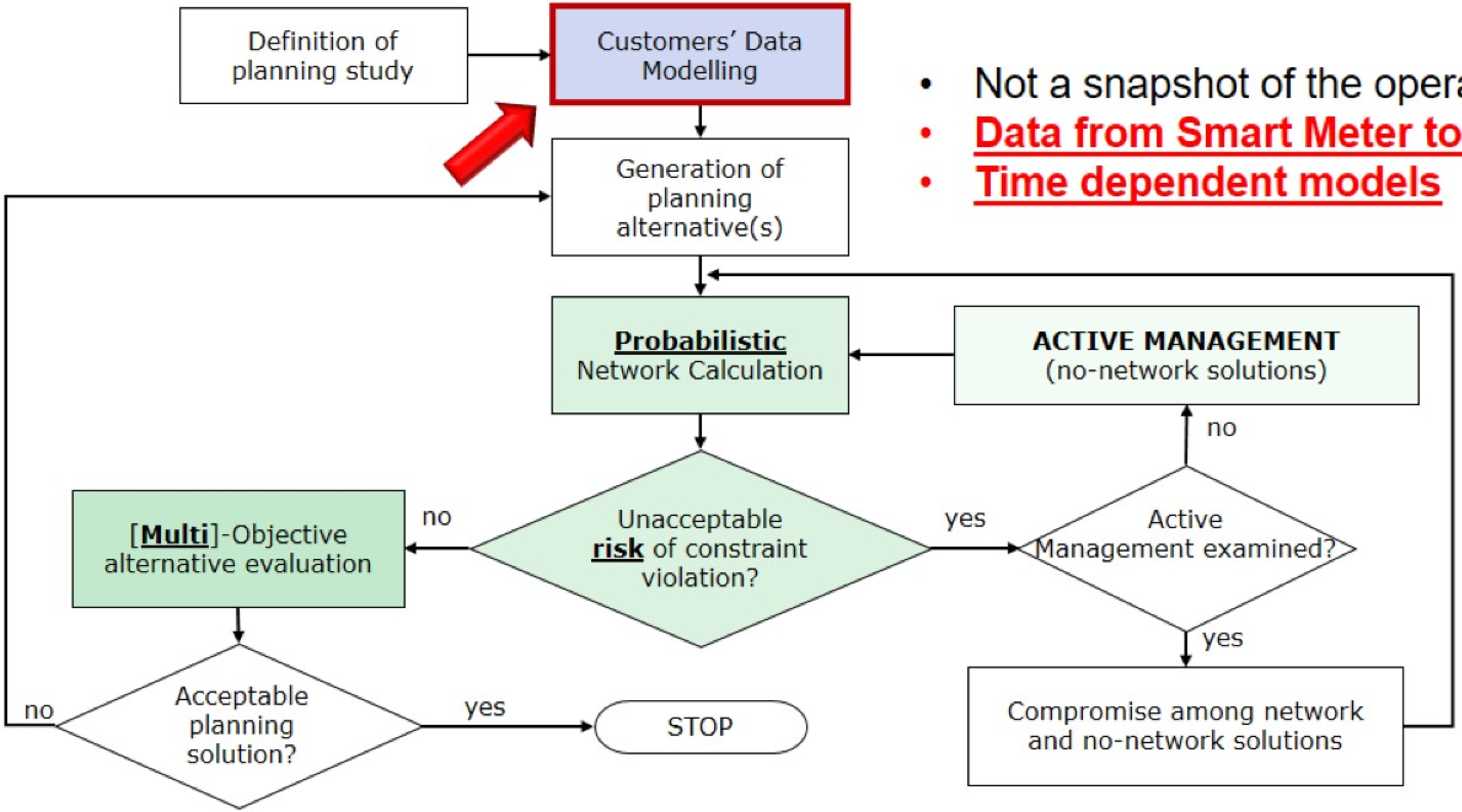
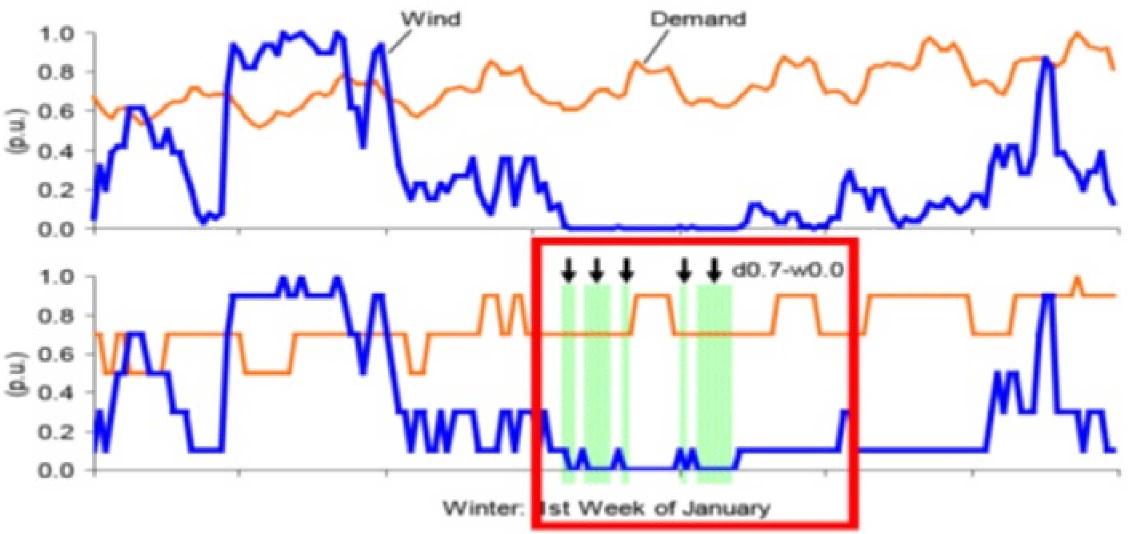
New distribution planning

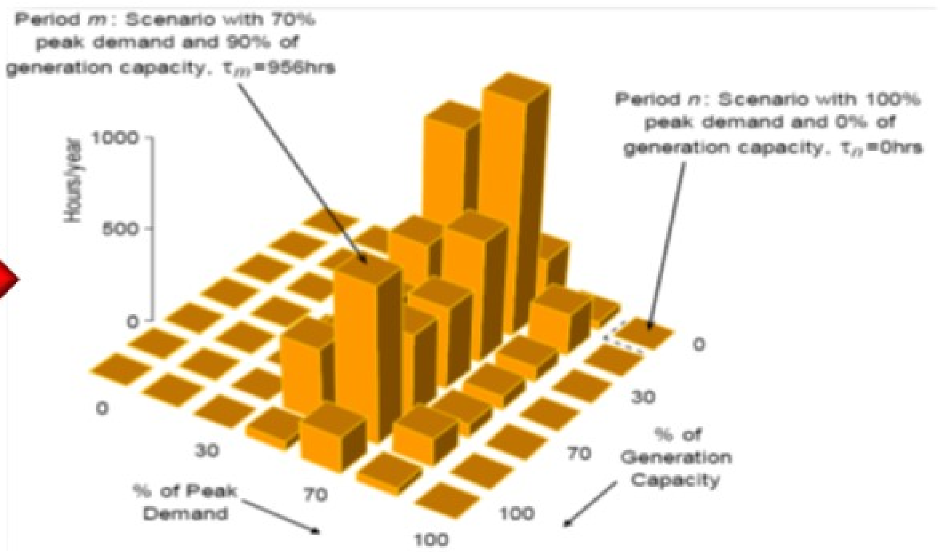


- Not a snapshot of the operating conditions
- **Data from Smart Meter to be used**
- **Time dependent models**

Novel planning – input data

1 Classification of all states in a year, grouped into some typical conditions (**clusters**)





Novel planning – input data

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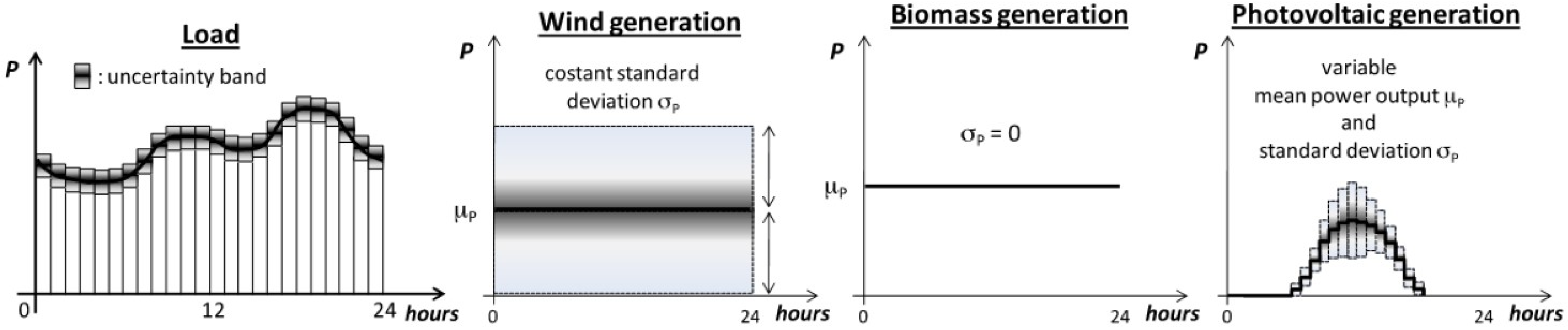
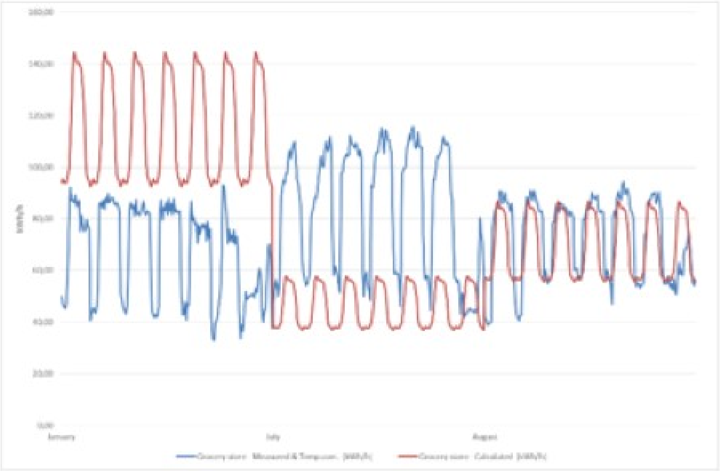
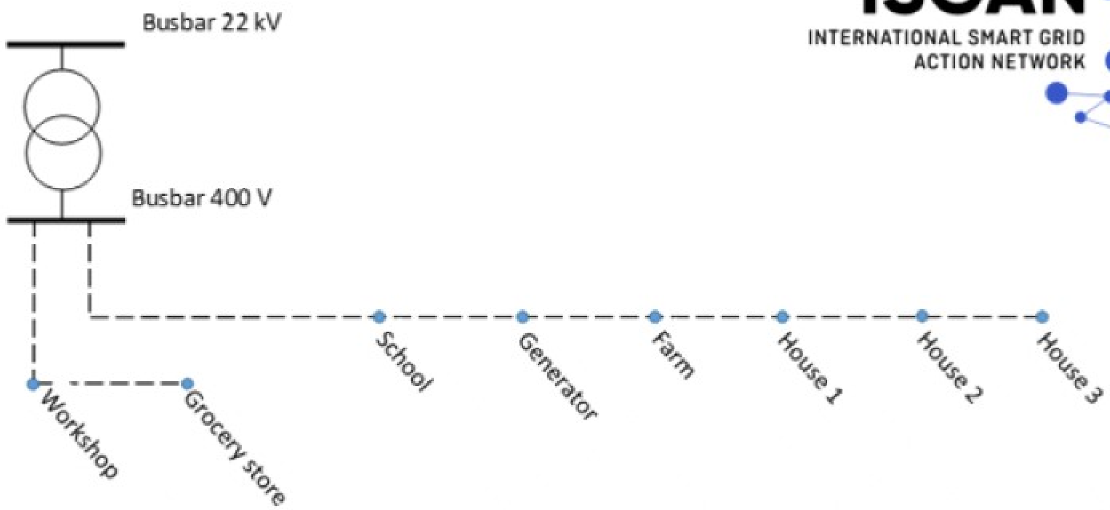
1. Classification of all states in a year, grouped into some typical conditions (**clusters**)

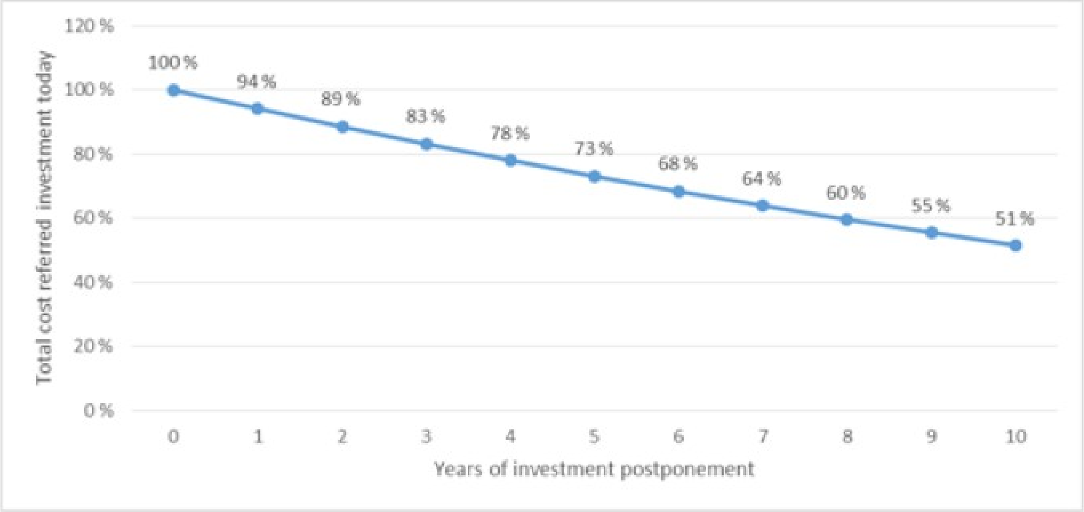
2. Identification of distinctive **daily patterns**, segmented in elementary intervals



The role of Smart meters







- Smart meters can provide better data
- Smart meters costs and ICT should be included in planning depending on the regulatory model

- E. Toenne, Planning of the Future Smart and Active Distribution Grids: With emphasis on probabilistic load and generation modelling based on data from smart meters
- PhD Thesis 2017, NTNU, Trondheim, Norway

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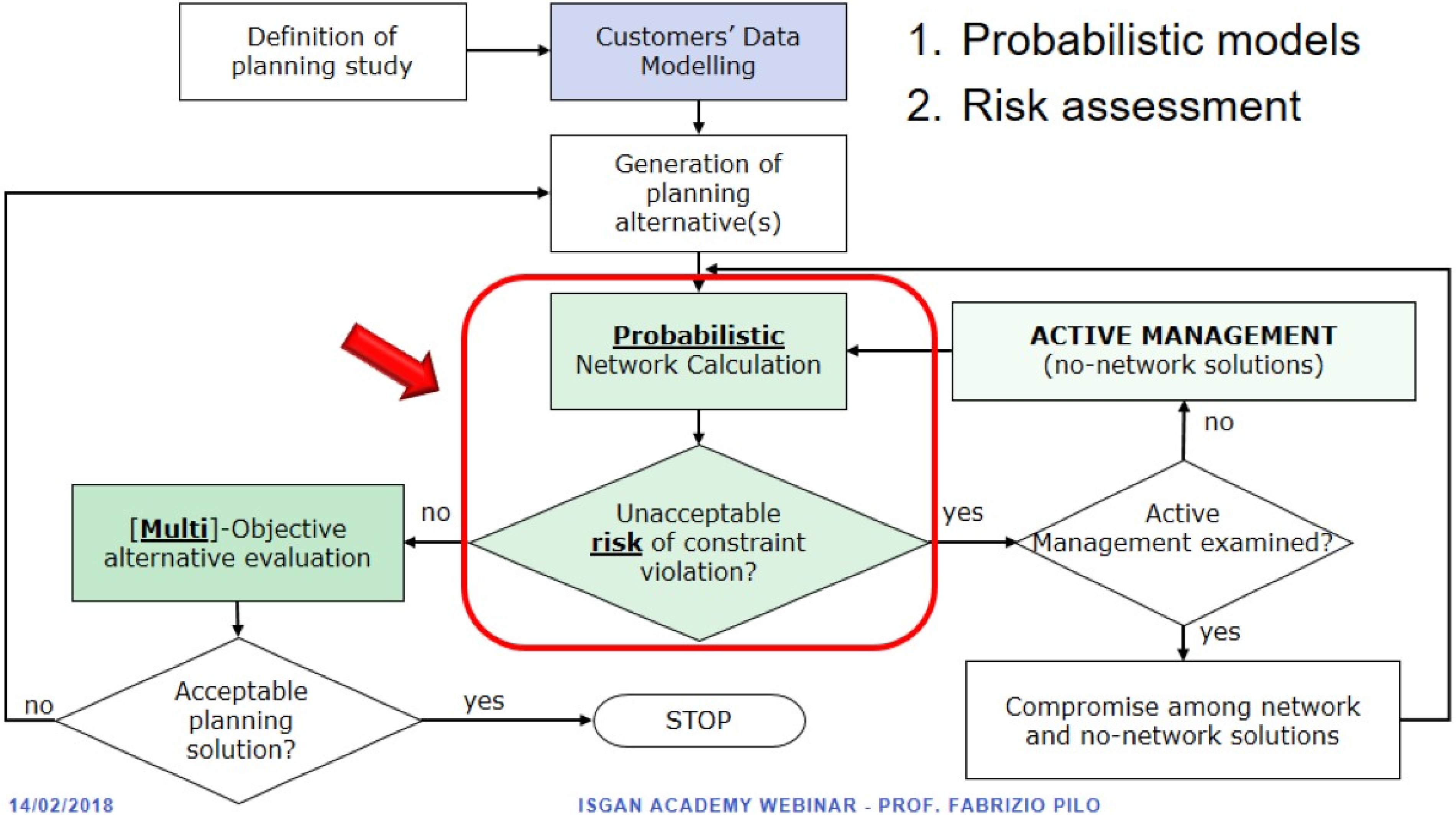
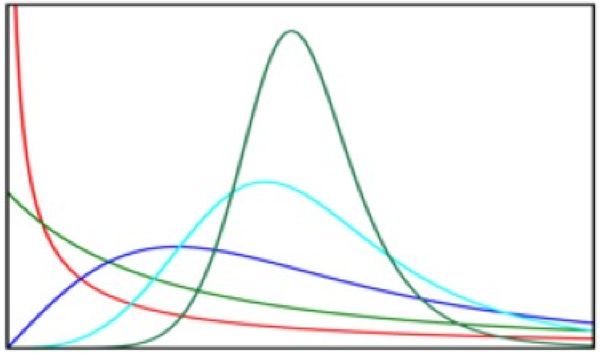
Novel planning – go probabilistic



1. Probabilistic models
2. Risk assessment

Probabilistic calculation

Main issue: data availability for probabilistic models definition.



If the probabilistic data are

available → **Model**: adoption of suitable probability density functions

unknown → **Model**: experience and knowledge

Network Calculation

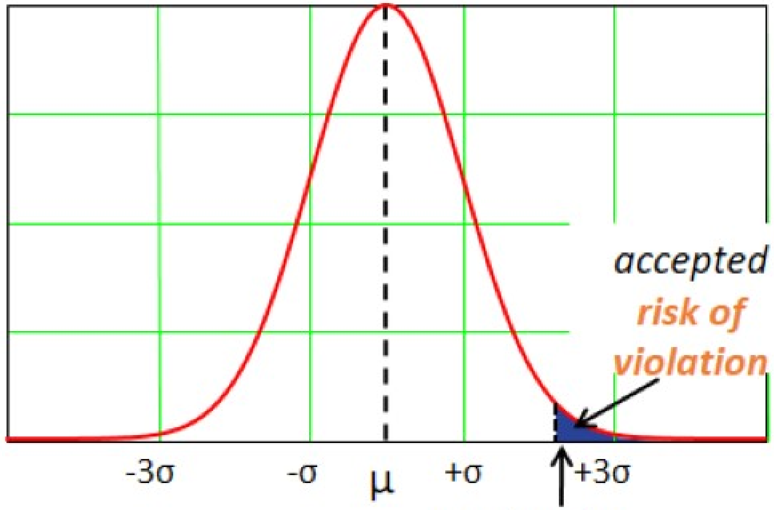
Probabilistic Load Flow algorithms

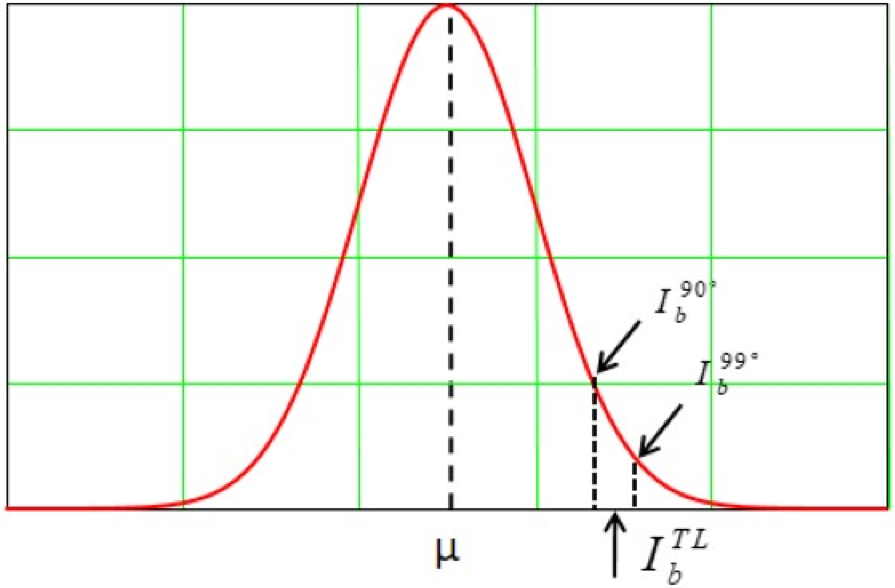
Monte Carlo simulations

Fuzzy Set theory

Probabilistic calculation

The results of the probabilistic network calculation are the **stochastic representation** of <u>nodal voltages</u> and <u>branch currents</u>





$I_b^{TL} = 140$ [A]

I_b with Gaussian distribution ($\mu_b = 120$ [A]; $\sigma_b = 10$ [A])

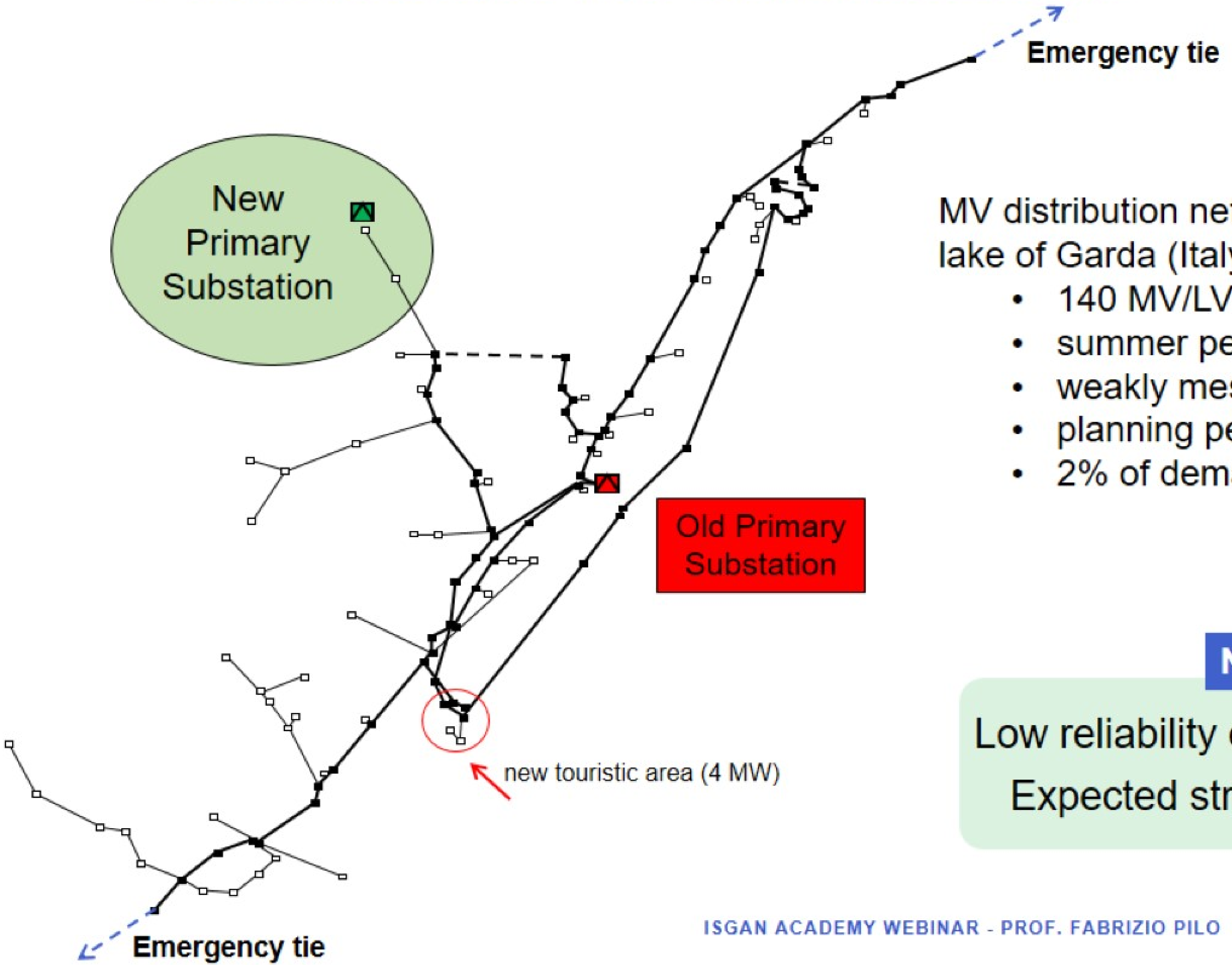
Assuming to accept **10%** of risk:

$$I_b^{90°} = 120 + 1.6 \cdot (10) = 136 \text{ [A]} < I_b^{TL}$$

Assuming, instead, a **1%** of risk:

$$I_b^{99°} = 120 + 2.3 \cdot (10) = 143 \text{ [A]} > I_b^{TL}$$

Probabilistic vs. Deterministic



MV distribution network in the north shore of the lake of Garda (Italy).

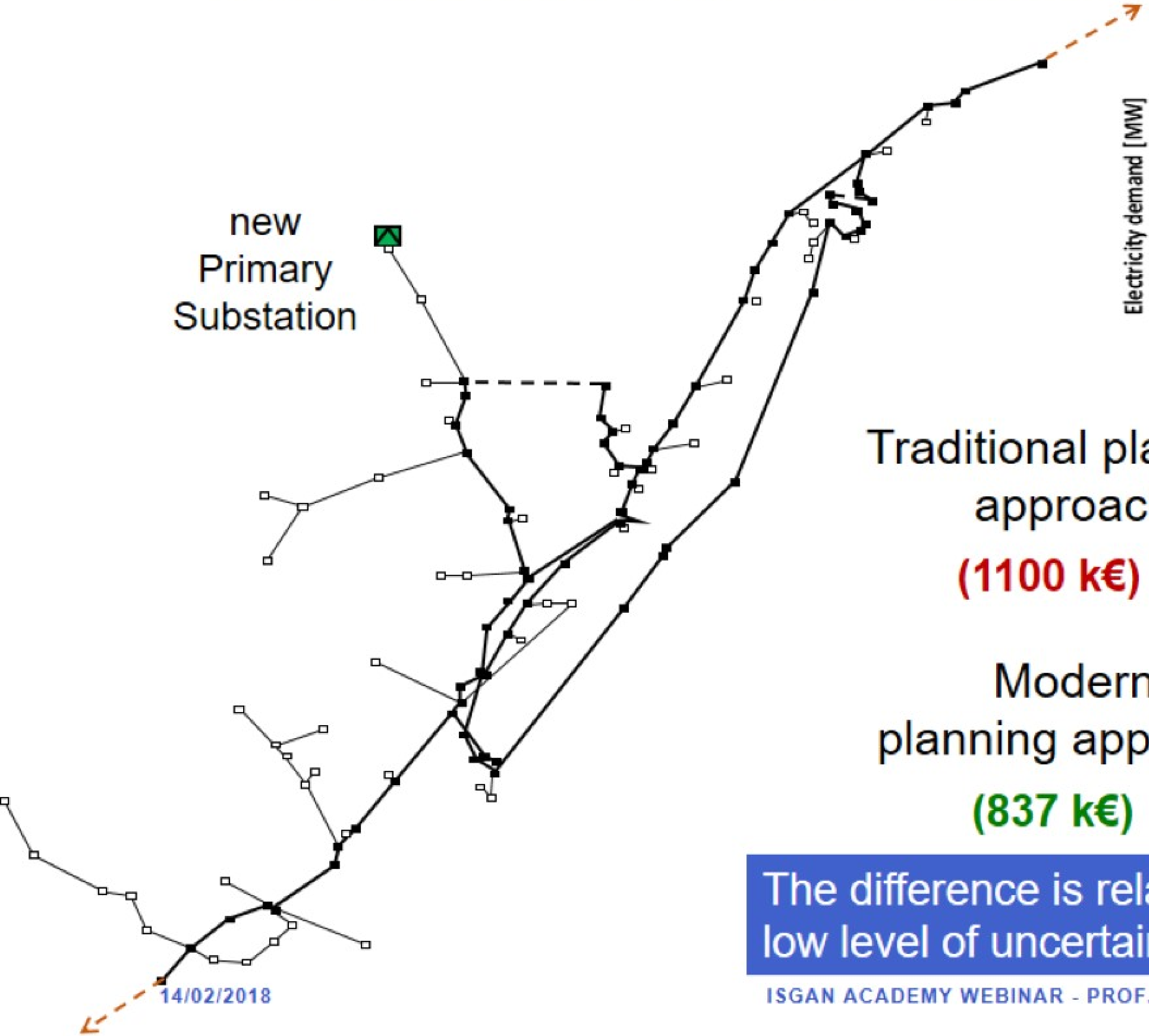
- 140 MV/LV secondary substations
- summer peak demand of about 8 MW
- weakly meshed but radially operated
- planning period 5 years
- 2% of demand growth of per year;

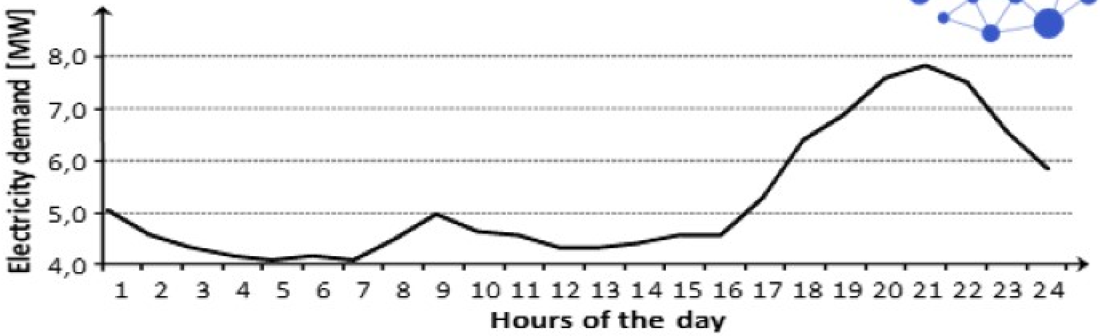
Network issues

Low reliability of the old primary substation

Expected strong increasing of demand

Probabilistic vs. Deterministic



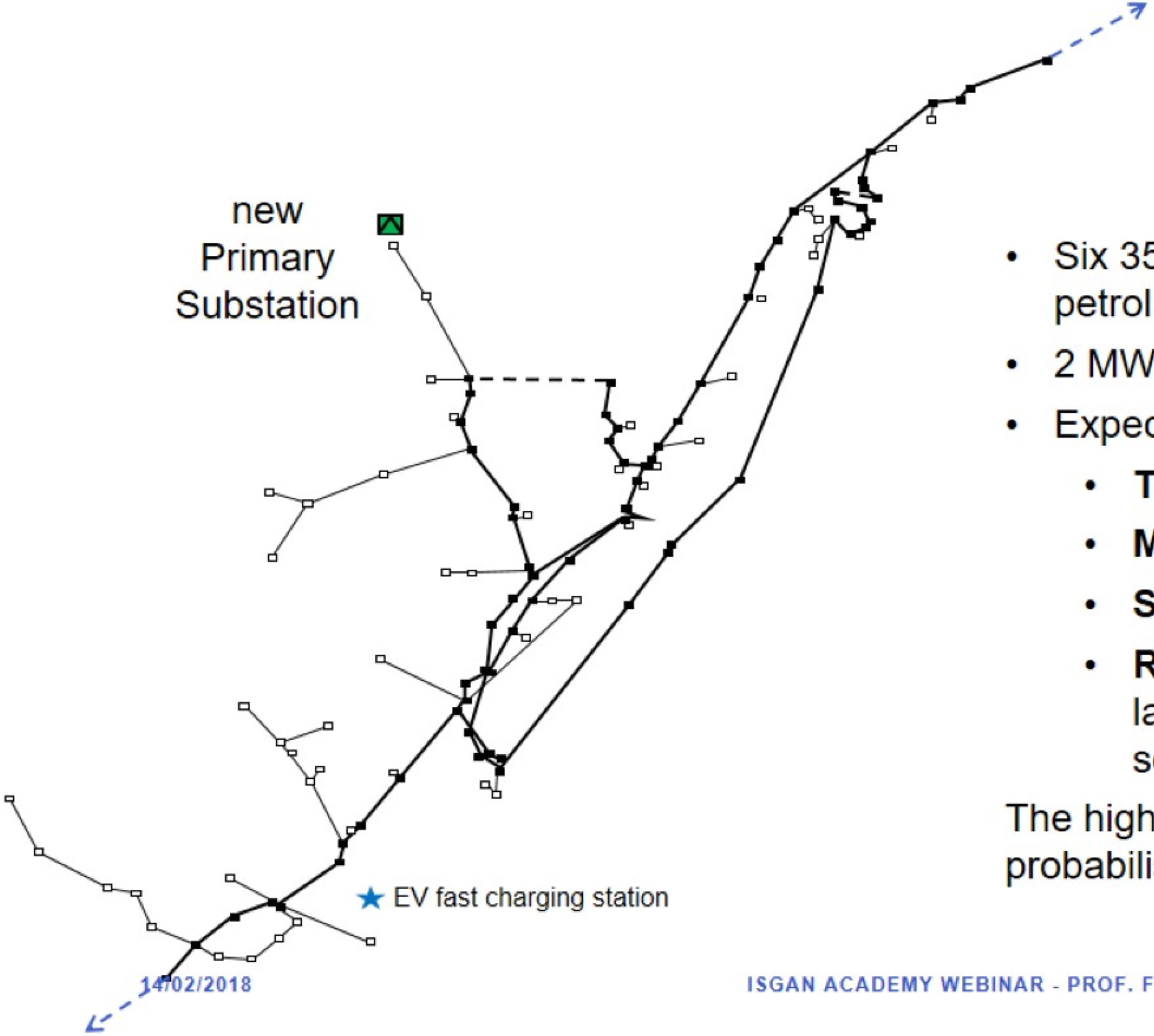


Traditional planning approach **(1100 k€)**
- ✓ Deterministic network calculation;
- ✓ Fit & Forget paradigm

Modern planning approach **(837 k€)**
- ✓ Probabilistic network calculation;
- ✓ Acceptable risk of 5%

The difference is relatively small (24% of CAPEX cut), due to the low level of uncertainties (related only to conventional loads).

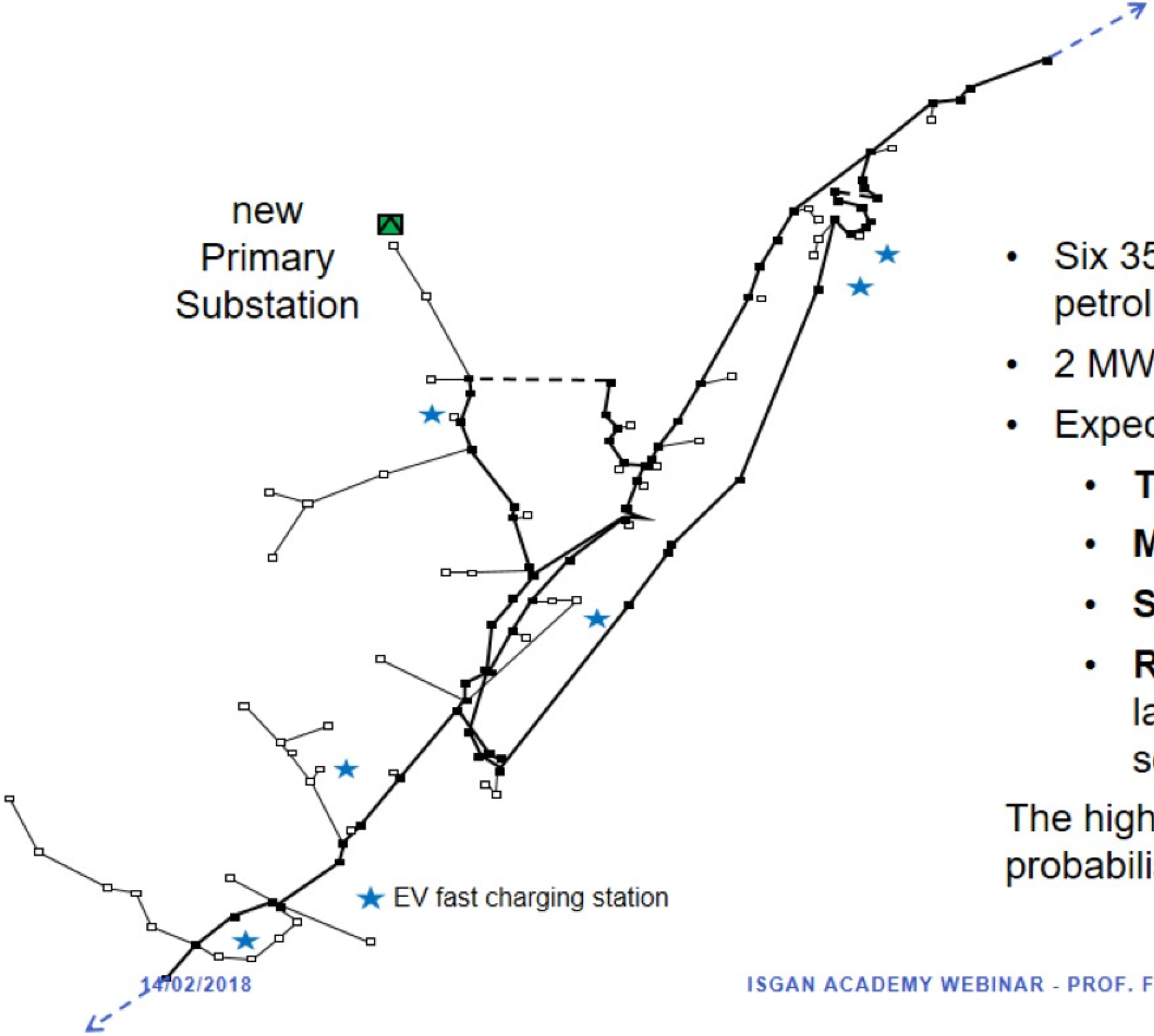
Probabilistic vs. deterministic



- Six 350 kW fast charging stations in existing petrol stations
- 2 MW of additional peak demand
- Expected CAPEX and OPEX increasing
  - **Traditional planning:** 2.128 k€
  - **Modern planning:** 1.017 k€
  - **Significant savings**
  - **Risk management** (voltage drop slightly larger than 10% in few nodes for less than 5 seconds per year during faults)

The higher the uncertainties the higher the worth of probabilistic approach

Probabilistic vs. deterministic



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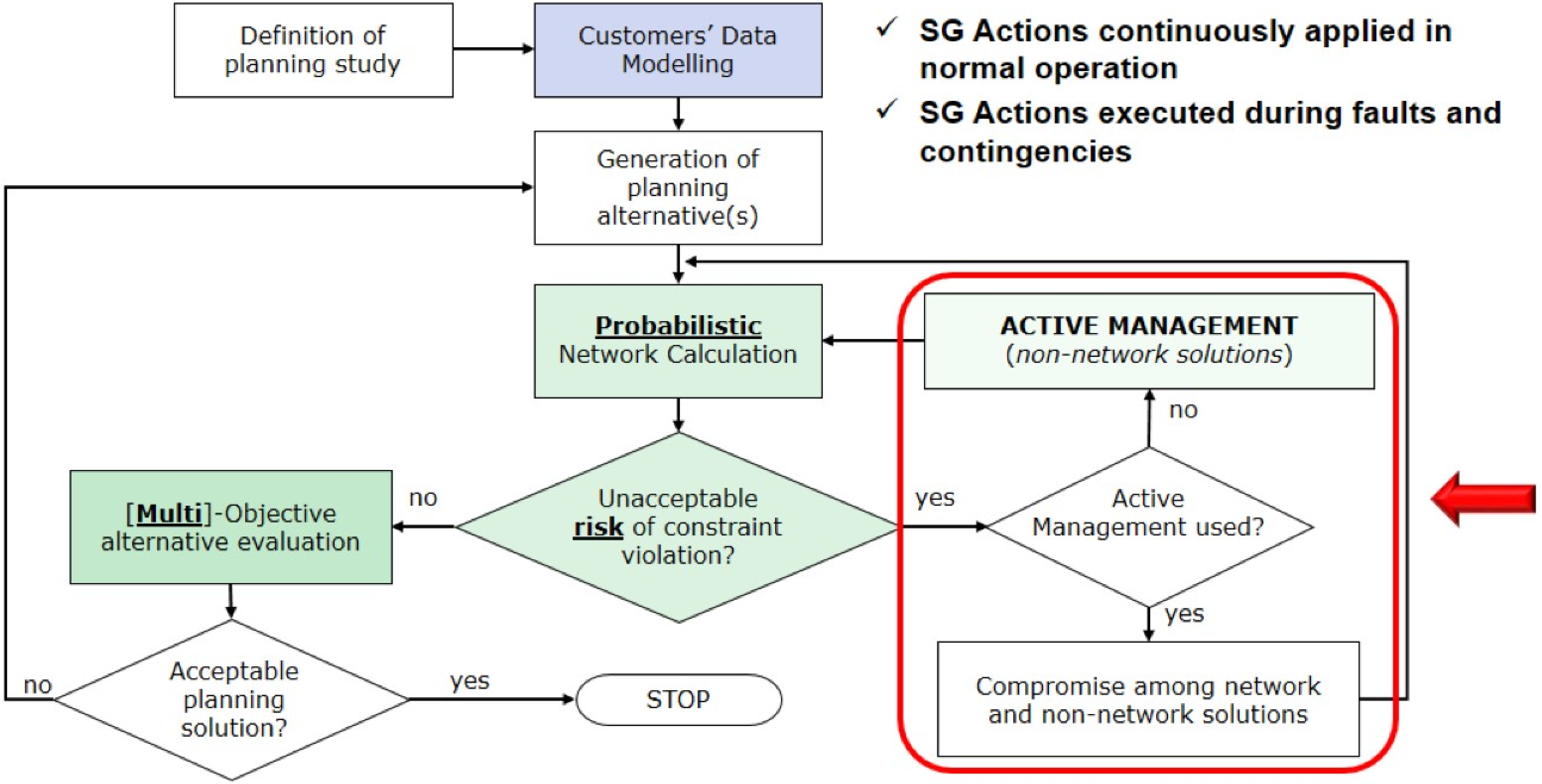
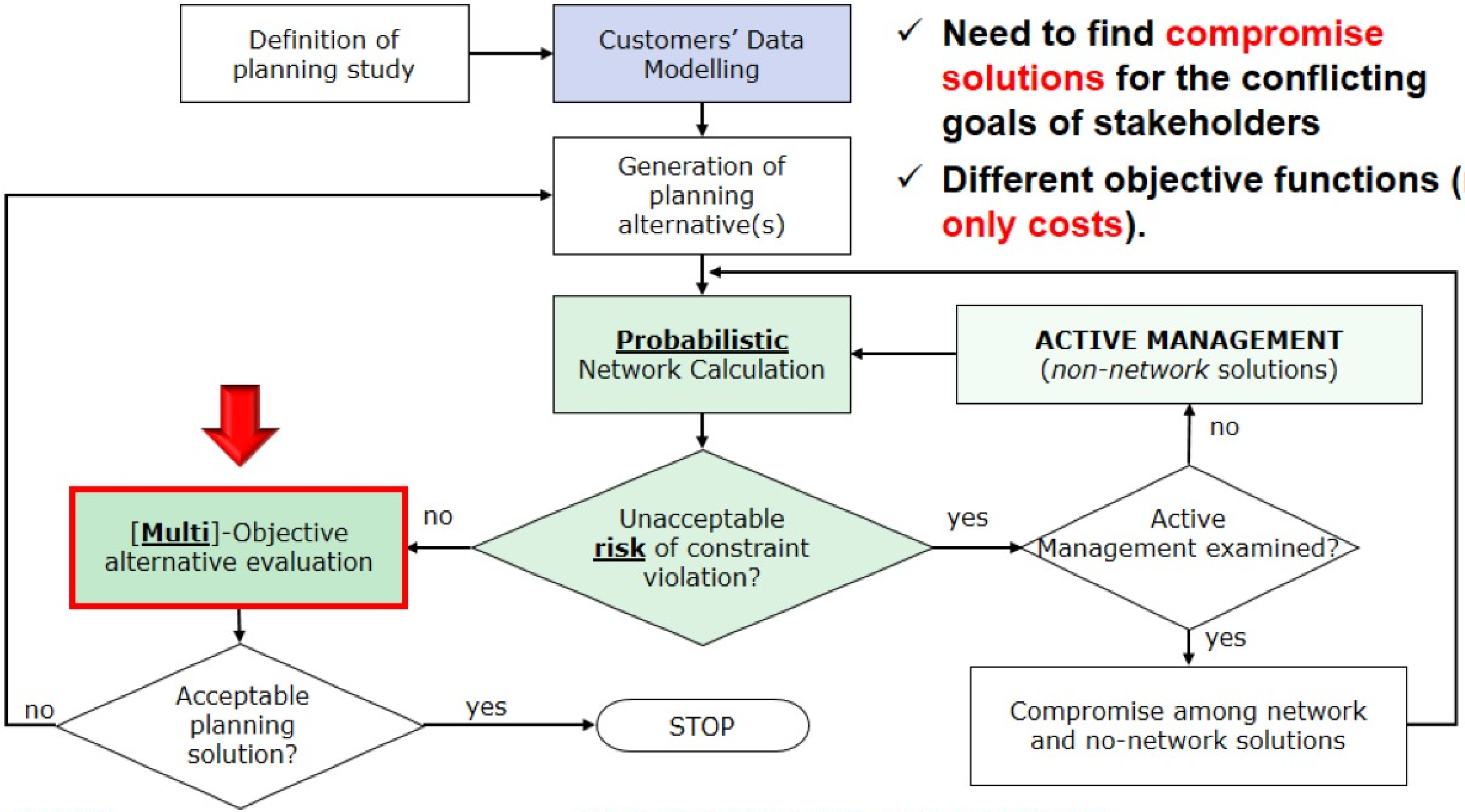
Operation and planning

- ✓ **SG Actions continuously applied in normal operation**
- ✓ **SG Actions executed during faults and contingencies**

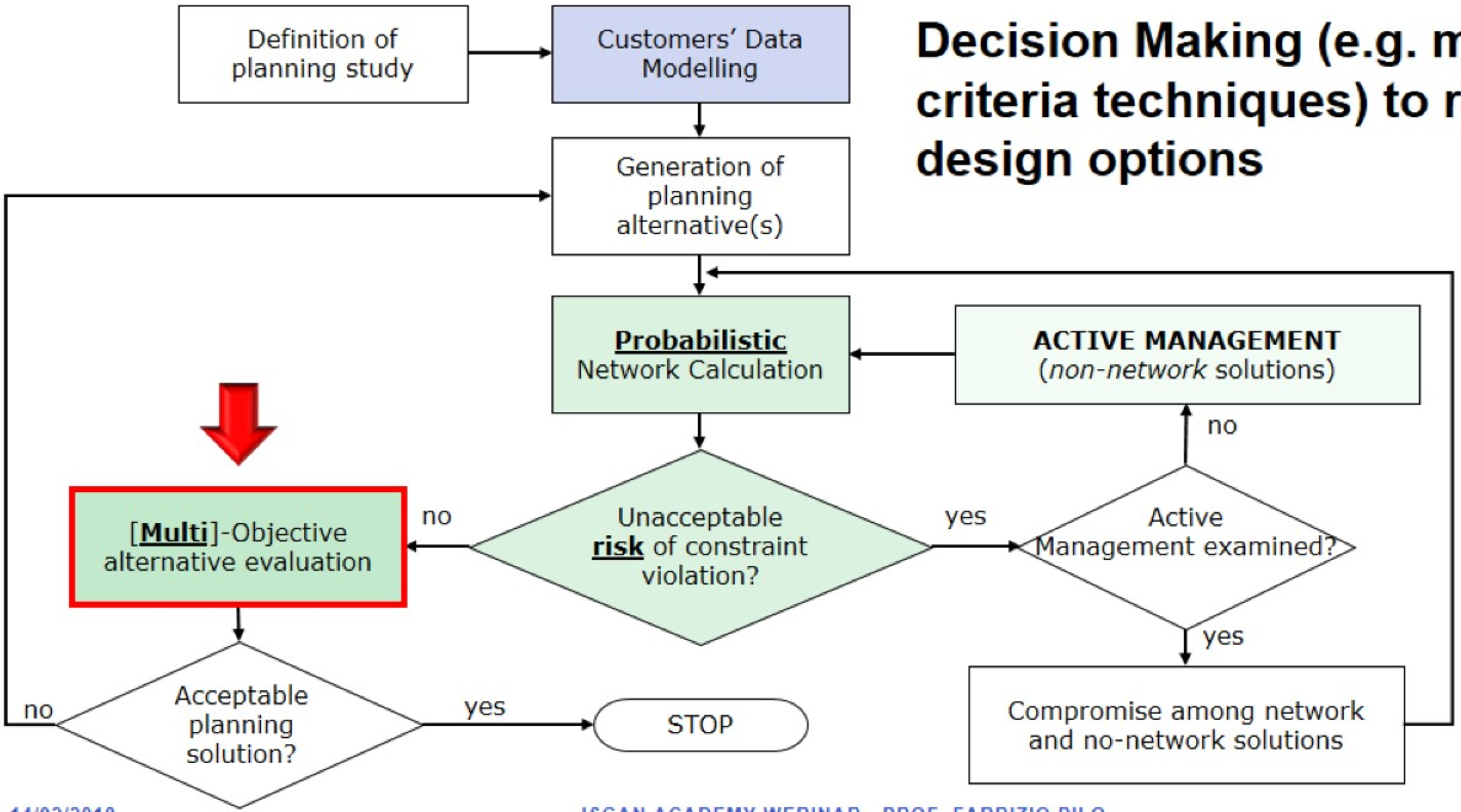


Multiobjective programming



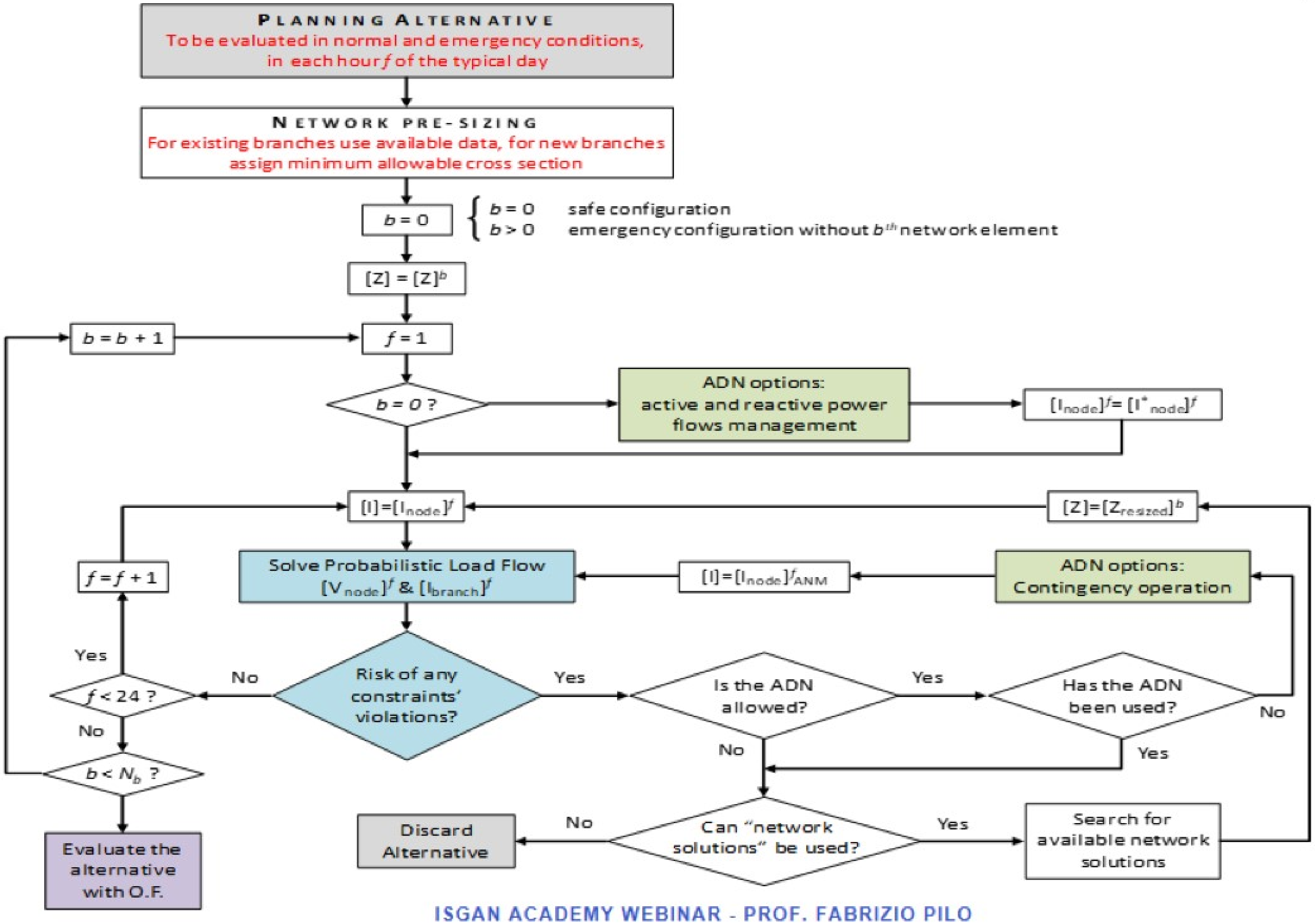
- ✓ **Need to find compromise solutions for the conflicting goals of stakeholders**
- ✓ **Different objective functions (not only costs).**

Multi-objective and decision making



Decision Making (e.g. multi criteria techniques) to rank design options

Flowchart for novel planning process



Different Planning Approaches

1st **Deterministic - Fit and Forget (F&F)**

Different Planning Approaches

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1st Deterministic - Fit and Forget (F&F)

2nd Probabilistic approach with 5% of allowable risk of constraint violation and traditional passive network (Prob_5%)

Different Planning Approaches

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1st Deterministic - Fit and Forget (F&F)

2nd Probabilistic approach with 5% of allowable risk of constraint violation and traditional passive network (Prob_5%)

3rd Probabilistic approach with 20% of allowable risk of constraint violation and traditional passive network (Prob_20%)

Different Planning Approaches

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1st Deterministic - Fit and Forget (F&F)

2nd Probabilistic approach with 5% of allowable risk of constraint violation and traditional passive network (Prob_5%)

3rd Probabilistic approach with 20% of allowable risk of constraint violation and traditional passive network (Prob_20%)

4th ADN with control of active and reactive DG power, and 20% allowable risk of constraint violation (AND_PQ)

Different Planning Approaches

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1st — Deterministic - Fit and Forget (F&F)

2nd — Probabilistic approach with 5% of allowable risk of constraint violation and traditional passive network (Prob_5%)

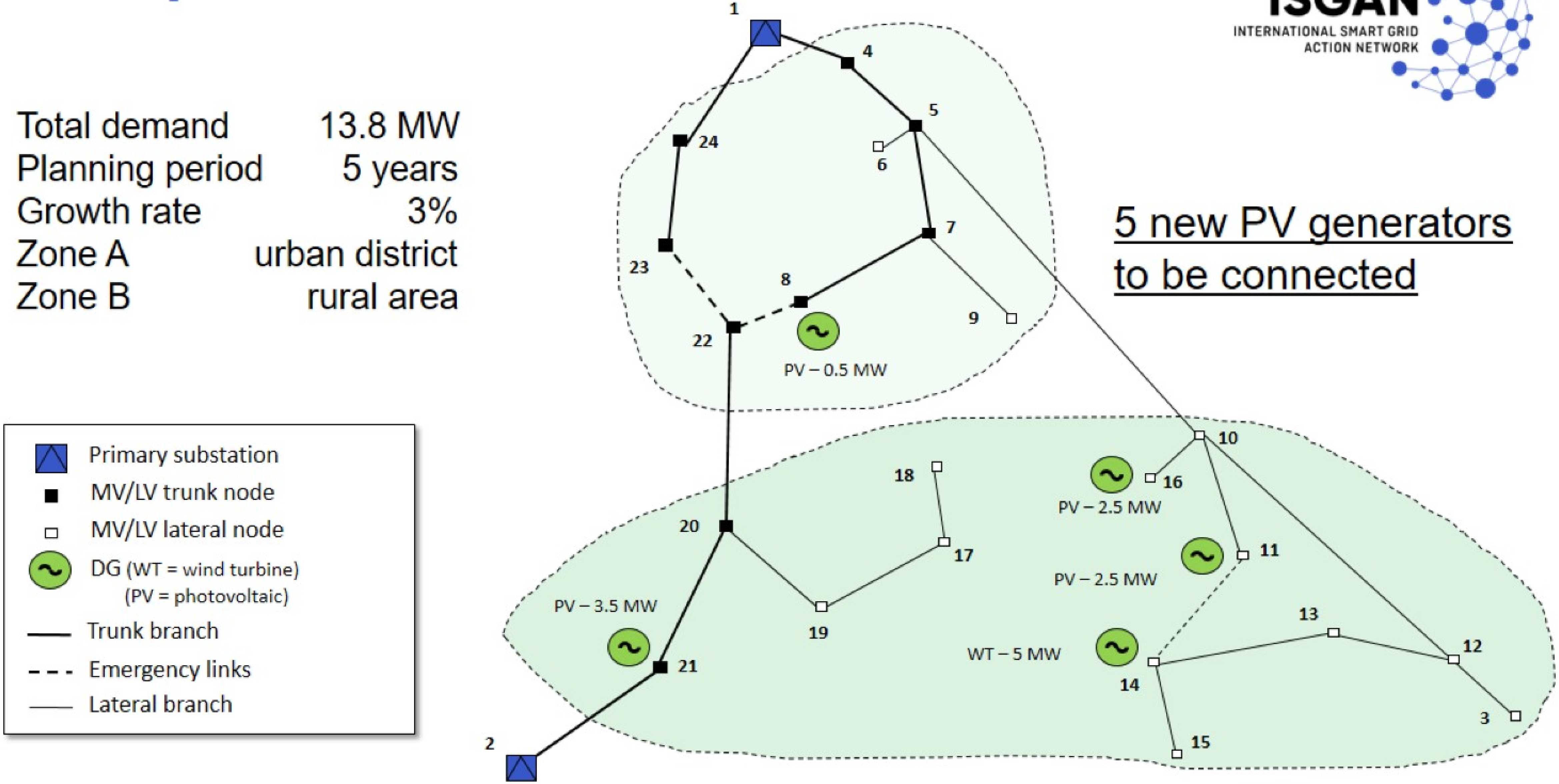
3rd — Probabilistic approach with 20% of allowable risk of constraint violation and traditional passive network (Prob_20%)

4th — ADN with control of active and reactive DG power, and 20% allowable risk of constraint violation (AND_PQ)

5th — ADN with installation of storage (3 MW – 8 h) in node 10, and 20% of allowable risk of constraint violation (DES)

Example – small MV network

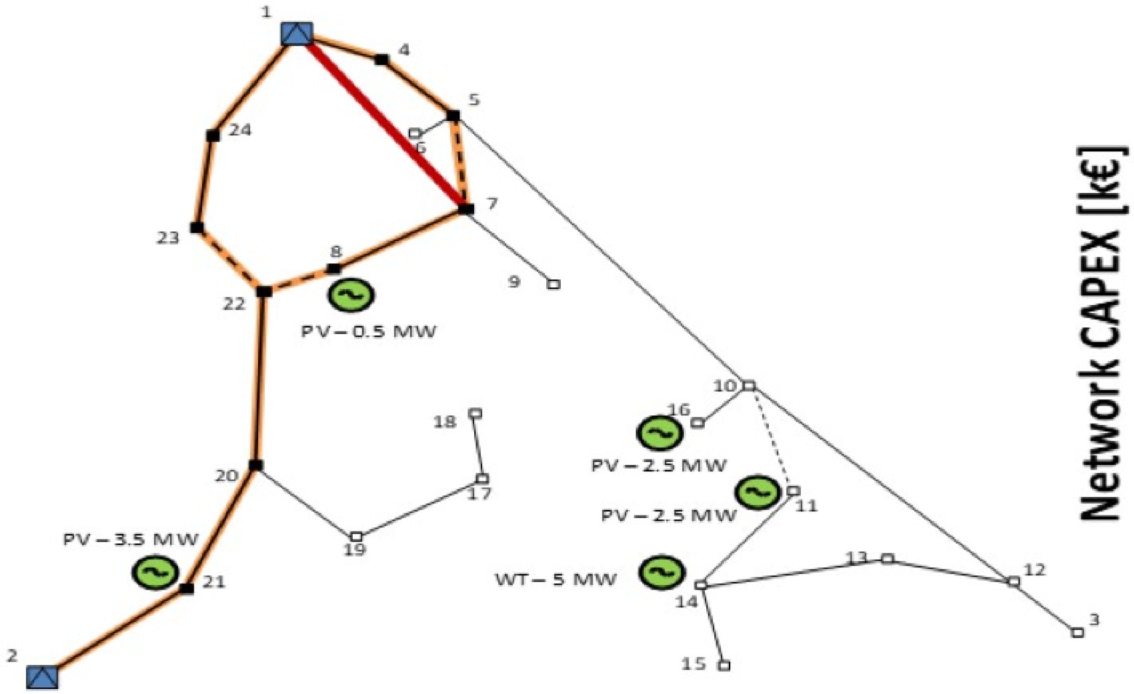
Total demand	13.8 MW
Planning period	5 years
Growth rate	3%
Zone A	urban district
Zone B	rural area

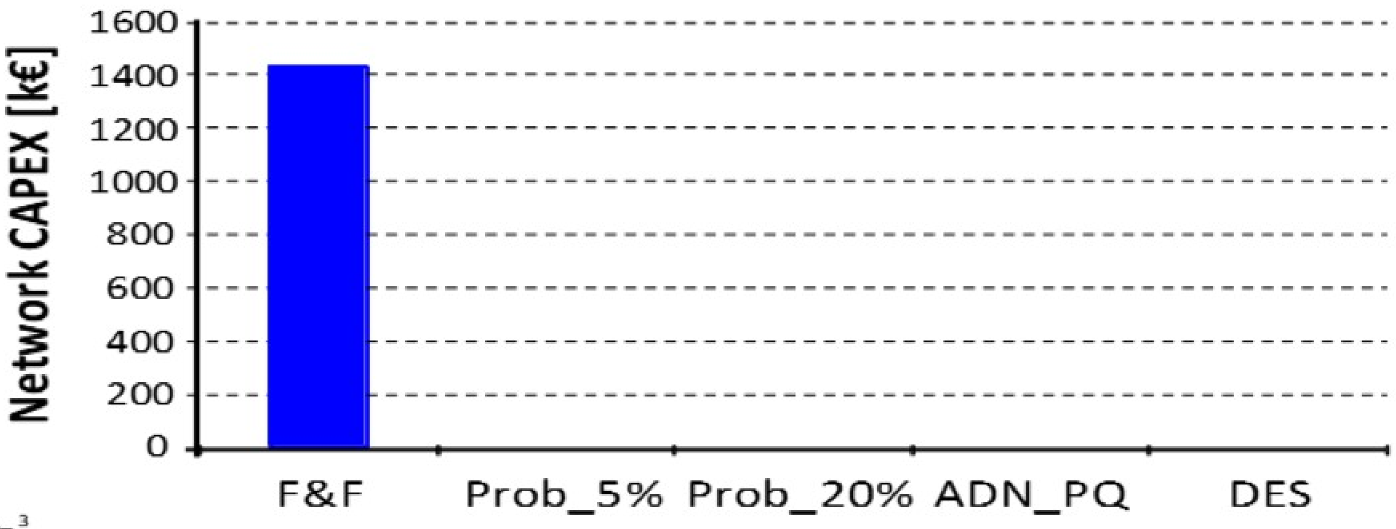


<u>5 new PV generators to be connected</u>

Results – Deterministic (F&F)

Due to overload expectation in the urban district → building of a new trunk line; refurbishment of all existing trunk feeders; no upgrades of laterals





Results - Probabilistic approach

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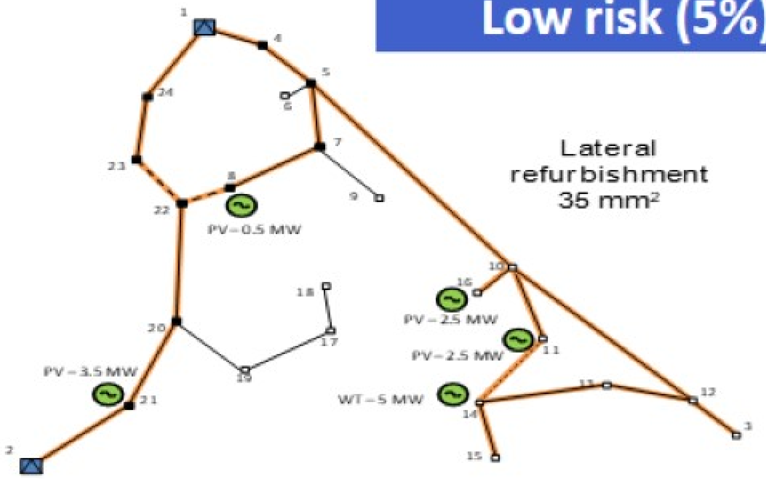
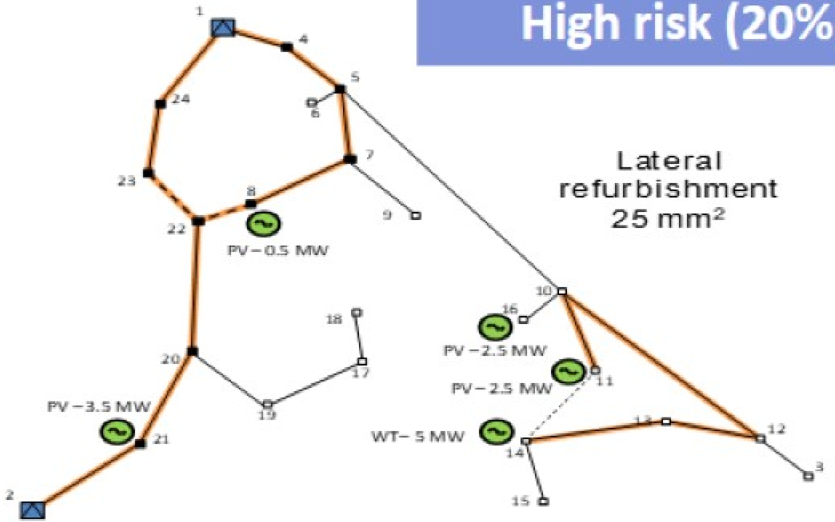
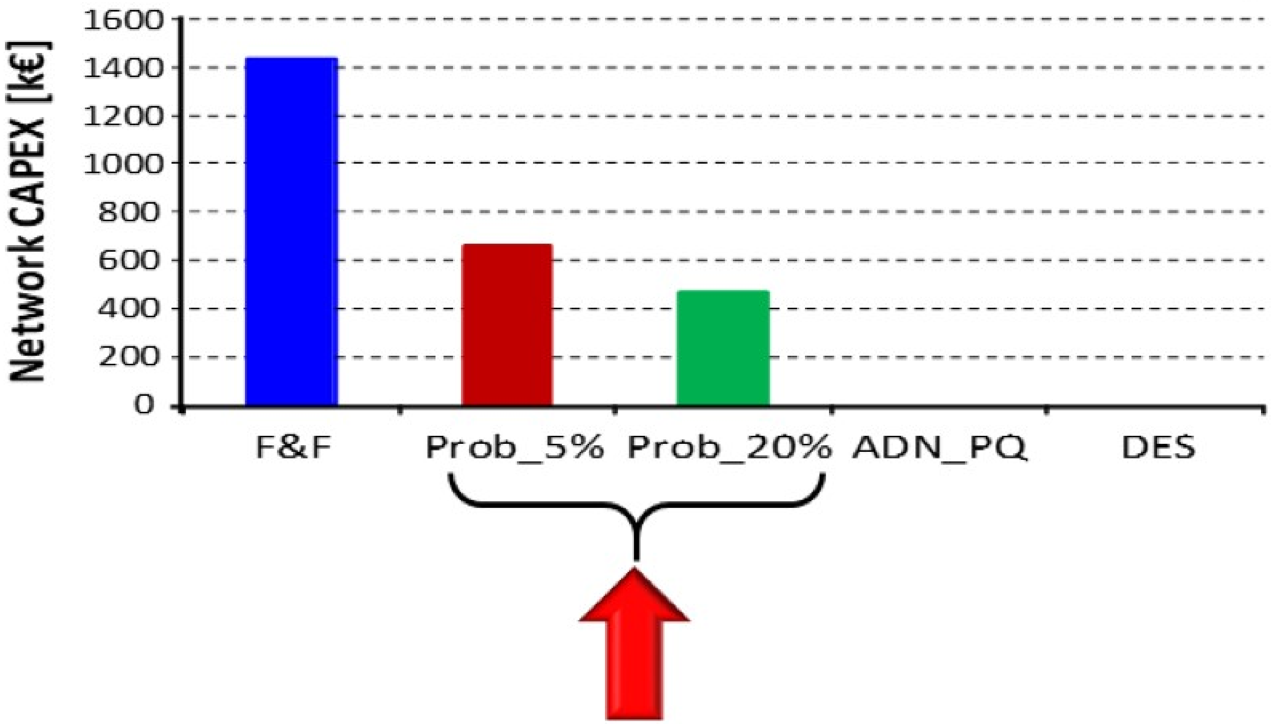
Low risk (5%)



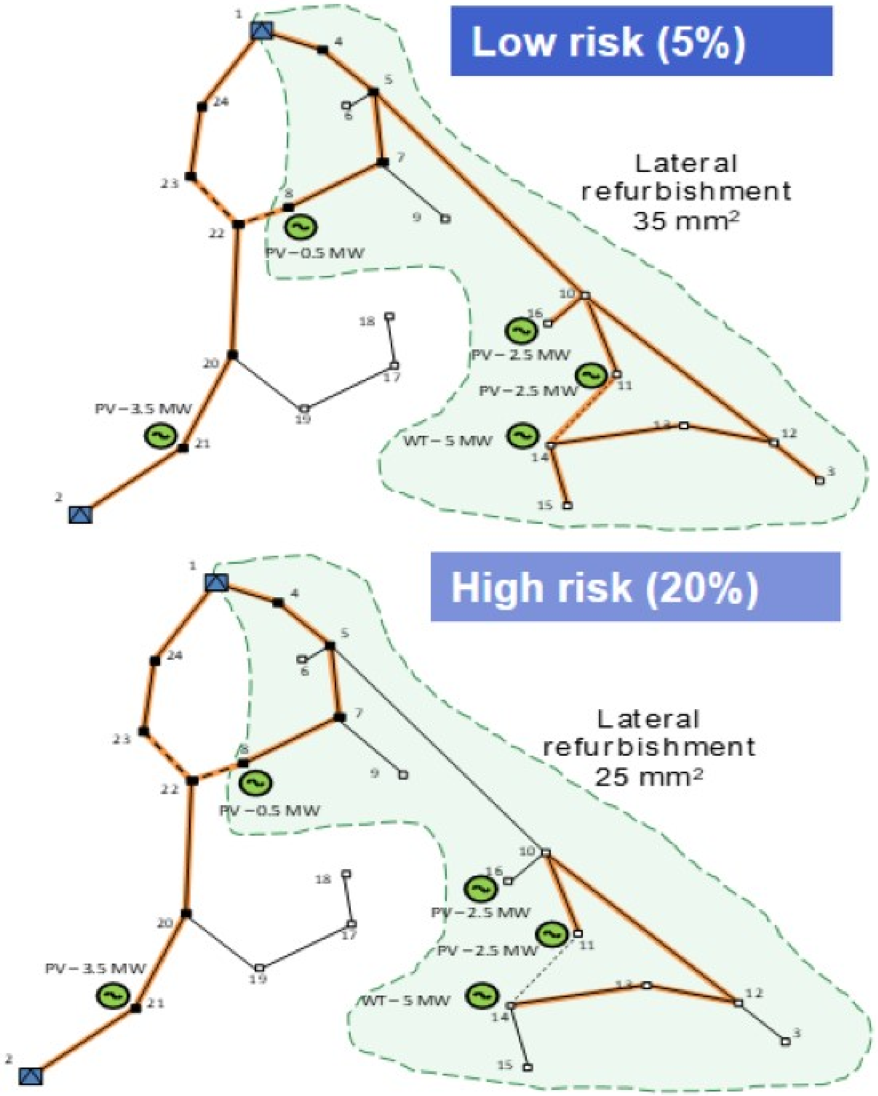
High risk (20%)

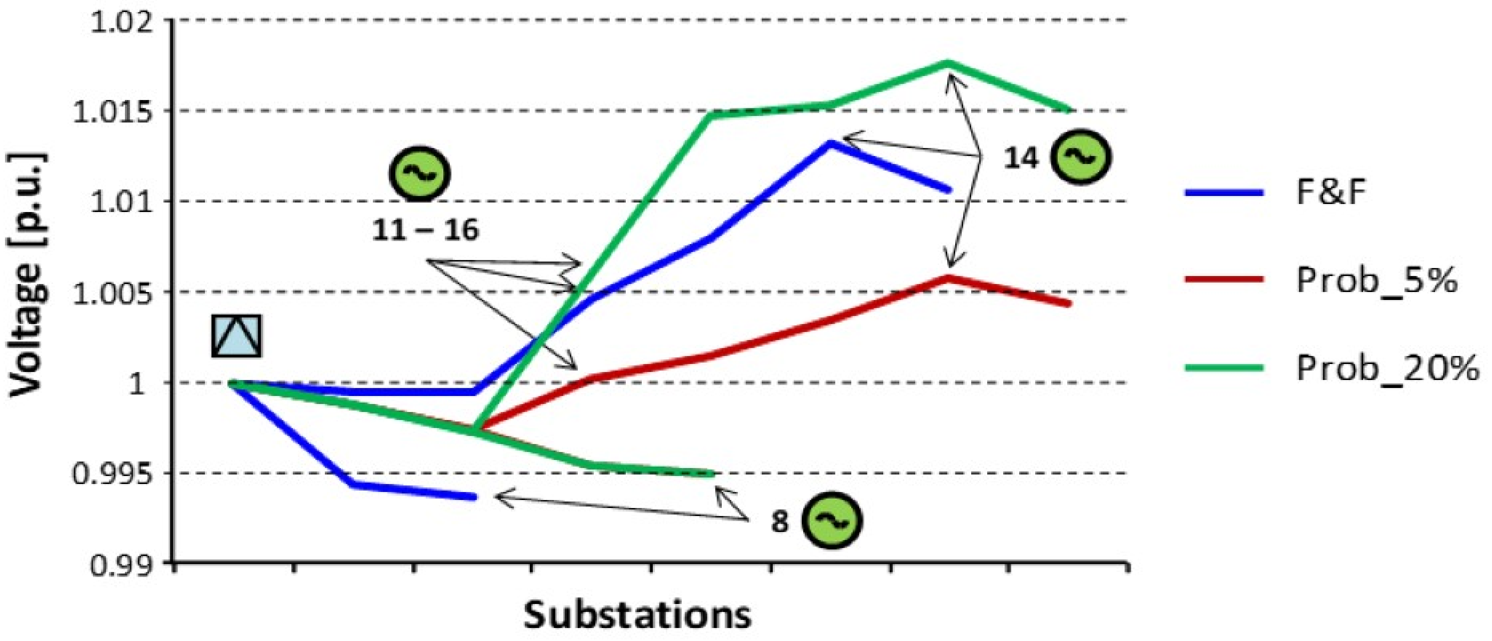




With 5% risk CAPEX is more than halved with higher risks it is reduced almost to one third of the F&F cost

Results – Probabilistic approach





Quality of voltage improved!

Results – Active Distribution Network

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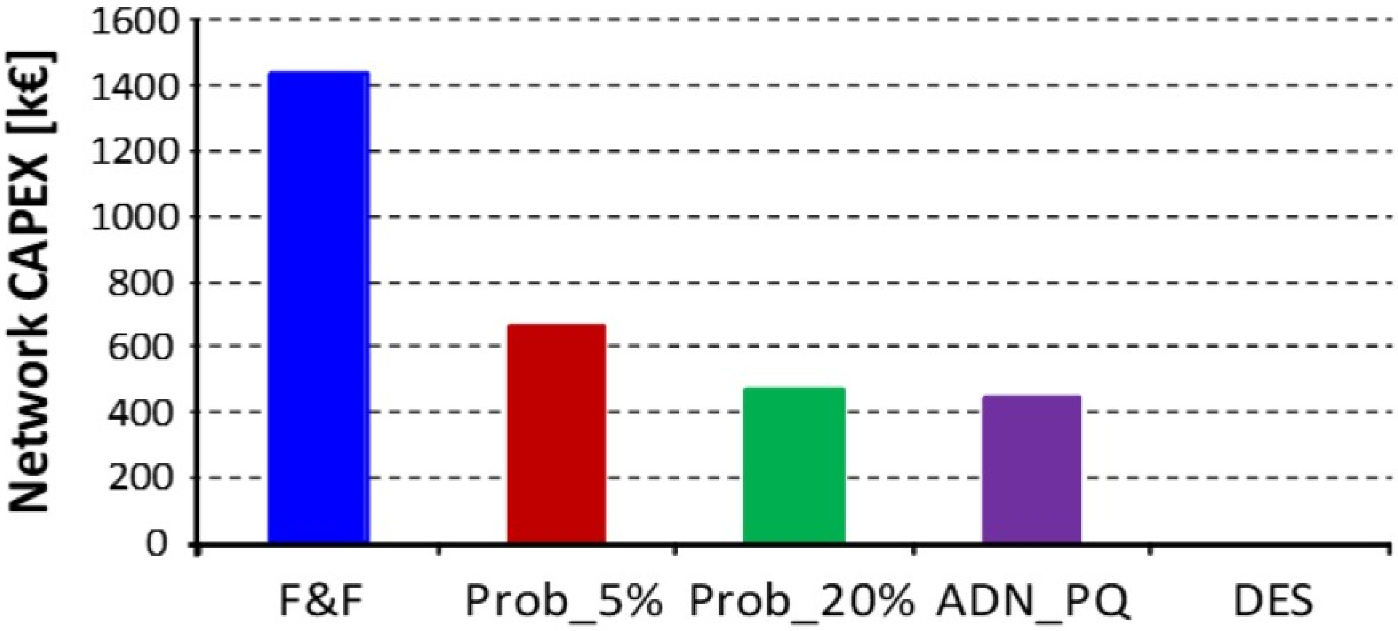
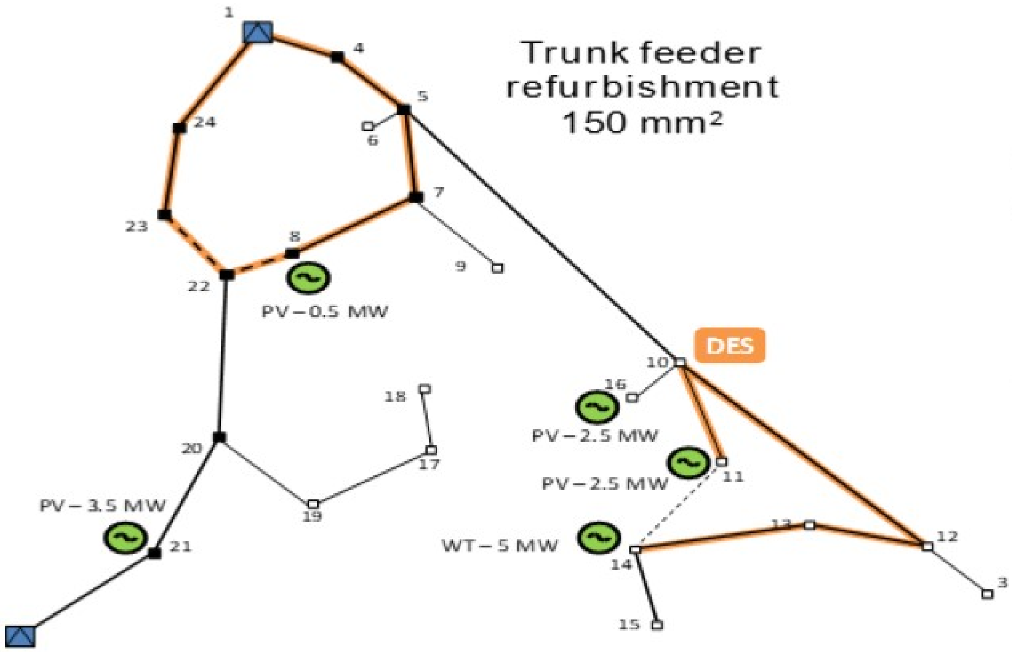
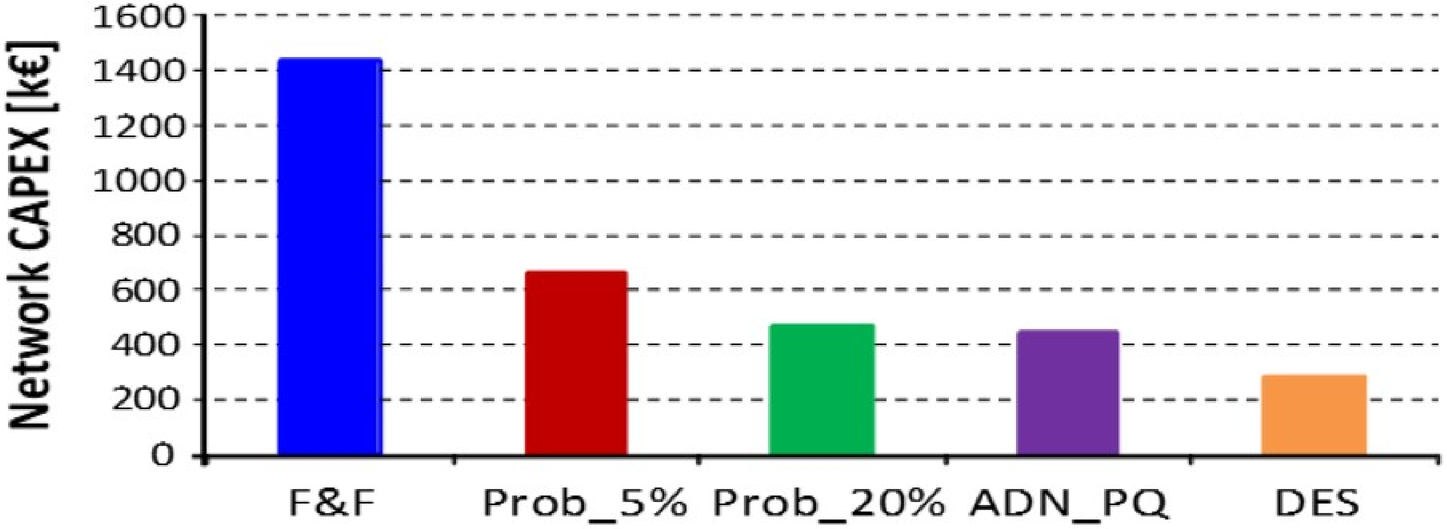
- The absence of controllable energy resources in the urban portion of the network (Demand Side Integration) does not make it possible to avoid the trunk feeder refurbishment.
- Better results by including Demand Response

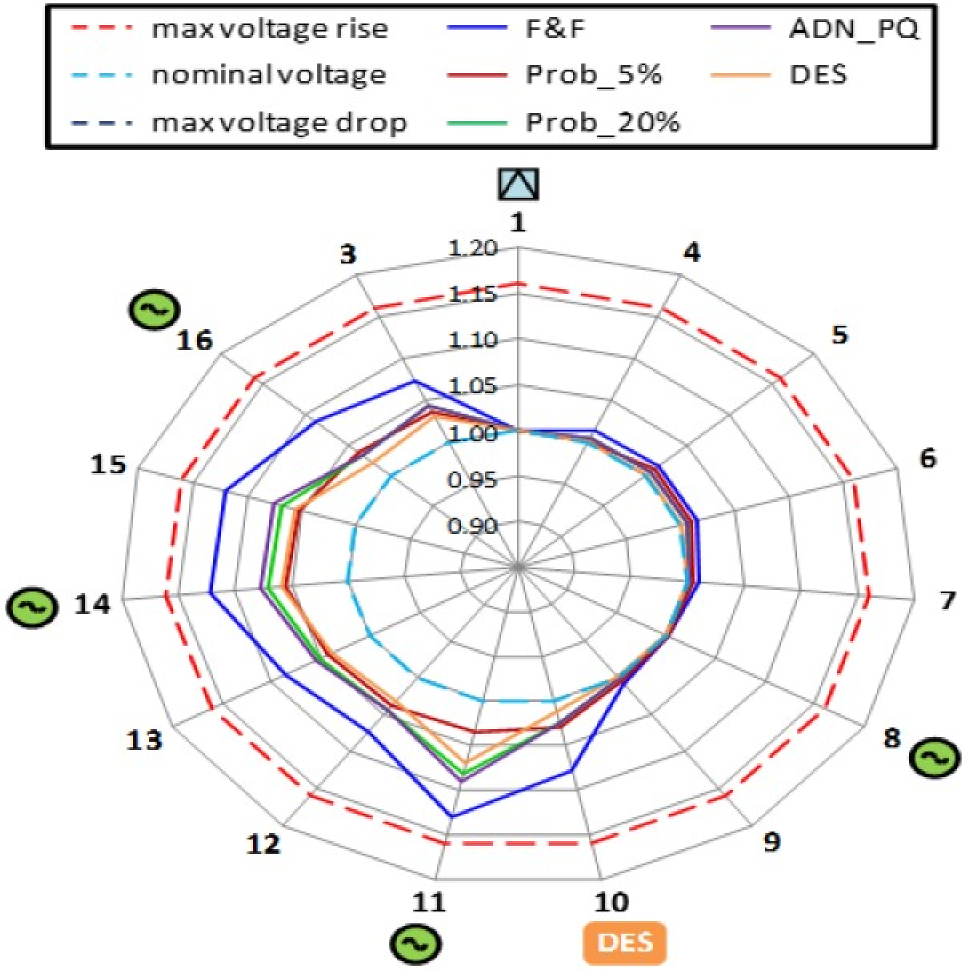


Results – Distribution Energy Storage

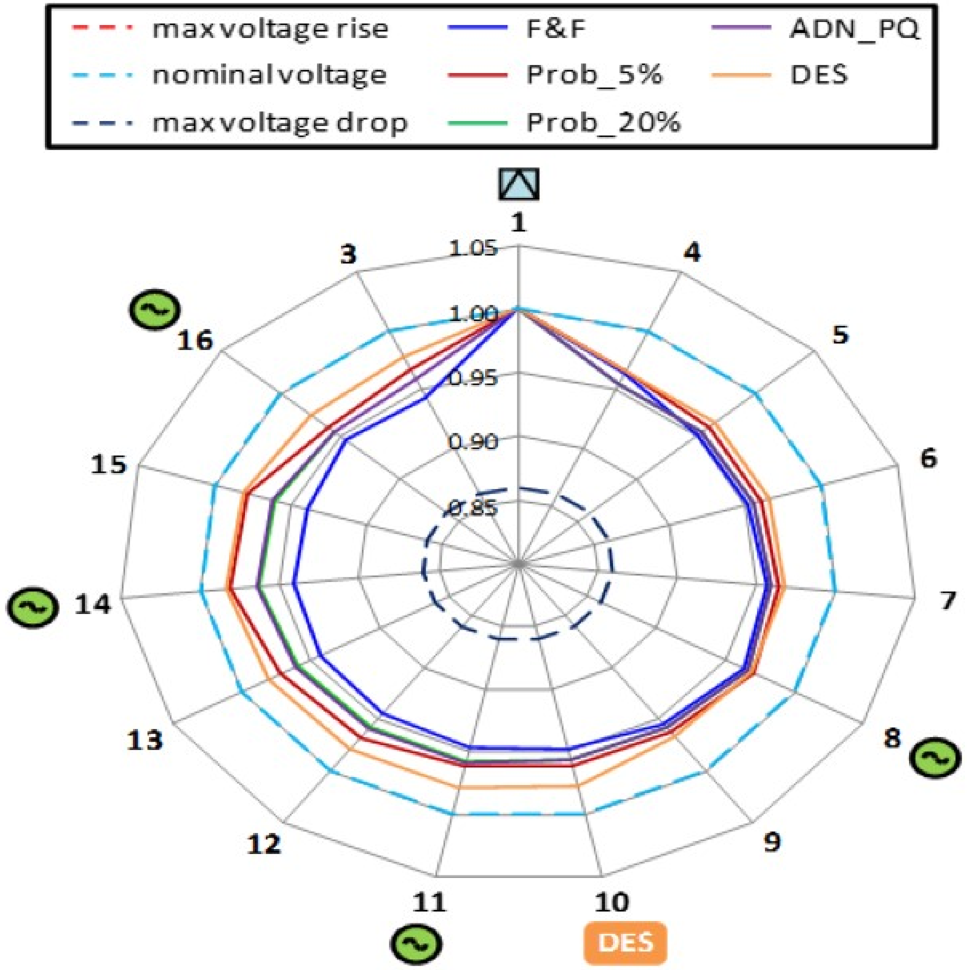




Results



max voltage rise
nominal voltage
max voltage drop
F&F
Prob_5%
Prob_20%
ADN_PQ
DES
1
3
4
5
6
7
8
9
10
11
12
13
14
15
16
1.20
1.15
1.10
1.05
1.00
0.95
0.90
DES



max voltage rise
nominal voltage
max voltage drop
F&F
Prob_5%
Prob_20%
ADN_PQ
DES
1
3
4
5
6
7
8
9
10
11
12
13
14
15
16
1.05
1.00
0.95
0.90
0.85
DES

Traditional Planning

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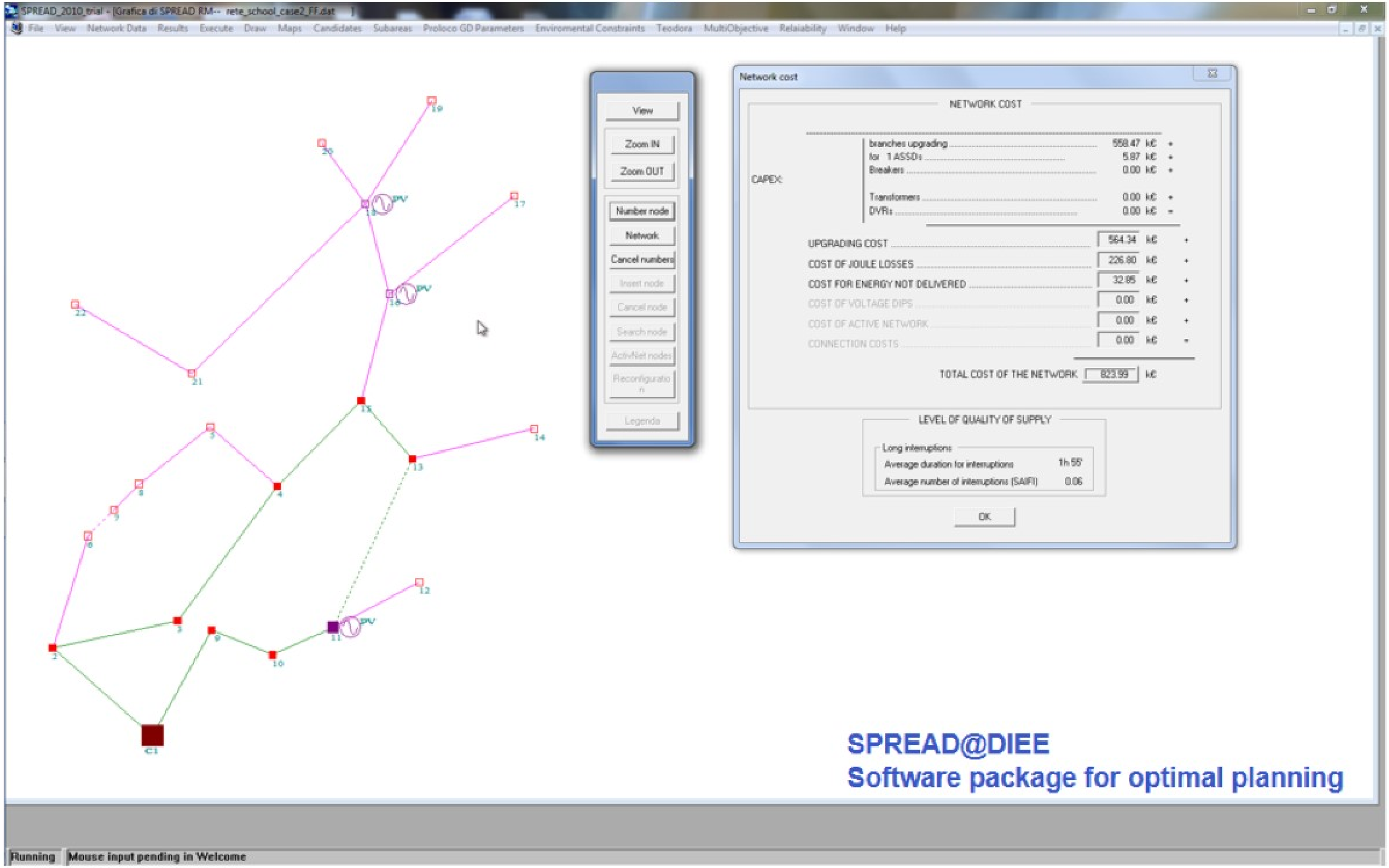
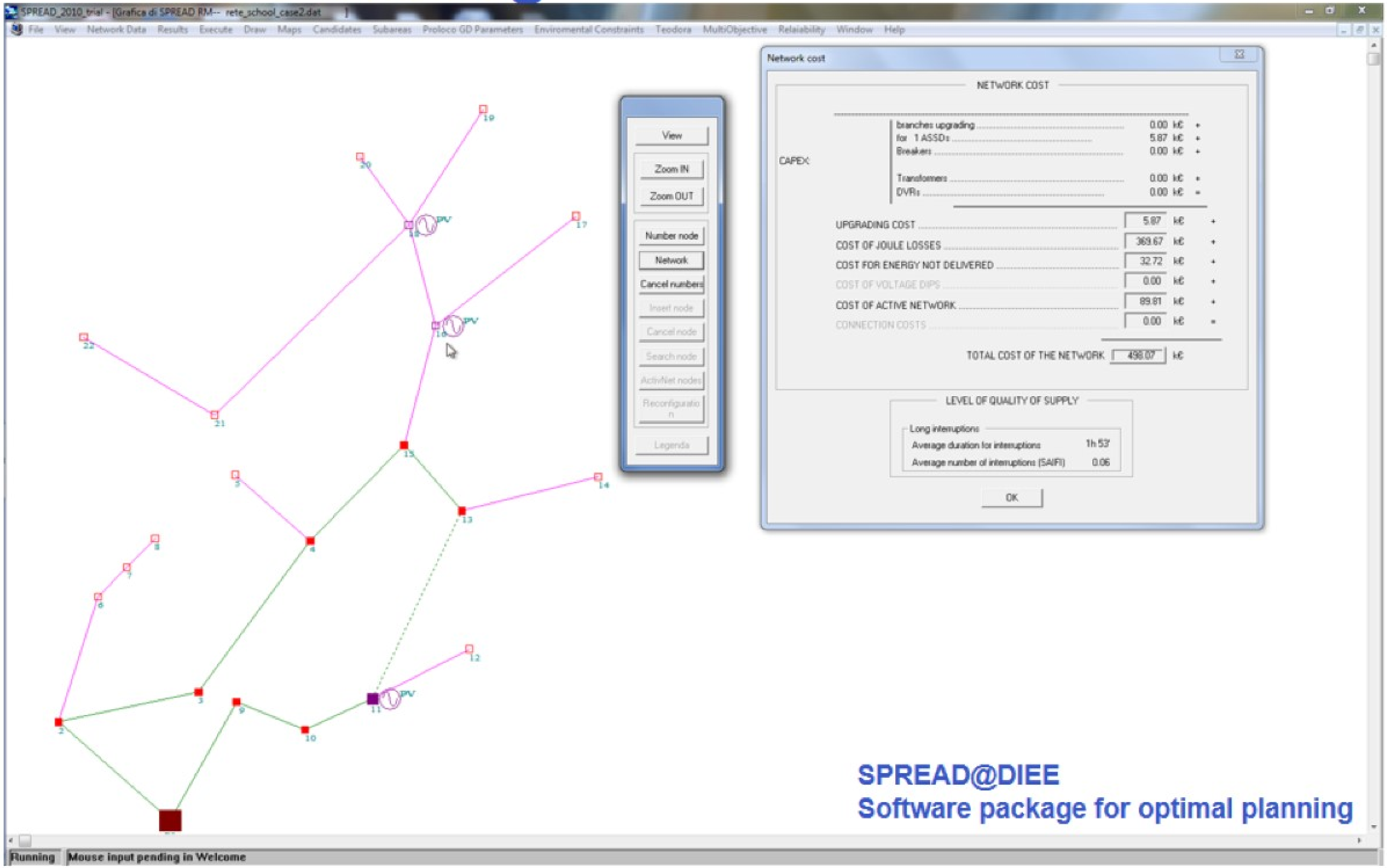


SPREAD@DIEE
Software package for optimal planning

- Primary substation
- MV/LV trunk node
- MV/LV lateral node
- DG (WT = wind turbine) (PV = photovoltaic)
- Trunk branch
- Emergency links

Novel Planning



SPREAD@DIEE
Software package for optimal planning

- Primary substation
- MV/LV trunk node
- MV/LV lateral node
- DG (WT = wind turbine) (PV = photovoltaic)
- Trunk branch
- Emergency links

Comparison between results

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Network cost

NETWORK COST

CAPEX:	branches upgrading	0.00	k€	+
	for 1 ASSDs	5.87	k€	+
	Breakers	0.00	k€	+
	Transformers	0.00	k€	+
	DVRs	0.00	k€	=
	UPGRADING COST	5.87	k€	+
	COST OF JOULE LOSSES	369.67	k€	+
	COST FOR ENERGY NOT DELIVERED	32.72	k€	+
	COST OF VOLTAGE DIPS	0.00	k€	+
	COST OF ACTIVE NETWORK	89.81	k€	+
	CONNECTION COSTS	0.00	k€	=
	TOTAL COST OF THE NETWORK	498.07	k€	

LEVEL OF QUALITY OF SUPPLY

Long interruptions

Average duration for interruptions	1h 53'
Average number of interruptions (SAIFI)	0.06

OK

Network cost

NETWORK COST

CAPEX:	branches upgrading	558.47	k€	+
	for 1 ASSDs	5.87	k€	+
	Breakers	0.00	k€	+
	Transformers	0.00	k€	+
	DVRs	0.00	k€	=
	UPGRADING COST	564.34	k€	+
	COST OF JOULE LOSSES	226.80	k€	+
	COST FOR ENERGY NOT DELIVERED	32.85	k€	+
	COST OF VOLTAGE DIPS	0.00	k€	+
	COST OF ACTIVE NETWORK	0.00	k€	+
	CONNECTION COSTS	0.00	k€	=
	TOTAL COST OF THE NETWORK	823.99	k€	

LEVEL OF QUALITY OF SUPPLY

Long interruptions

Average duration for interruptions	1h 55'
Average number of interruptions (SAIFI)	0.06

OK

Outline

- **About ISGAN**
- **Context and motivation**
- Distribution planning
- Deterministic distribution planning
- Novel Distribution Planning
    - Input data - Examples
    - Managing uncertainties and risks - Examples
    - Planning with Smart Grids - Examples
- **Future works**
- Conclusions

Future work

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- Low voltage systems in planning
- Impact of active demand in planning
- Data analytics for load modeling
- Choice of proper time granularity
- Interface TSO/DSO
- Reduction of complexity
- Integration of multiple services/infrastructures/energy
- Simulation of the role of energy and service markets in distribution planning

Outline

- About ISGAN
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- Deterministic distribution planning
- Novel Distribution Planning
  - Input data - Examples
  - Managing uncertainties and risks - Examples
  - Planning with Smart Grids - Examples
- Future works
- **Conclusions**

Italian rural network (projection to 2020) Passive operation

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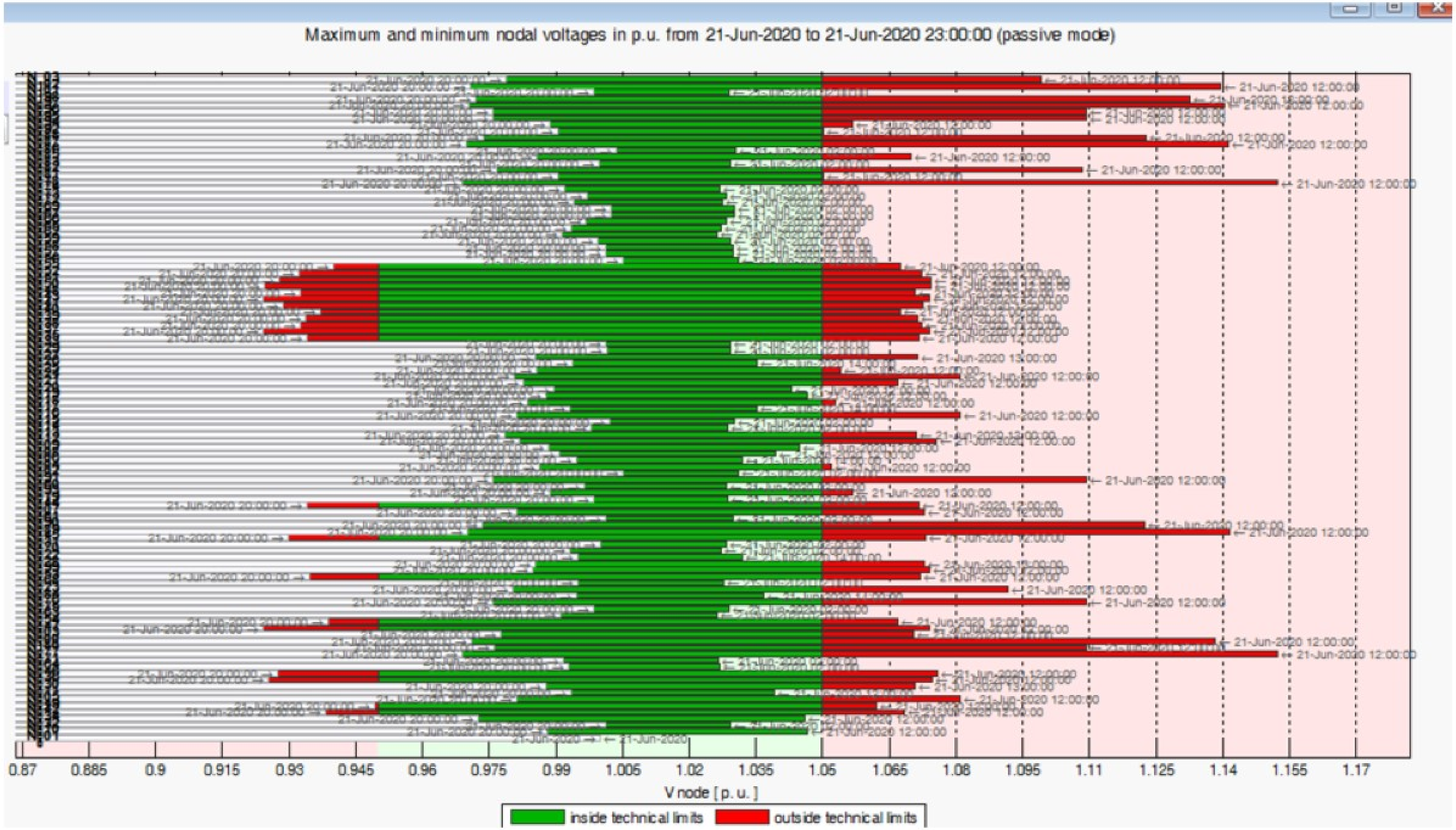
INTERNATIONAL SMART GRID ACTION NETWORK



Italian rural network (projection to 2020)
Active operation

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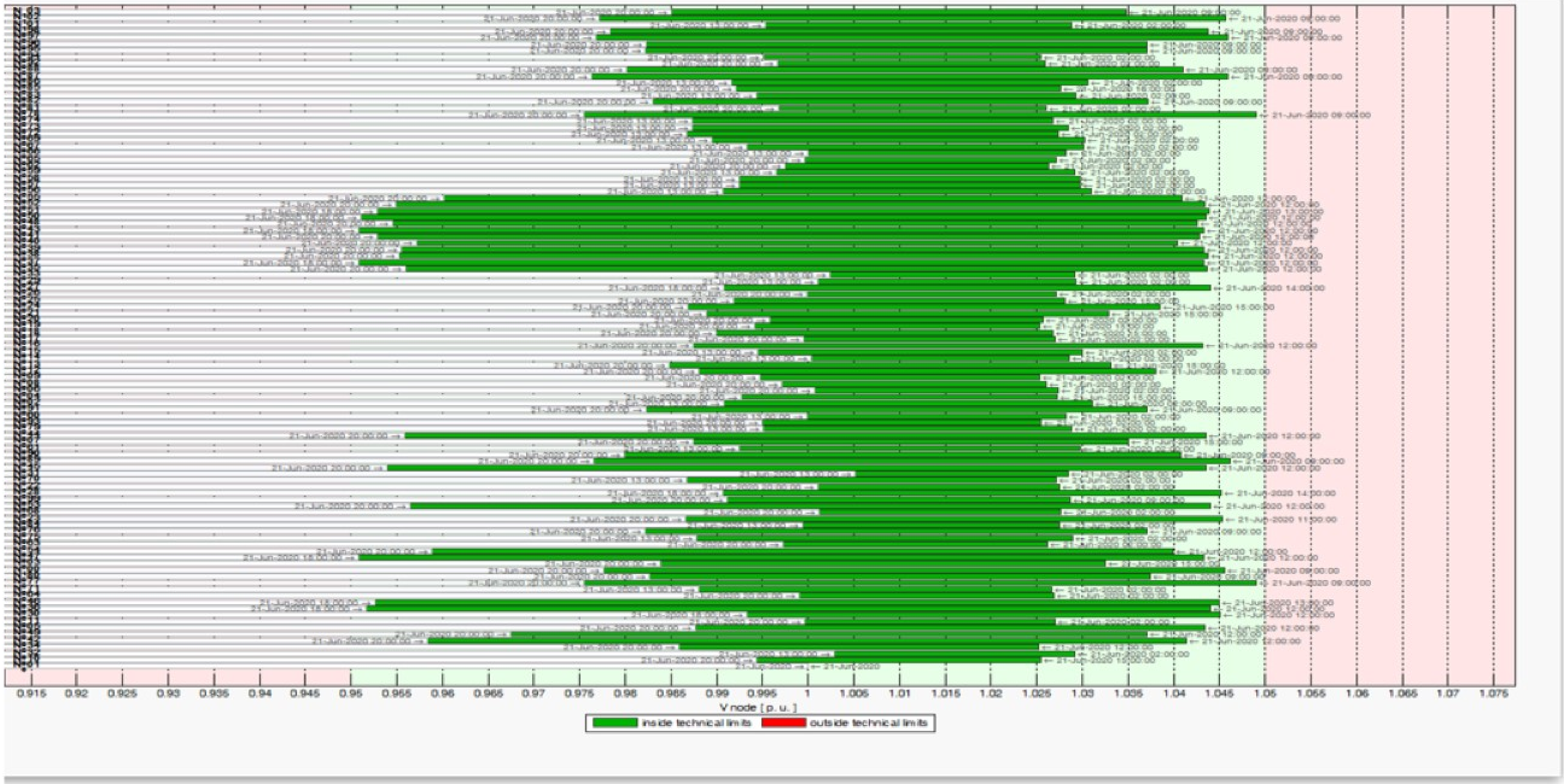
INTERNATIONAL SMART GRID ACTION NETWORK



Conclusions

- DSOs still adopt traditional planning tools
- Traditional planning is not suited for smart distribution
- New planning methodologies are required
  - Data Modelling and Smart meters
  - Operation & planning
  - Role of flexible demand/generation/storage in planning
  - Risk and reliability analysis
  - Co-simulation of ICT and Power Systems
- CIGRE WG C6.19 with TB 591/2014 started working on the topic of new planning
- CIGRE/CIRED JWG C1.C6.37 on TSO/DSO integrate planning is on-going

Further readings

- Ruggeri, S., Celli, G., Pilo, F., Malarange, G., Pagnetti, A., Simplified LV feeders model in presence of DG for MV network studies (2018) Sustainable Energy, Grids and Networks, 13, pp. 19-28, DOI: 10.1016/j.segan.2017.10.002
- Garau, M., Celli, G., Ghiani, E., Pilo, F., Corti, S. Evaluation of Smart Grid Communication Technologies with a Co-Simulation Platform (2017) IEEE Wireless Communications, 24 (2), art. no. 7909156, pp. 42-49. DOI: 10.1109/MWC.2017.1600214 ISSN: 15361284
- Mocci, S., Natale, N., Pilo, F., Ruggeri, S. Demand side integration in LV smart grids with multi-agent control system (2015) Electric Power Systems Research, 125, art. no. 4291, pp. 23-33. DOI: 10.1016/j.epsr.2015.03.021 ISSN: 03787796
- Celli, G., Pegoraro, P.A., Pilo, F., Pisano, G., Sulis, S. DMS cyber-physical simulation for assessing the impact of state estimation and communication media in smart grid operation (2014) IEEE Transactions on Power Systems, 29 (5), art. no. 6733312, pp. 2436-2446. DOI: 10.1109/TPWRS.2014.2301639 ISSN: 08858950
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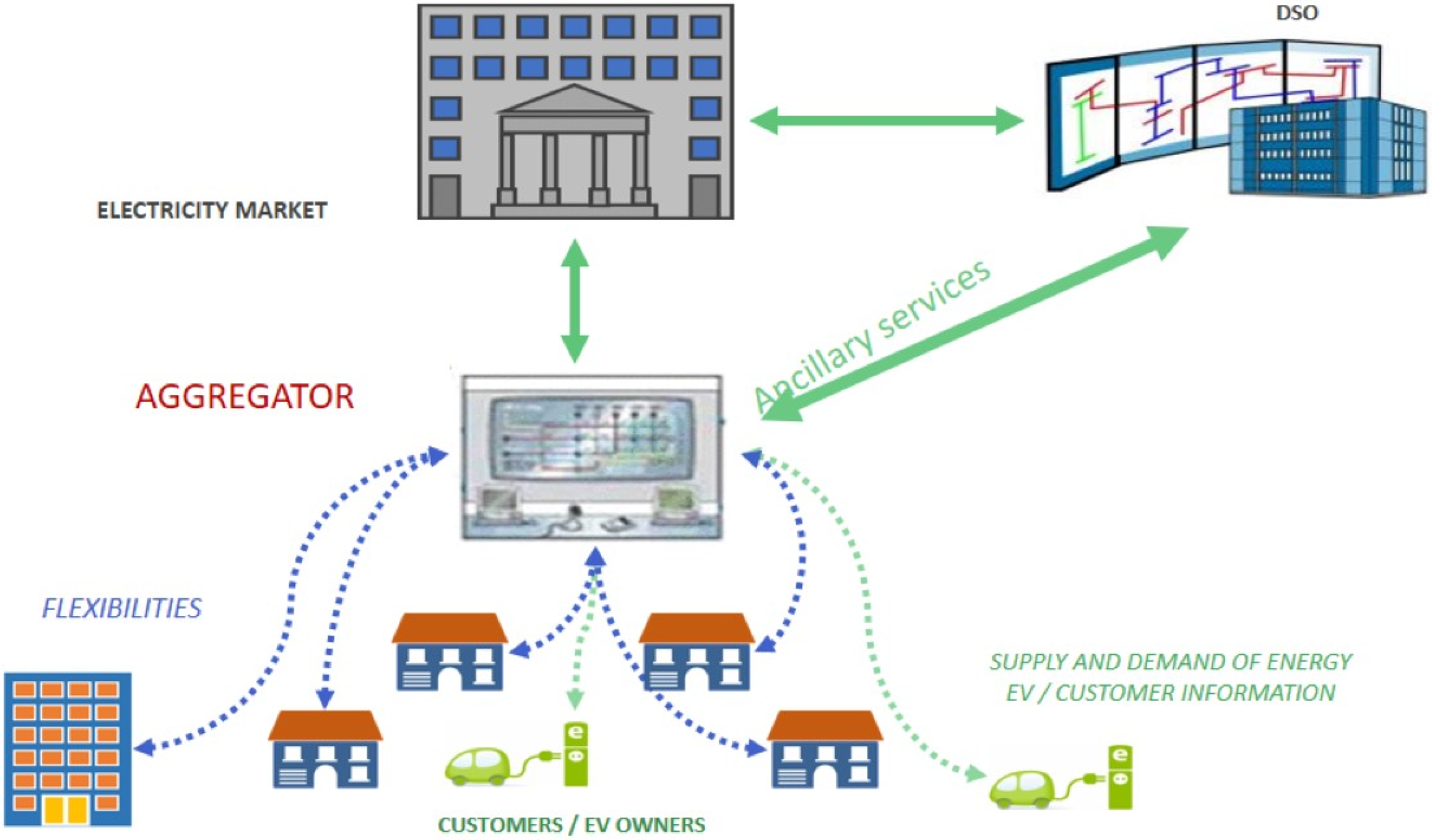
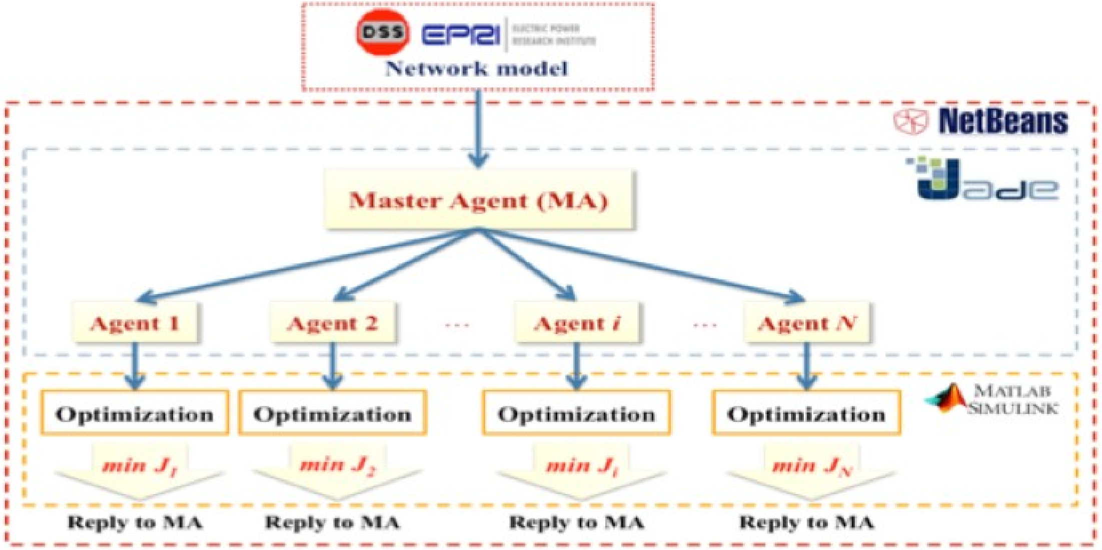
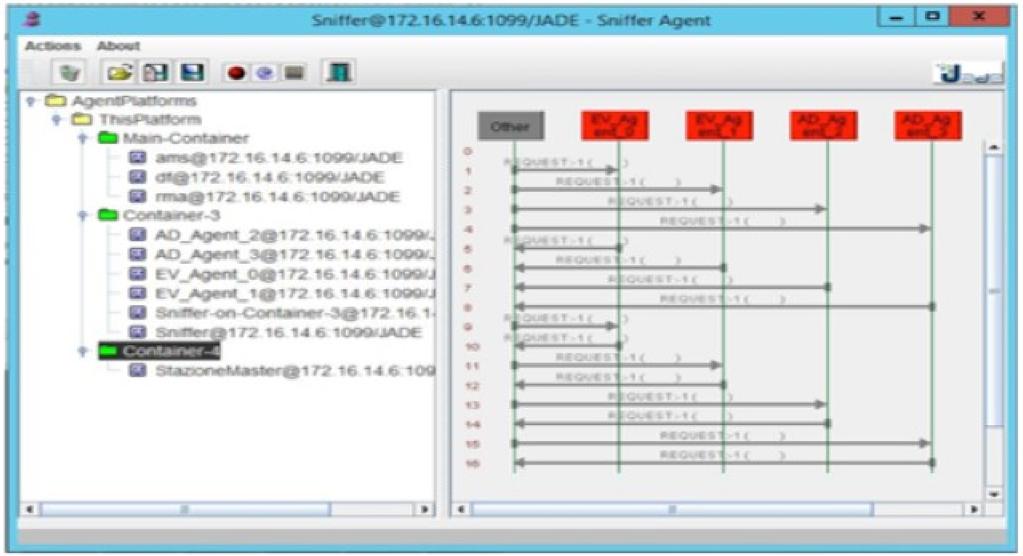
- Celli, G., Ghiani, E., Pilo, F., Soma, G.G. Reliability assessment in smart distribution networks (2013) Electric Power Systems Research, 104, pp. 164-175. DOI: 10.1016/j.epsr.2013.07.001 ISSN: 03787796
- Celli G, Ghiani E, Pilo F, Soma G G (2013). New electricity distribution network planning approaches for integrating renewable. WILEY INTERDISCIPLINARY REVIEWS. ENERGY AND ENVIRONMENT, vol. 2, p. 140-157, ISSN: 2041-840X, doi: 10.1002/wene.70
- Celli G., Ghiani E., Mocci S., Pilo F. (2005). A Multi-Objective Evolutionary Algorithm for the Sizing and Siting of Distributed Generation. IEEE TRANSACTIONS ON POWER SYSTEMS, vol. 20, p. 750-757, ISSN: 0885-8950, doi: 10.1109/TPWRS.2005.846219
- CIGRE TB 591, Pilo F, Jupe S, Silvestro F, Abbey C, Baitch A, Bak-Jensen B, Carter-Brown C, Celli G, El Bakari K, Fan M, Georgilakis P, Hearne T, Ochoa L, Petretto G, Taylor J (2014). Planning and optimization methods for active distribution systems. PARIS: CIGRE', ISBN: 978-2-85873-289-0

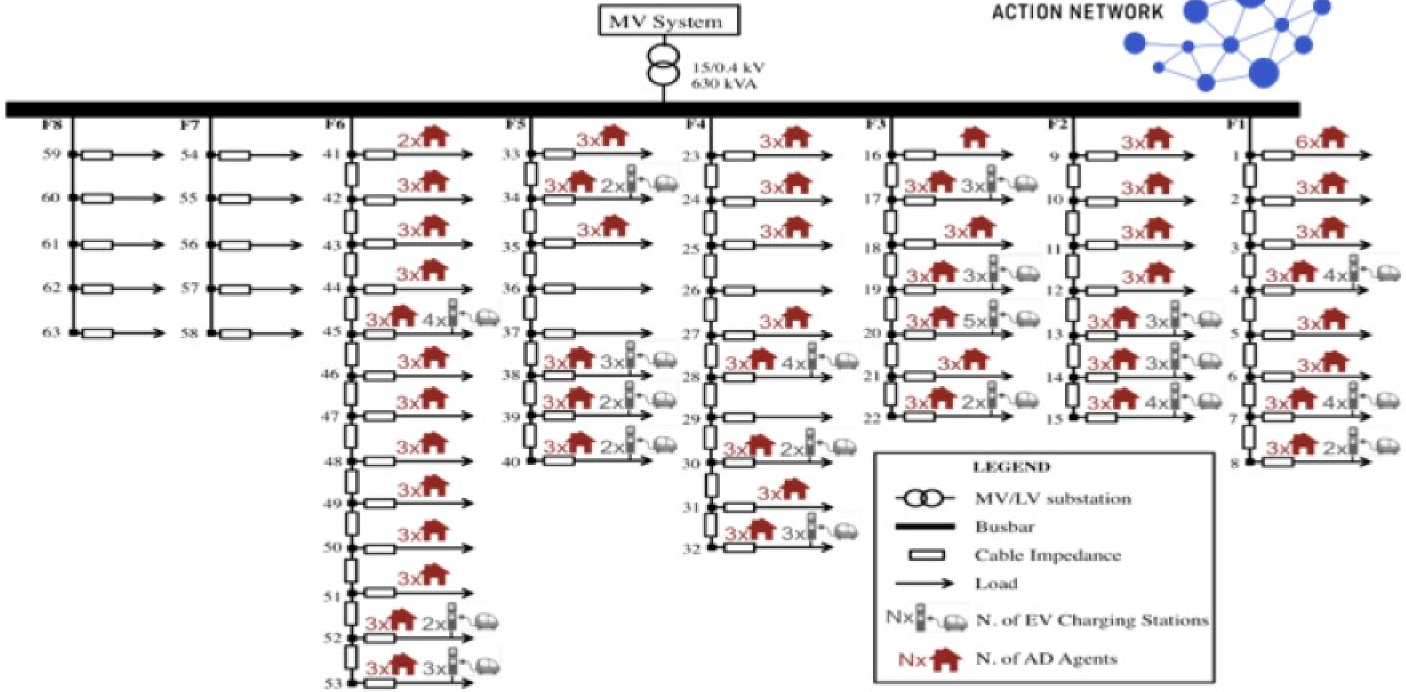
Demand side integration - active demand



Decentralised control systems







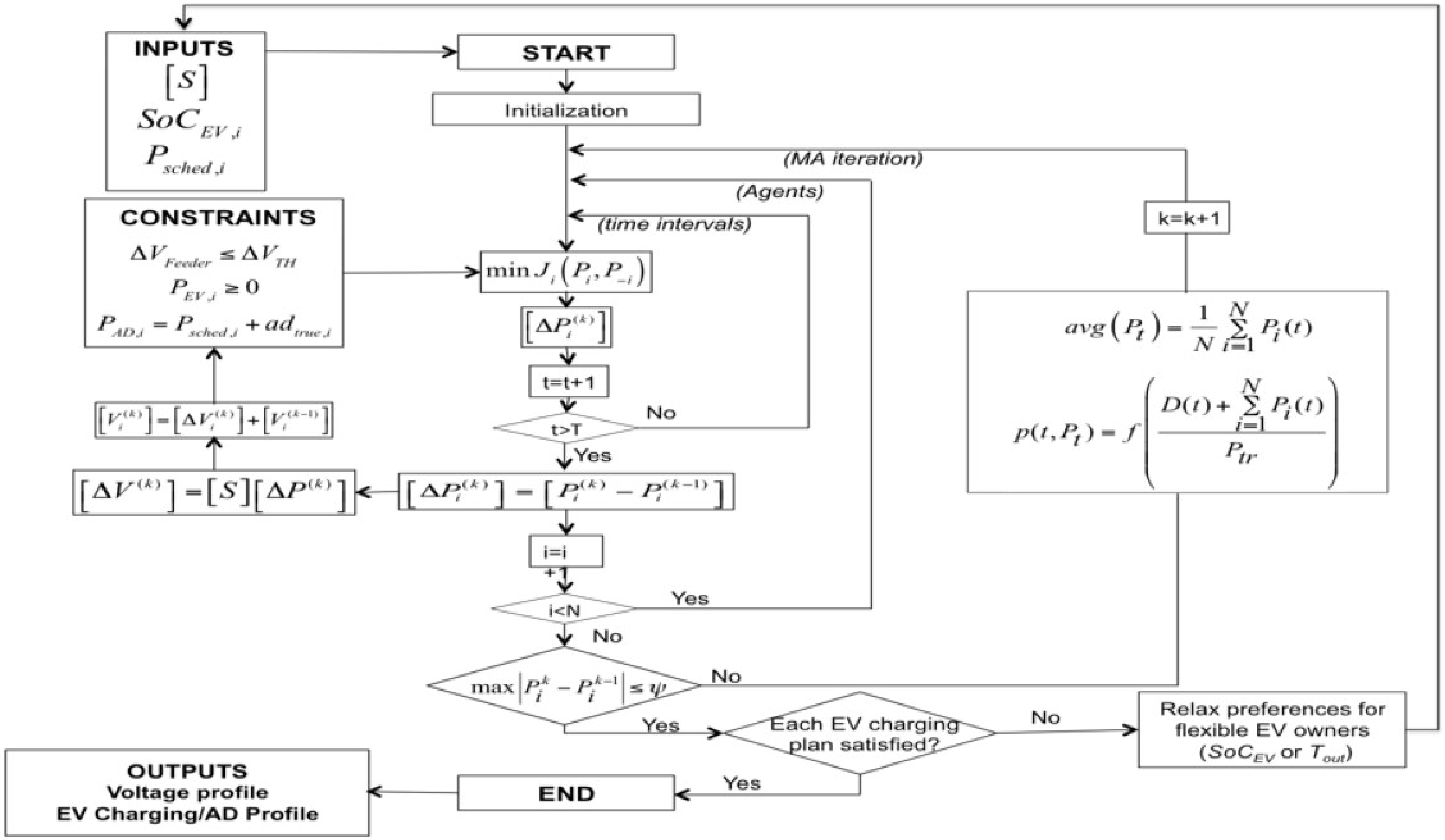
EVs = 59 (40% residential loads)

EV Set	Number of EVs	T_{in}	T_{out}	SOC_{in}	SOC_{out}
1	41 (70% of tot Evs)	18:00	7:00	30%	100%
2	18 (30% of tot Evs)	17:00	23:00		

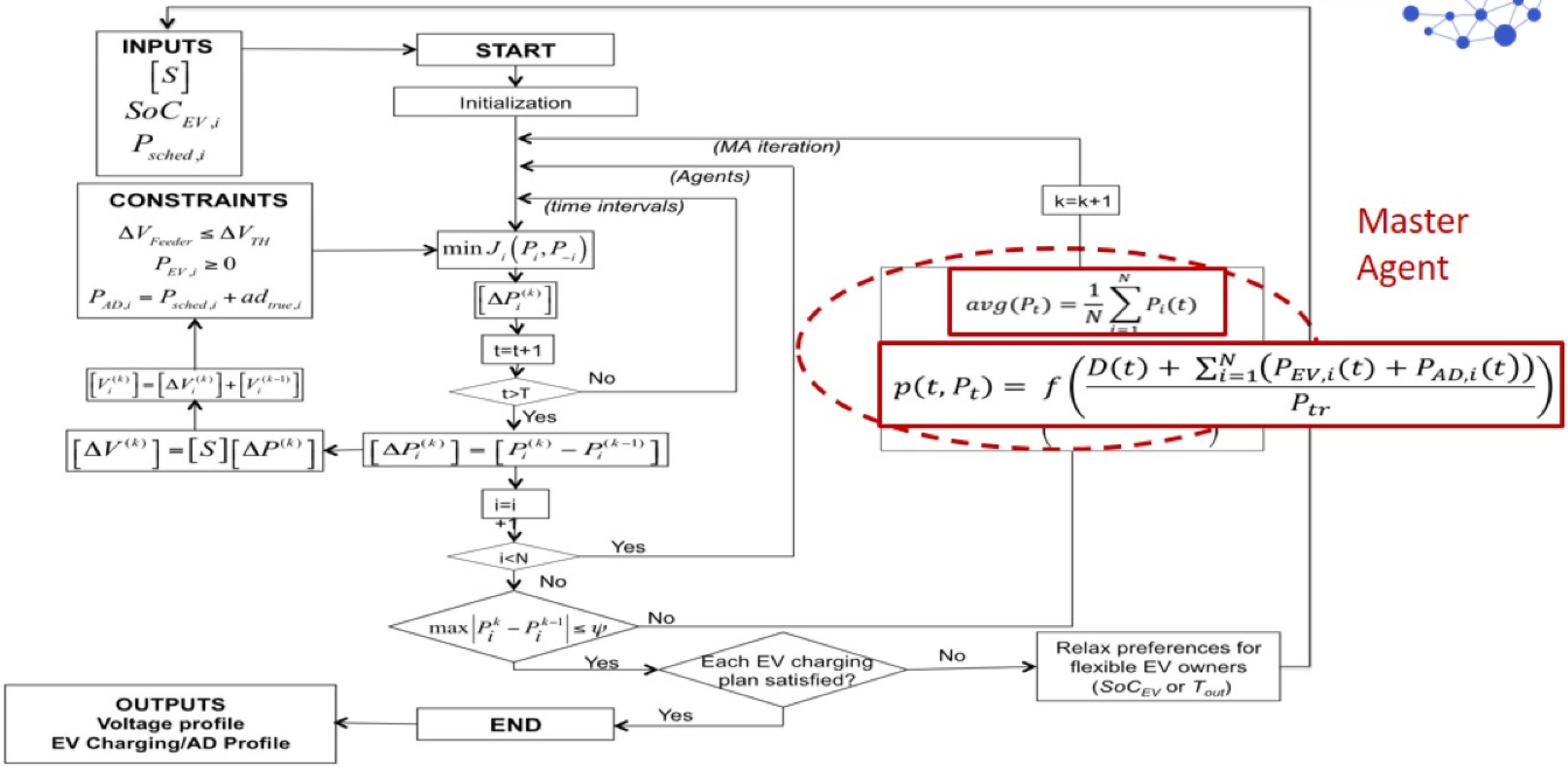
Homes involved in the active demand program = 147

AD Model parameters: $f_0 = 0{,}55$; $f_1 = 0{,}4$; $f_2 = 0{,}05$

FLOWCHART

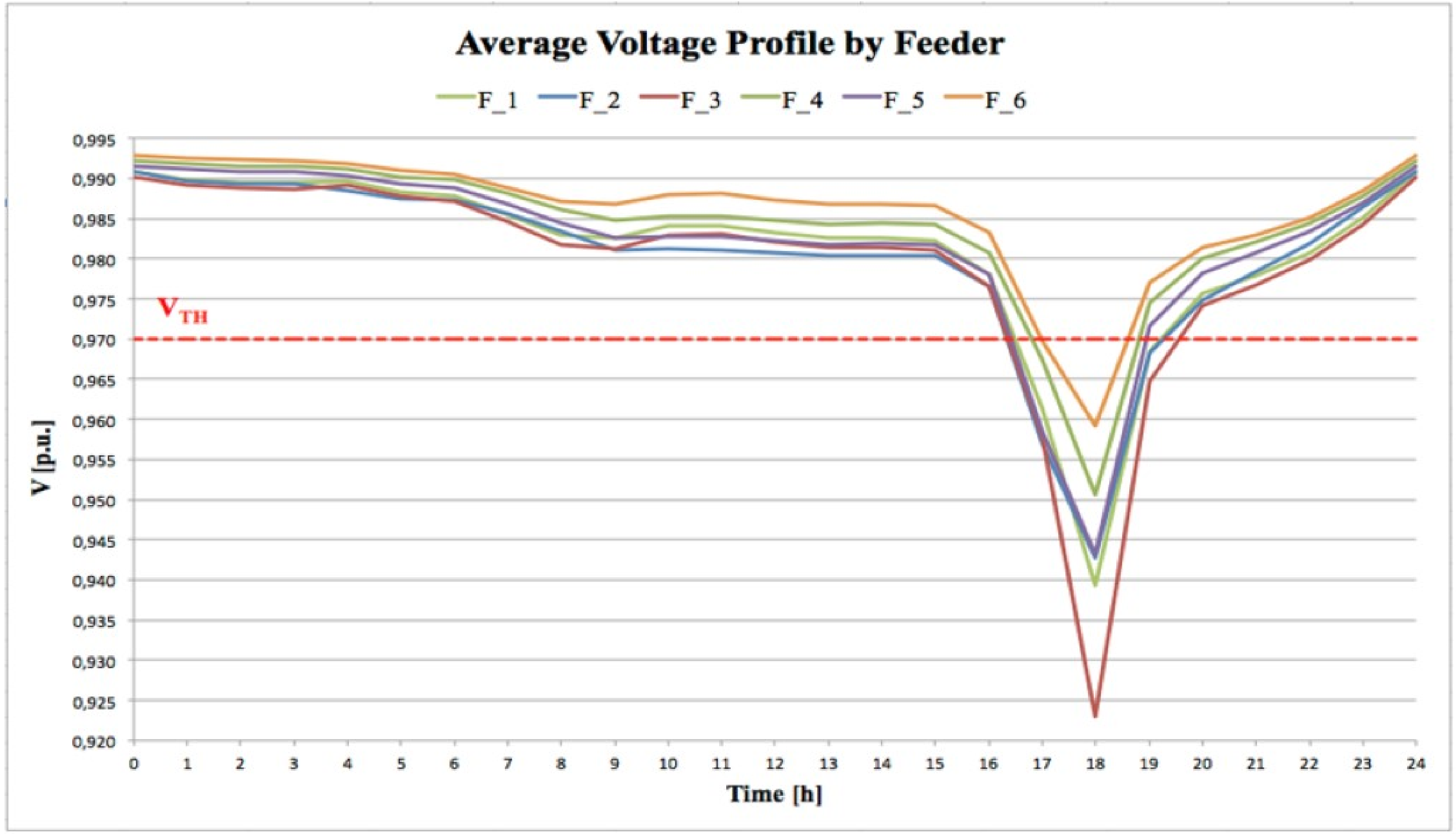

INPUTS
$[S]$
$SoC_{EV,i}$
$P_{sched,i}$
START
Initialization
(MA iteration)
(Agents)
(time intervals)
k=k+1
CONSTRAINTS
$\Delta V_{Feeder} \leq \Delta V_{TH}$
$P_{EV,i} \geq 0$
$P_{AD,i} = P_{sched,i} + ad_{true,i}$
$\min J_i(P_i, P_{-i})$
$[\Delta P_i^{(k)}]$
t=t+1
t>T
No
Yes
$avg(P_t) = \frac{1}{N}\sum_{i=1}^{N} P_i(t)$
$p(t, P_t) = f\left(\frac{D(t) + \sum_{i=1}^{N} P_i(t)}{P_{tr}}\right)$
$[V_i^{(k)}] = [\Delta V_i^{(k)}] + [V_i^{(k-1)}]$
$[\Delta V^{(k)}] = [S][\Delta P^{(k)}]$
$[\Delta P_i^{(k)}] = [P_i^{(k)} - P_i^{(k-1)}]$
i=i+1
i<N
Yes
No
$\max|P_i^k - P_i^{k-1}| \leq \psi$
No
Yes
Each EV charging plan satisfied?
No
Relax preferences for flexible EV owners (SoC_{EV} or T_{out})
Yes
END
OUTPUTS
Voltage profile
EV Charging/AD Profile

FLOWCHART

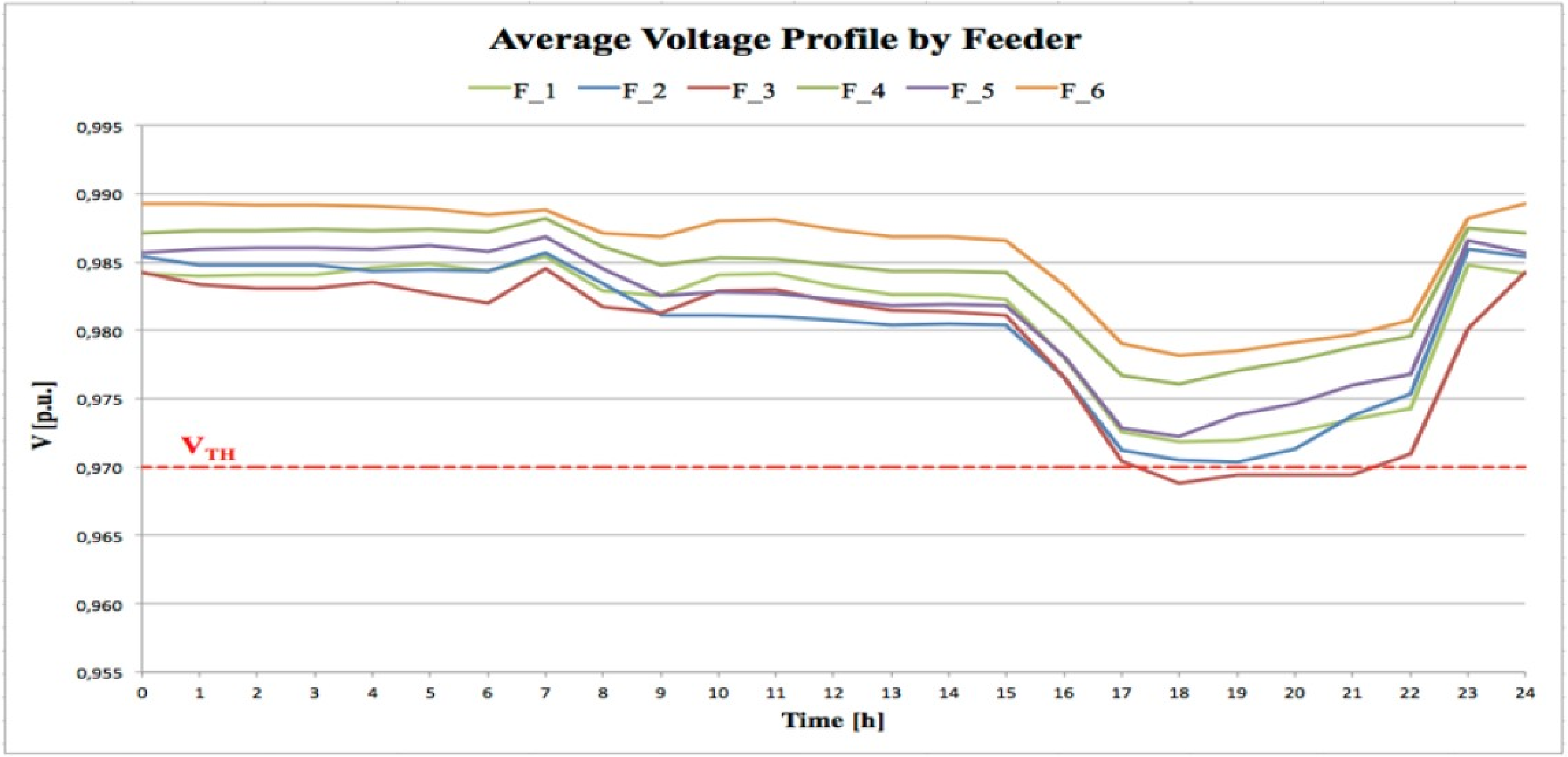


INPUTS
$[S]$
$SoC_{EV,i}$
$P_{sched,i}$
START
Initialization
(MA iteration)
(Agents)
(time intervals)
k=k+1
CONSTRAINTS
$\Delta V_{Feeder} \leq \Delta V_{TH}$
$P_{EV,i} \geq 0$
$P_{AD,i} = P_{sched,i} + ad_{true,i}$
$\min J_i(P_i, P_{-i})$
$[\Delta P_i^{(k)}]$
t=t+1
t>T
No
Yes
$[V_i^{(k)}] = [\Delta V_i^{(k)}] + [V_i^{(k-1)}]$
$[\Delta V^{(k)}] = [S][\Delta P^{(k)}]$
$[\Delta P_i^{(k)}] = [P_i^{(k)} - P_i^{(k-1)}]$
i=i+1
i<N
Yes
No
$\max |P_i^k - P_i^{k-1}| \leq \psi$
No
Yes
Each EV charging plan satisfied?
No
Relax preferences for flexible EV owners (SoC_{EV} or T_{out})
Yes
END
OUTPUTS
Voltage profile
EV Charging/AD Profile
Master Agent
$avg(P_t) = \frac{1}{N}\sum_{i=1}^{N} P_i(t)$
$p(t, P_t) = f\left(\frac{D(t) + \sum_{i=1}^{N}(P_{EV,i}(t) + P_{AD,i}(t))}{P_{tr}}\right)$

Dumb charging

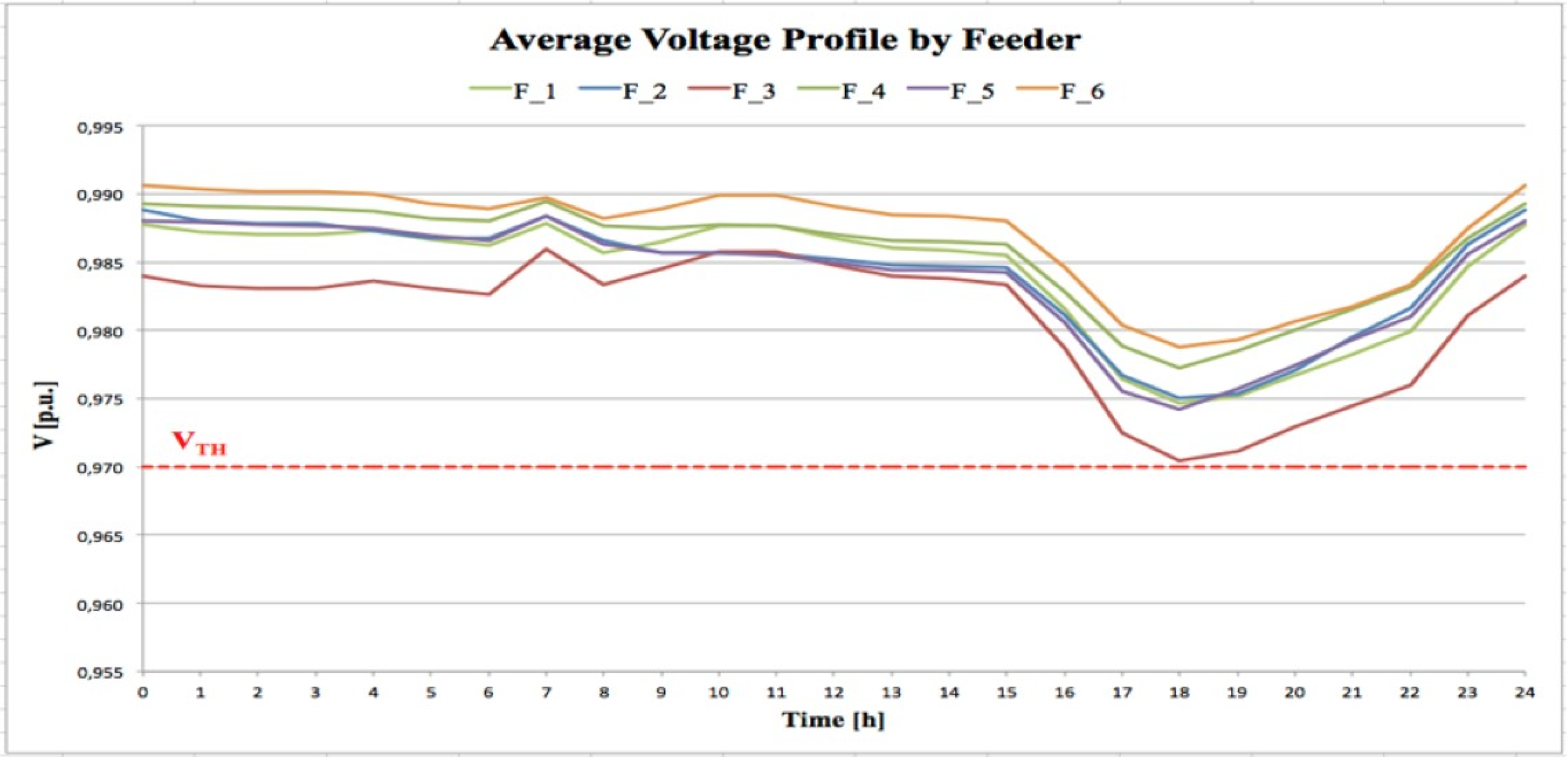


Smart charging – no active demand



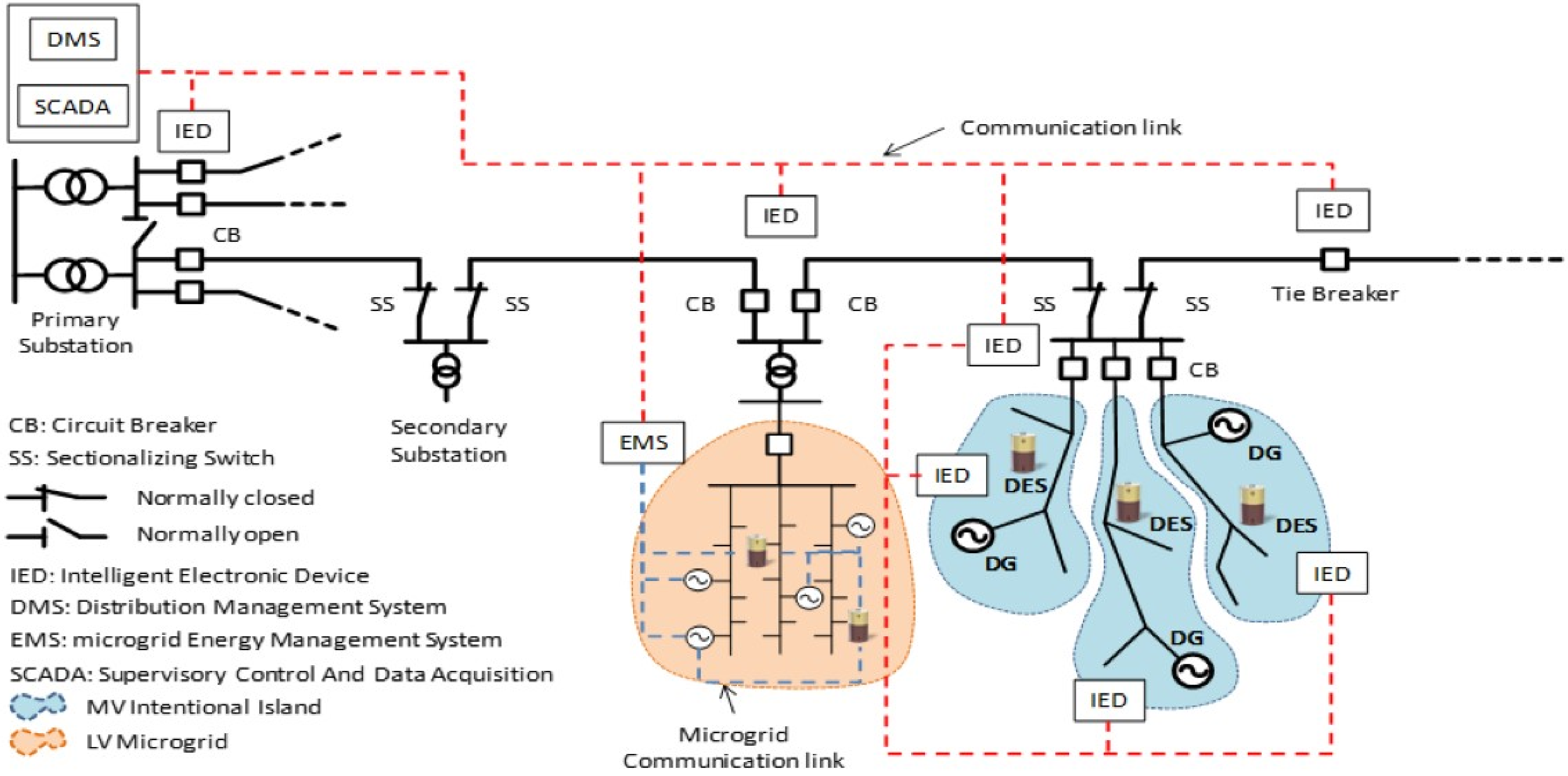
EV Set	Number of EVs	T_{in}	T_{out}	SOC_{in}	SOC_{out}
1	41 (70% of tot EVs)	18:00	7:00	30%	100%
2	18 (30% of tot EVs)	17:00	23:00	30%	100%

Smart charging and active support

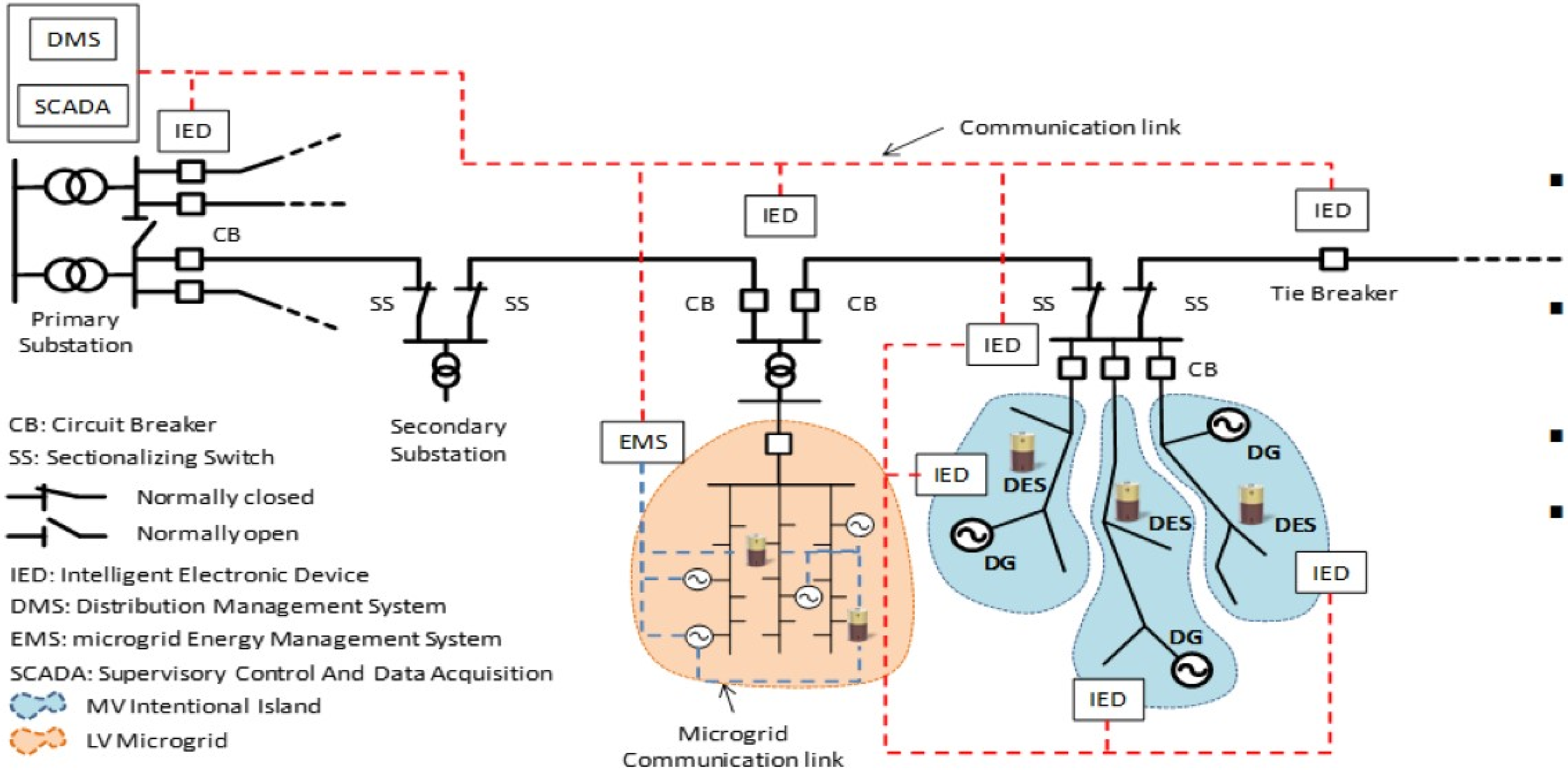


EV Set	Number of EVs	T_{in}	T_{out}	SOC_{in}	SOC_{out}
1	41 (70% of tot EVs)	18:00	7:00	30%	100%
2	18 (30% of tot EVs)	17:00	23:00	30%	**100%**

ICT – the enabling technology



ICT – the enabling technology



- ICT infrastructure is not an add-on of the power systems
- Performances depend on ICT
- Reliability depend on ICT
- Cyber-physical simulation

Reliability studies with Smart Grid

ADN Operations

- Bi-directional power
- Adv. controls
- DER variations
- Self Healing
- Customer participation
- Islanding
- Energy storage

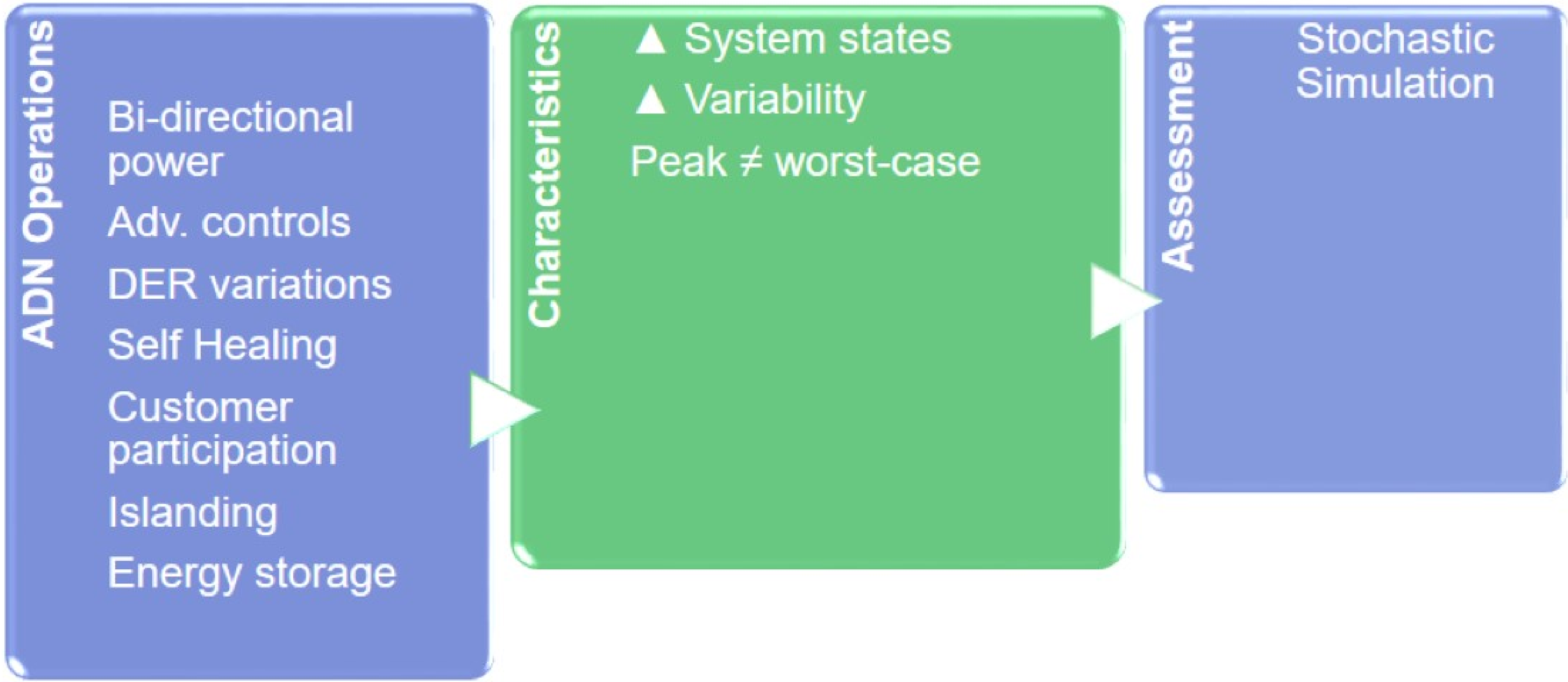
Characteristics

- ▲ System states
- ▲ Variability
- Peak ≠ worst-case

Assessment

- Stochastic Simulation

Reliability studies with Smart Grid



- State-Enumeration (*small and simple systems*)
- Monte Carlo Simulation (*no chronological aspect*)
- Sequential MCS (*highest computational burden*)
- **Pseudo-Sequential MCS** (*good compromise*)

Cyber-physical simulation

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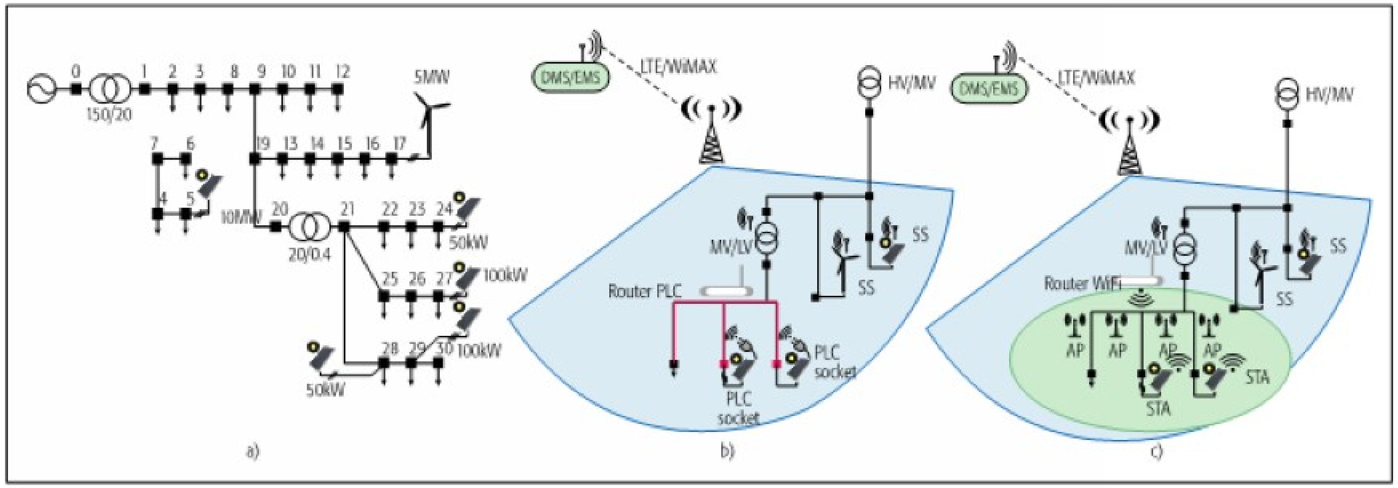

FIGURE 2. a) MV/LV network; b) LTE/WiMAX + PLC communication scheme; c) LTE/WiMAX + Wi-Fi communication scheme.

From/to	WiMAX (ms)	LTE (ms)	LTE+Wi-Fi (ms)	LTE+PLC (ms)
IED-DMS	40.40	28.92	34.46	368.82
DMS-N05	39.82	13.90	34.07	36.02
DMS-N17	40.06	14.00	32.12	32.12
DMS-N24	40.23	16.90	39.38	370.82
DMS-N27	39.90	13.82	46.42	1305.92
DMS-N28	39.98	16.00	72.87	2028.92
DMS-N29	40.16	14.99	97.95	2435.62

TABLE 1. Average latencies in the active management of the SG (the term "average" is related to the procedure by which the results are extracted by the simulations with ns3).

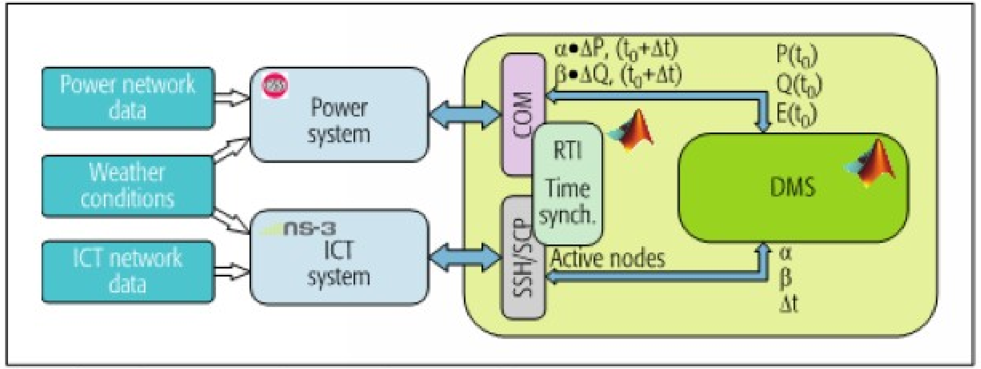

FIGURE 1. Architecture of co-simulation tool.

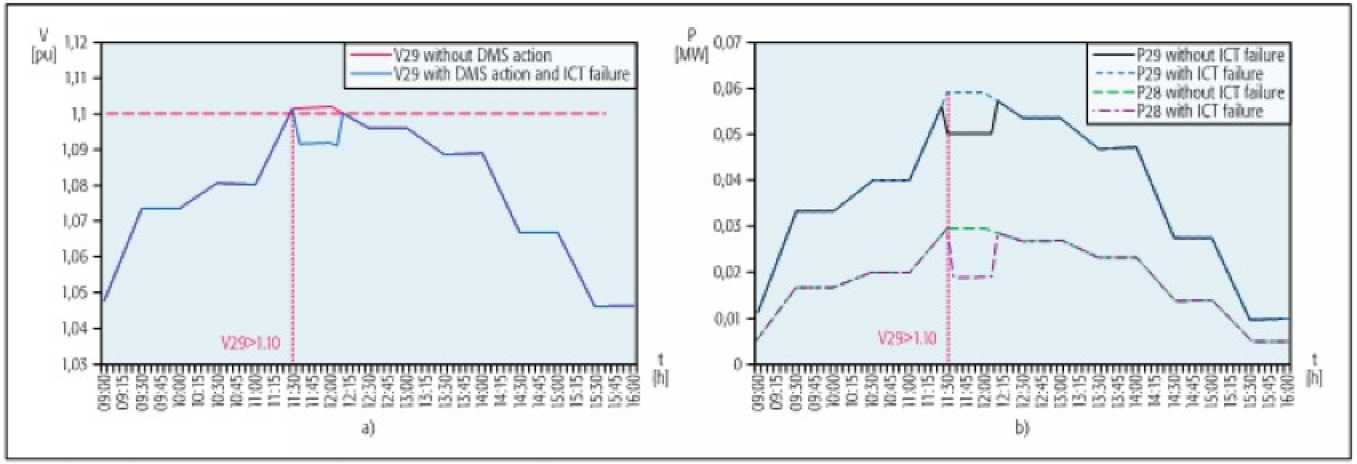

FIGURE 5. a) voltage profile at N29; b) active power profile at N28 - N29.