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FlexPlan

Decomposition methods for long-term network planning

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Recapitulation of the FlexPlan approach

Candidate transmission lines & cables, HVDC connections, PSTs, storage, demand flexibility

Quantify landscape impact costs

Carbon footprint analysis using LCA

Generation and demand time series for 2030, 2040, 2050

T & D grid data based on ENTSO –e TYNDP

Optimization model

Objective: Maximum social welfare consisting of investment costs, power plant operational costs, environmental impact, system security impact

Decision variables: Investment decision (binary), hourly generator dispatch, flexibility activation, storage usage, PST & HVDC set points

Constraints: T&D grid constraints, T&D security constraints, flexibility characteristics, storage constraints

Optimization objective – General structure

- The maximum social welfare objective formulated as a cost minimization
  - Quantification of potential benefits not straight-forward without market assumptions
  - Danger of double counting benefits / costs due to complex flow of money
  - Eventually, all cost needs to be borne by consumers in some in way
- Objective function structure:
  - $\min \sum_y [\sum_t [\sum_i (C_{y,t,i}) + \sum_{y,j} \alpha_{y,j} (C_{y,t,j}) + \widetilde{U}_{y,t,c} \Delta t \sum_c C_{u,t,y}^{voll} \Delta P_{u,c,t,y}] + \sum_j \alpha_{y,j} I_{y,j}]$

Operational cost of existing equipment

Operational cost of candidate equipment

Expected cost due to outages

CAPEX of candidate equipment

i… set of existing equipment
j… set of candidate equipment
α… binary decision variable
t….set operational time points (8760h)
y... set of planning horizons (2030, 2040, 2050)

  - Environmental impact cost considered as part of operational and CAPEX cost

Detailed formulation of the objective function

$$
\begin{aligned}
\min \sum_{y\in S_y} \Bigg\{ & f_y^{d,o} \sum_{t\in S_t} \Bigg[\sum_{g\in S_g} \left[C^{aq}_{g,y} + \left(\theta^{CO_2} G^{pf} + \theta^{f}\right)\eta^{f}_{g}\right] P_{g,t,y} + C^{res,curt}_{g,y}\,\Delta P^{res}_{g,t,y} + \\
& \sum_{j\in S_j}\left[C^{abs}_{j,t,y}P^{abs}_{j,t,y} + C^{inj}_{j,t,y}P^{inj}_{j,t,y}\right] + \sum_{j\in S_{jc}}\left[C^{abs}_{jc,t,y}P^{abs}_{jc,t,y} + C^{inj}_{jc,t,y}P^{inj}_{j,t,y}\right] + \\
& \sum_{u\in S_u}\left[C^{nce}_{u,t,y}\left(P^{ref}_{u,t,y} - P^{nce}_{u,t,y}\right) + C^{ds}_{u,t,y}\left(\Delta P^{ds,up}_{u,t,y} + \Delta P^{ds,dn}_{u,t,y}\right) + C^{lc}_{u,t,y}\Delta P^{lc}_{u,t,y}\right] + \\
& \sum_{n\in S_n}\left(C^{EE}_{n,t,y} EE_{n,t,y} + C^{LL}_{n,t,y} LL_{n,t,y}\right) \Bigg] + \\
& f_y^{d} \Bigg[\sum_{j\in S_{jc}} \alpha_{jc,y}\left(I^{E}_{jc,y}\left(E^{max}_{j}\right) + I^{P}_{jc,y}\left(P^{max}_{j}\right) + FP^{CO_2}_{jc,y}\right) + \sum_{u\in S_u}\alpha_{u,y}\left(I_{u,y} + FP^{CO_2}_{u,y}\right) + \\
& \sum_{lc\in S^{ac}_{lc}} \alpha_{lc,y}\left(I_{lc,y} + FP^{CO_2}_{lc,y} + LS_{lc,y}\right) + \sum_{dc\in S^{dc}_{lc}} \alpha_{dc,y}\left(I_{dc,y} + FP^{CO_2}_{dc,y} + LS_{dc,y}\right) + \\
& \sum_{zc\in S_{zc}} \alpha_{zc,y}\left(I_{zc,y} + FP^{CO_2}_{zc,y} + LS_{zc,y}\right) + \sum_{bc\in S_{bc}} \alpha_{bc,y}\left(I_{bc,y} + FP^{CO_2}_{bc,y} + LS_{bc,y}\right) \Bigg] \Bigg\}
\end{aligned}
$$

Air quality impact cost

Generator operational costs

Storage operational costs

Flexible demand operational costs

Grid security related costs

Capex storage + Capex demand flexibility

Capex AC and DC lines

Capex DC converters & PSTs

Carbon footprint & landscape impact cost

Model dimensions:

- Set of grid elements (x1000)
- Set of planning hours (8760)
- Set of planning years (2030 – 2040 - 2050)

Detailed formulation of the objective function

$$
\min \sum_{s} \pi_s \Bigg\{ \sum_{y \in S_y} f_y^{d,o} \Bigg\{ \sum_{t \in S_t} \Bigg[\sum_{g \in S_g} \left[C_{g,y}^{aq} + \left(\theta^{CO_2} G^{pf} + \theta^{f}\right)\eta_g^{f} \right] P_{g,t,y,s} + C_{g,y}^{res,curt} \Delta P_{g,t,y,s}^{res} + \sum_{j \in S_j} \left[C_{j,t,y}^{abs} P_{j,t,y,s}^{abs} + C_{j,t,y}^{inj} P_{j,t,y,s}^{inj} \right] + \sum_{j \in S_{jc}} \left[C_{jc,t,y}^{abs} P_{jc,t,y,s}^{abs} + C_{jc,t,y}^{inj} P_{j,ct,y,s}^{inj} \right] + \sum_{u \in S_u} \left[C_{u,t,y}^{nce} \left(P_{u,t,y,s}^{ref} - P_{u,t,y,s}^{nce}\right) + C_{u,t,y}^{ds} \left(\Delta P_{u,t,y,s}^{ds,up} + \Delta P_{u,t,y,s}^{ds,dn}\right) + C_{u,t,y}^{lc} \Delta P_{u,t,y}^{lc} \right] + \sum_{n \in S_n} \left(C_{n,t,y}^{EE} EE_{n,t,y,s} + C_{n,t,y}^{LL} LL_{n,t,y,s} \right) \Bigg] + f_y^{d} \Bigg[\sum_{j \in S_{jc}} \alpha_{jc,y} \left(I_{jc,y}^{E}\left(E_{jc}^{max}\right) + I_{jc,y}^{P}\left(P_{jc}^{max}\right) + FP_{jc,y}^{CO_2} \right) + \sum_{u \in S_u} \alpha_{u,y} \left(I_{u,y} + FP_{u,y}^{CO_2} \right) + \sum_{lc \in S_{lc}^{ac}} \alpha_{lc,y} \left(I_{lc,y} + FP_{lc,y}^{CO_2} + LS_{lc,y} \right) + \sum_{dc \in S_{lc}^{dc}} \alpha_{dc,y} \left(I_{dc,y} + FP_{dc,y}^{CO_2} + LS_{dc,y} \right) + \sum_{zc \in S_{zc}} \alpha_{zc,y} \left(I_{zc,y} + FP_{zc,y}^{CO_2} + LS_{zc,y} \right) + \sum_{bc \in S_{bc}} \alpha_{bc,y} \left(I_{bc,y} + FP_{bc,y}^{CO_2} + LS_{bc,y} \right) \Bigg] \Bigg\} \Bigg\}
$$

Model dimensions:

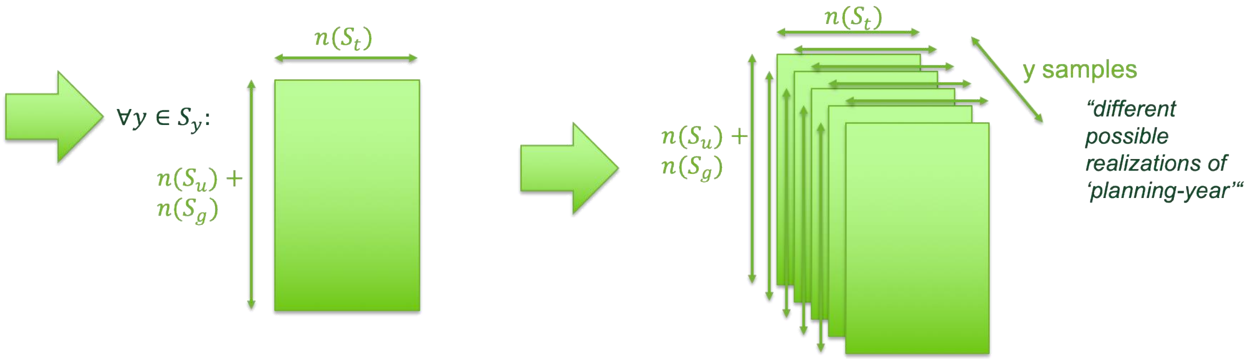
- Set of grid elements (x1000)
- Set of planning hours (8760)
- Set of planning years (2030 – 2040 - 2050)
- Set of planning scenarios

MILP problems will millions of decision variables and constraints

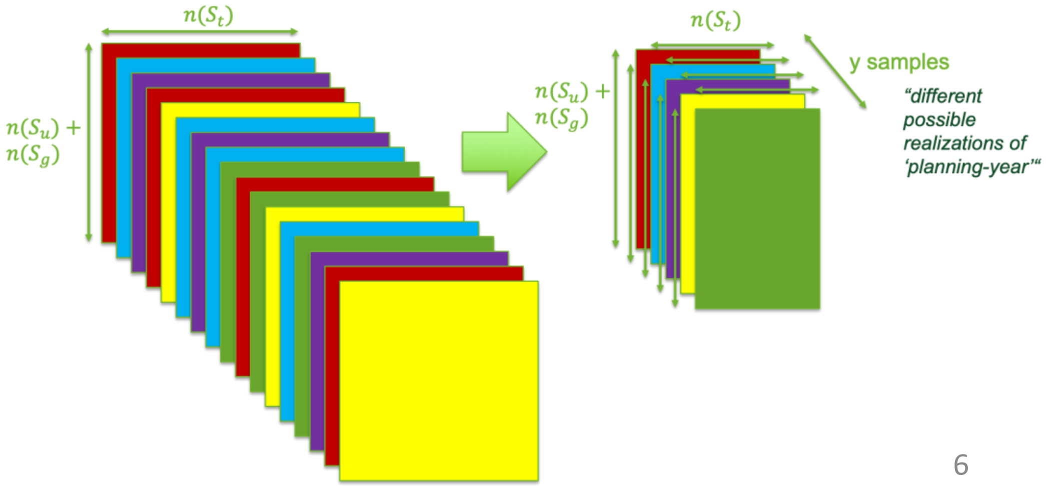
Model decompositions are needed!

Monte Carlo scenario generation and reduction to reduce problem size

- Generation of a high number of MC planning years from a limited set of scenarios with nodal resolution



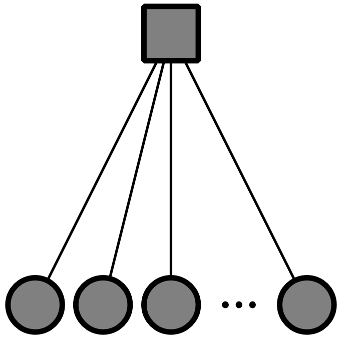
- Reduction of the number of time series based on clustering techniques
- Reduction of the length of the time series (if required for computational reasons



Benders decomposition

Solve smaller problems, but solve them multiple times

main problem



subproblems

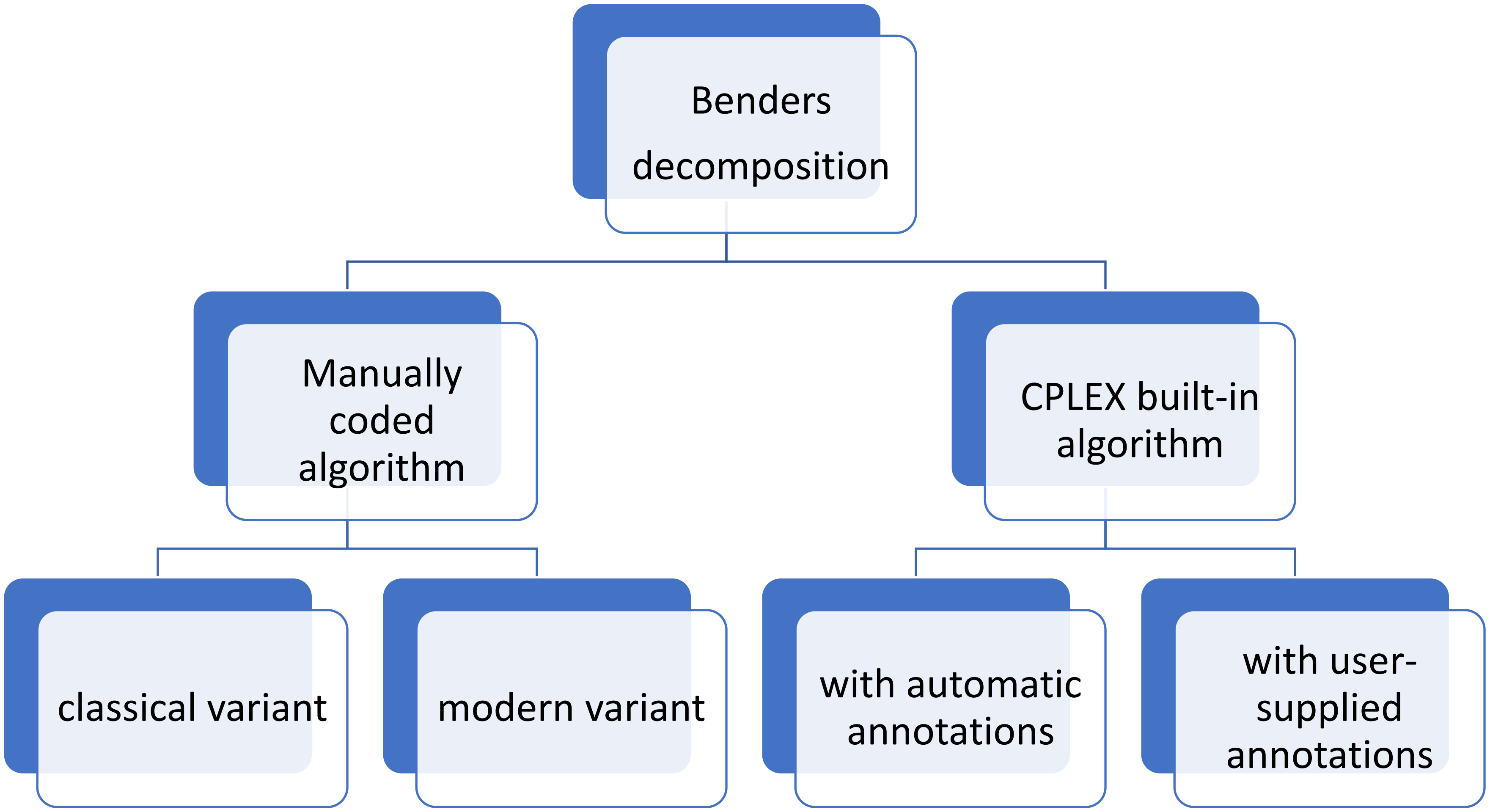
□ MILP

○ LP

- Main MILP problem:
  - optimizes **investments** (binary variables)
  - passes a set of **decisions** (whether to build network components) to subproblems
- 15 LP subproblems (3 years x 5 scenarios):
  - optimize **operations** (continuous variables)
  - provide a **surrogate** of the **operations cost** to the main problem

- The decomposition is exact (not an approximation)
- It can be stopped at any time, providing an approximate result

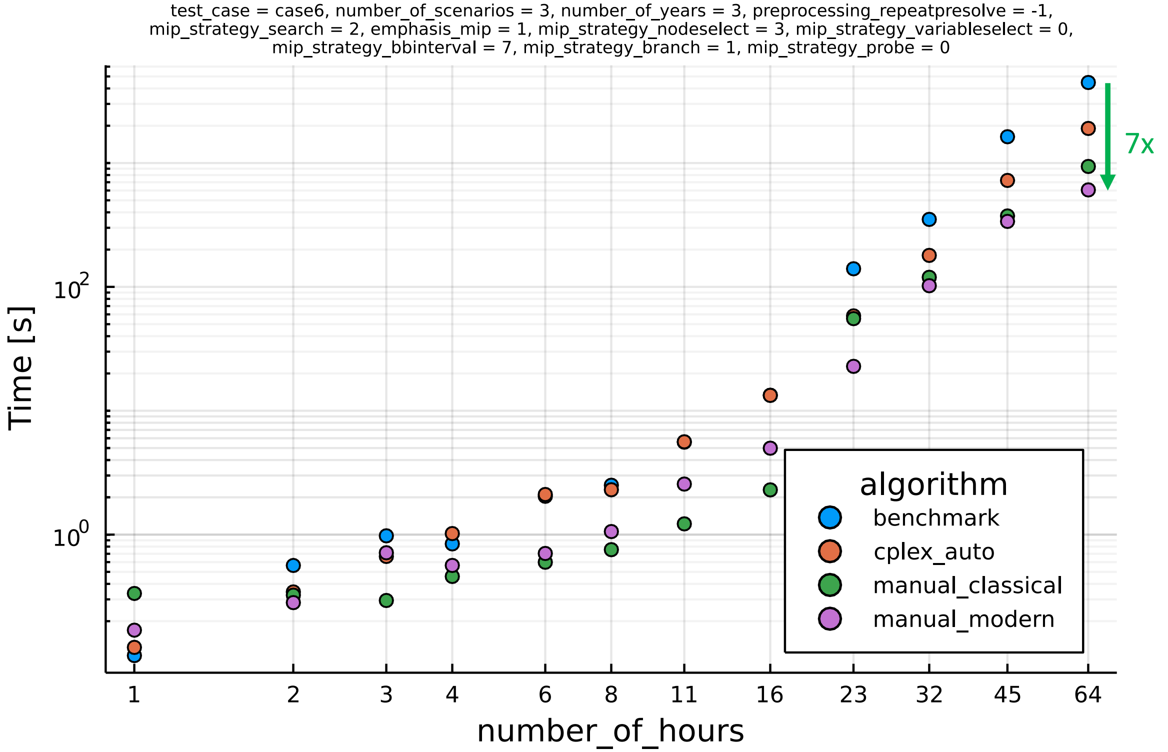
Implementation alternatives

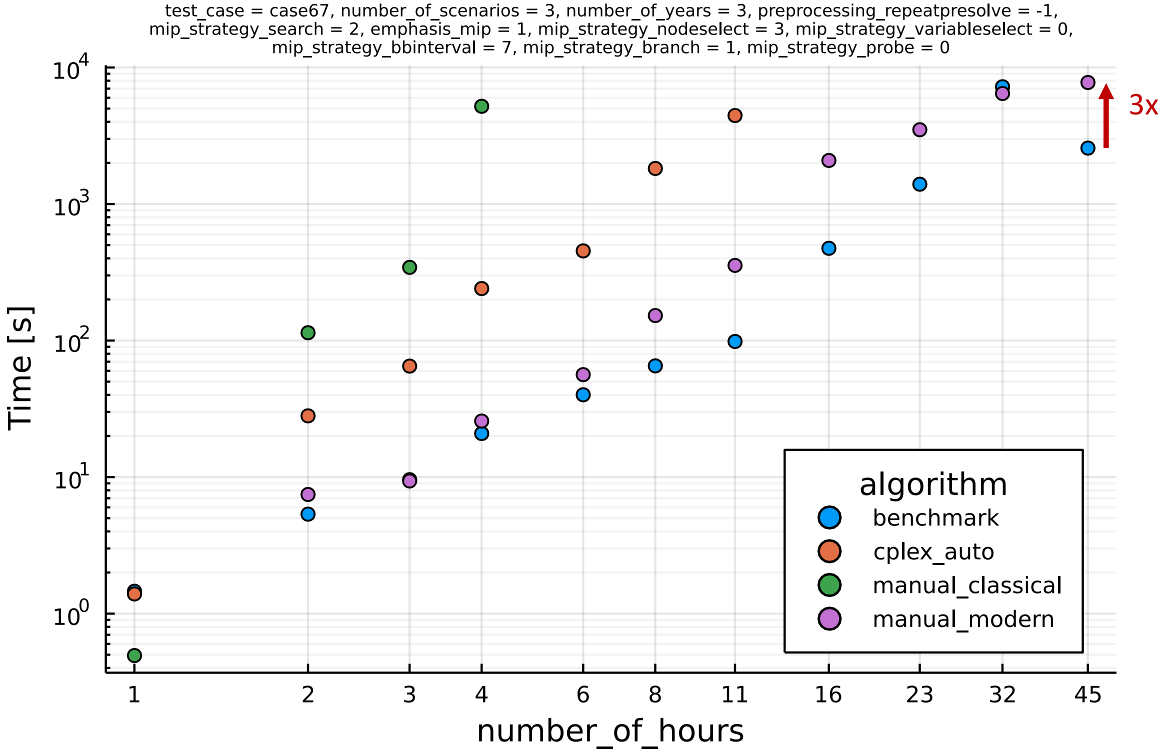


Comparison of different implementations

The performance of the different variants is very case dependent

Performance of decompositions vs. single shot MILP problem (benchmark) on two different networks:



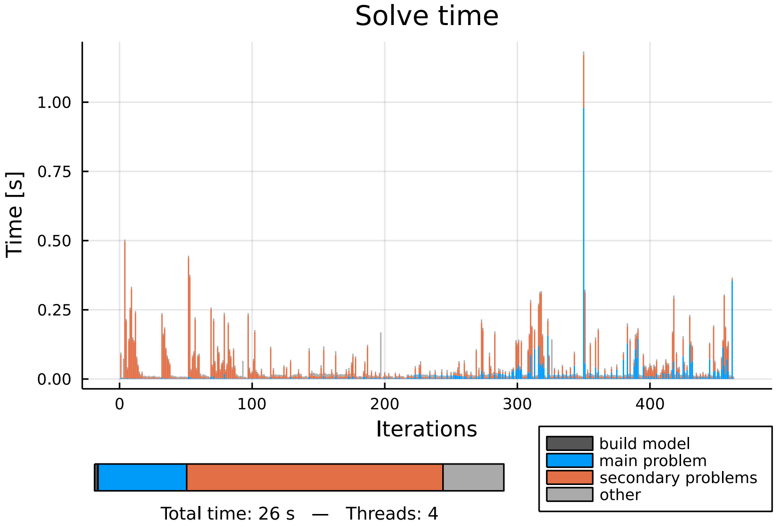


Performance of modern Benders decomposition

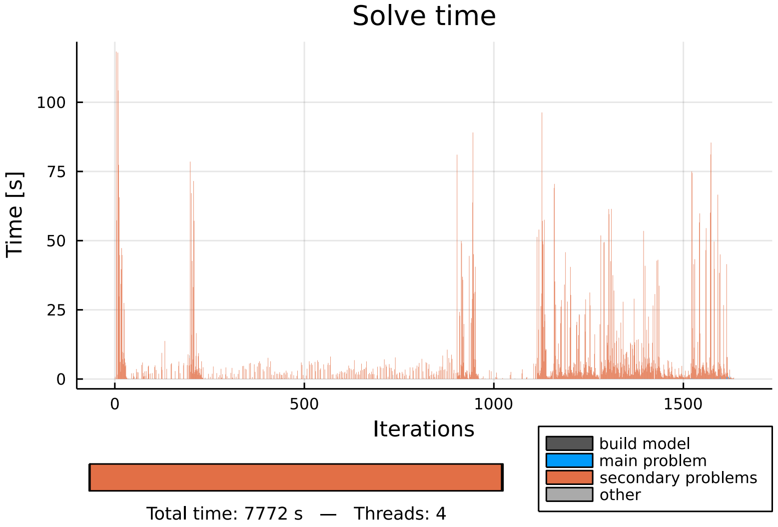
How is CPU time split between main problem and subproblems?

Comparison with different number of hours:

4 hours



45 hours



- As the size of the subproblems increases:
  - Time per iteration grows more than linearly
  - The number of iterations grows less than linearly
- Net effect: most of the time is spent on secondary problems

Takeaways

- The **time** of each iteration depends on secondary problem settings

  ⇒ Tune the secondary problem solver
- The **number** of iterations depends mostly on main problem setting

  ⇒ Tune the main problem solver

Preliminary conclusions

- Solver tuning is essential both for decomposed and single shot solutions
  - Challenge: finding suitable tuning parameters for different test cases

- The effect of an improved parallelization has to be investigated. It may have a beneficial effect to the simulation time.
  - Tests: 9 (3x3) subproblems on 4 cores ⇒ 3 passes
  - Final configuration: 15 (5x3) subproblems on 16 cores ⇒ 1 pass

- So far, all tests have been carried out on single machines with limited performance; performance on more powerful machines to be verified

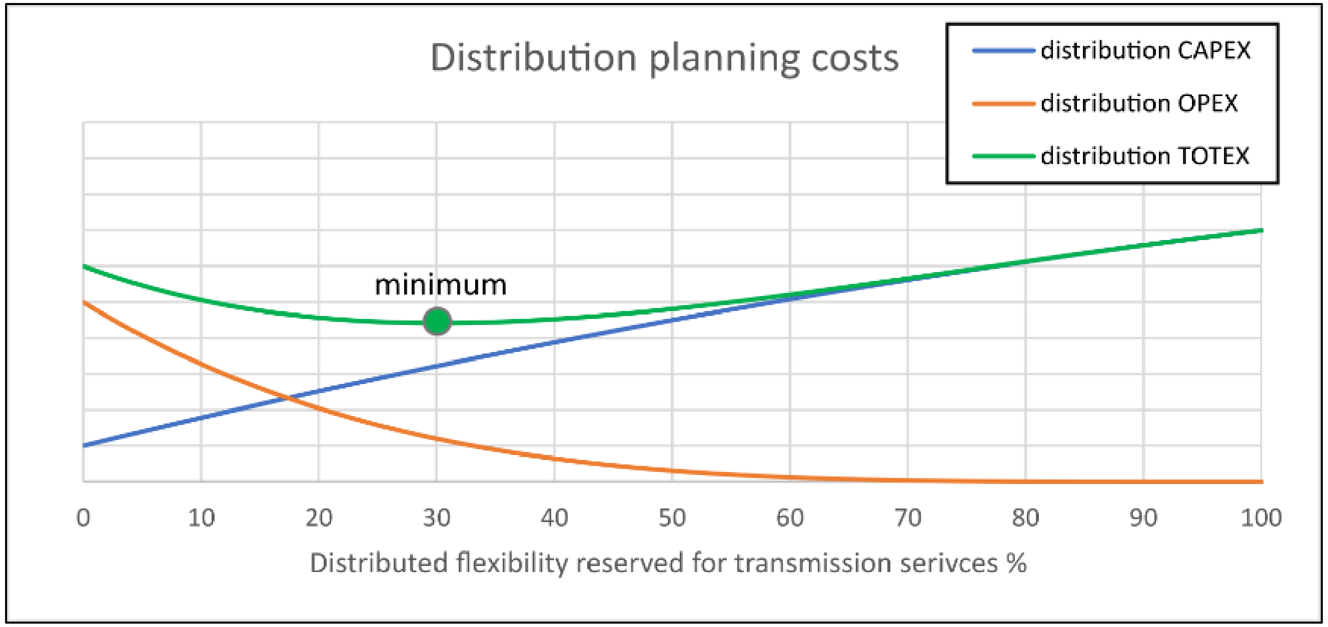
Optimization of distribution network planning

(taking into account that local flexibility can be reserved for transmission services)

FlexPlan

Literature and experience demonstrates that **exploiting local flexibility can reduce investments in reinforced lines and transformers**, potentially leading to lower planning costs.

For this reason, the EU directive 2019/944 states that (art.32.3) *the network development plan shall also include the use of demand response, energy efficiency, energy storage facilities or other resources that the distribution system operator is to use as an alternative to system expansion*.



CAPEX capital expenditure
(mostly related to new/reinforced network asset)

OPEX operational expenditure
(mostly related to the operation of flexible resources)

TOTEX CAPEX+OPEX

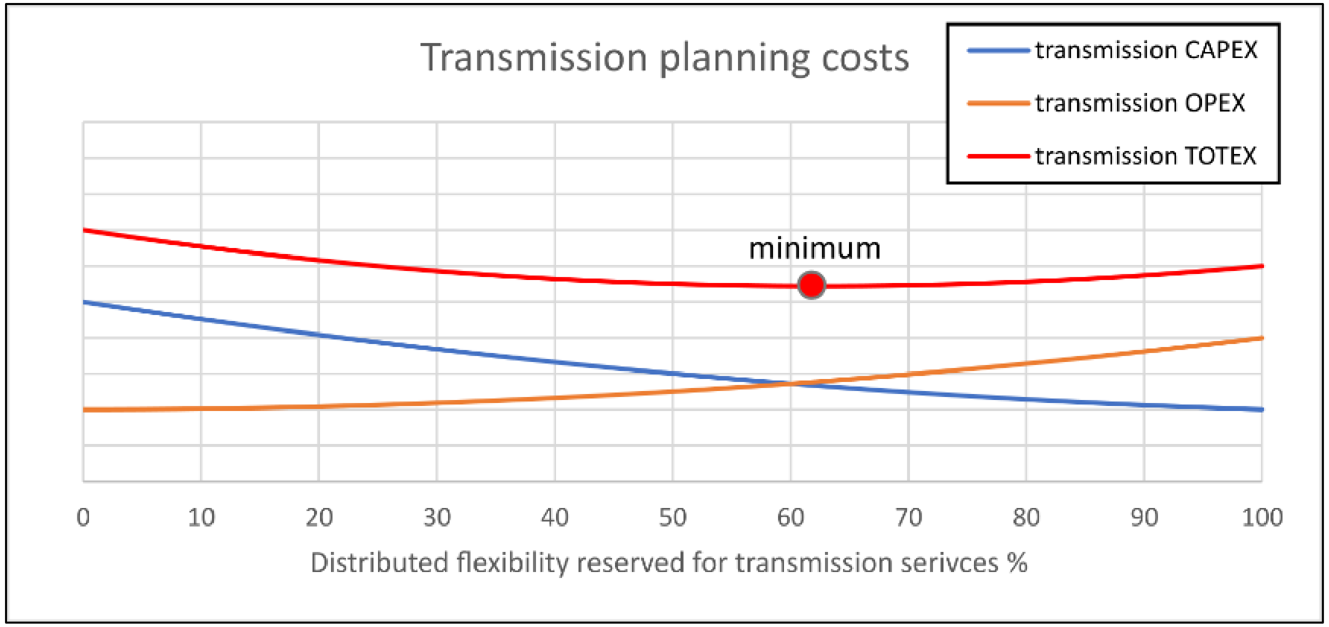
Optimization of distribution network planning

(taking into account that local flexibility can be reserved for transmission services)

FlexPlan

However, the resulting DSO-TSO share of distribution flexibility might be **non-optimal** from the transmission system perspective.

For this reason, the EU directive 2019/944 states that (art.40.5) *transmission system operators (shall) procure such services from providers of demand response or energy storage and shall promote the uptake of energy efficiency measures, where such services cost-effectively alleviate the need to upgrade or replace electricity capacity and support the efficient and secure operation of the transmission system*



CAPEX capital expenditure
(mostly related to new/reinforced network asset)

OPEX operational expenditure
(mostly related to the operation of flexible resources)

TOTEX CAPEX+OPEX

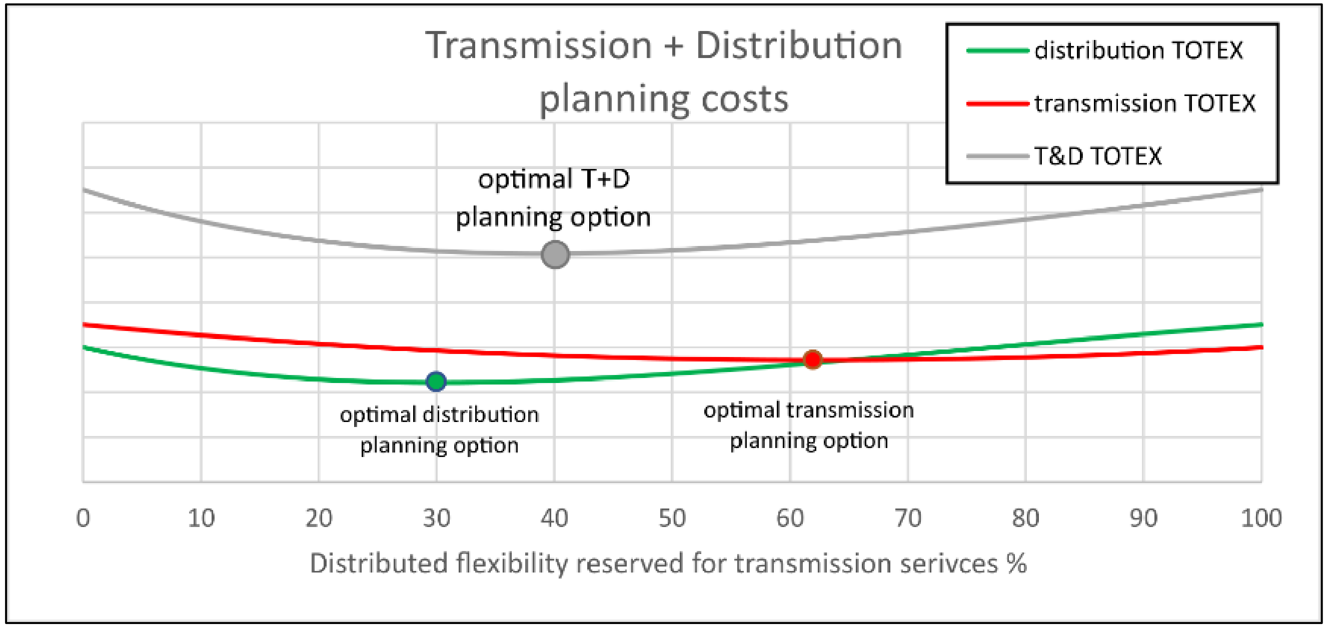
Collaborative planning of transmission and distribution network

FlexPlan

For this reason**, TSO and DSO should coordinate the exploitation of distribution flexibility**, which can be beneficial for the planning of both the networks and, eventually, the entire system.

Indeed, the EU directive 2019/944 states that

- *The distribution system operator shall consult all relevant system users and the relevant transmission system operators on the network development plan.* (art.32.4)



A **collaborative** (integrated) **planning of both transmission and distribution systems** allows the identification of the **global optimum**, which does not generally coincide with the ones resulting from a separated optimization limited to the perimeter of DSO and TSO respectively.

Planning of distribution network

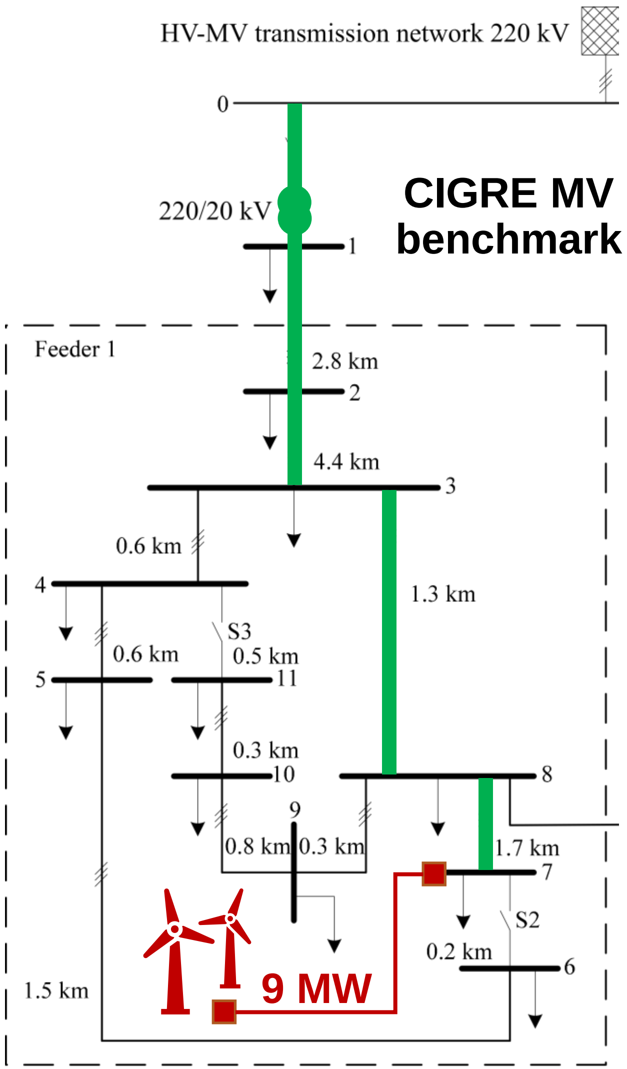
FlexPlan

Flexible demand/generation/storage can provide a multitude of services and distribution system operators could exploit them as **alternative planning option** with respect to conventional grid reinforcement.

min **CAPEX**

such that

- distribution grid constraints are respected



Planning of distribution network with flexibility

FlexPlan

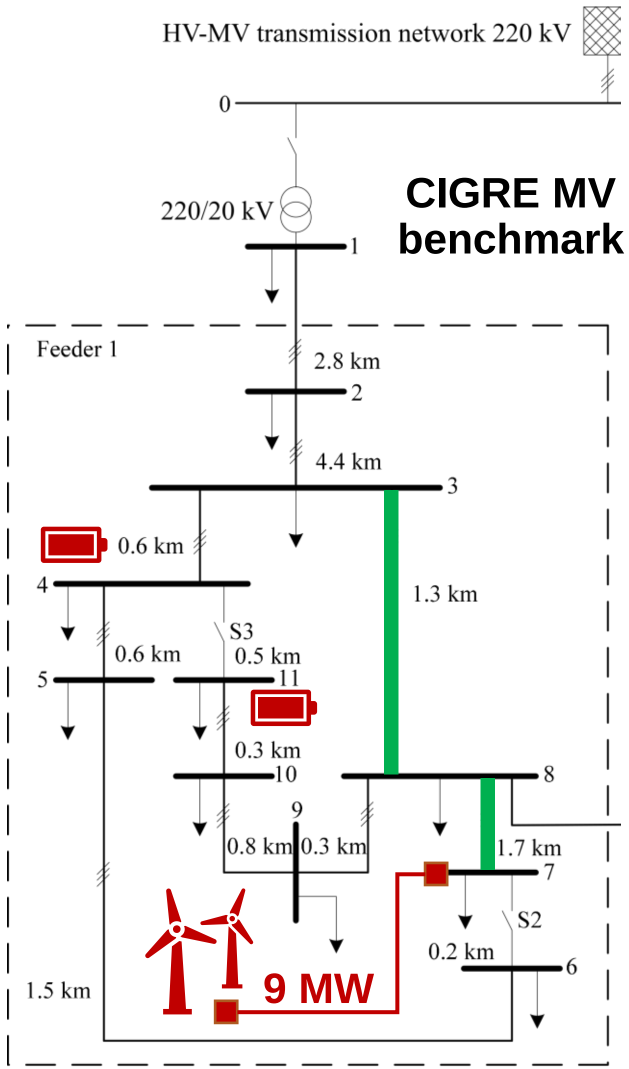
Flexible demand/generation/storage can provide a multitude of services and distribution system operators could exploit them as **alternative planning option** with respect to conventional grid reinforcement.

min **CAPEX**+**OPEX**

such that

- distribution grid constraints are respected

The engagement of existing/new flexible resources and the related **operational expenditure** can be competitive with respect to the reinforcement of grid sections.



Planning of transmission network with flexibility

FlexPlan

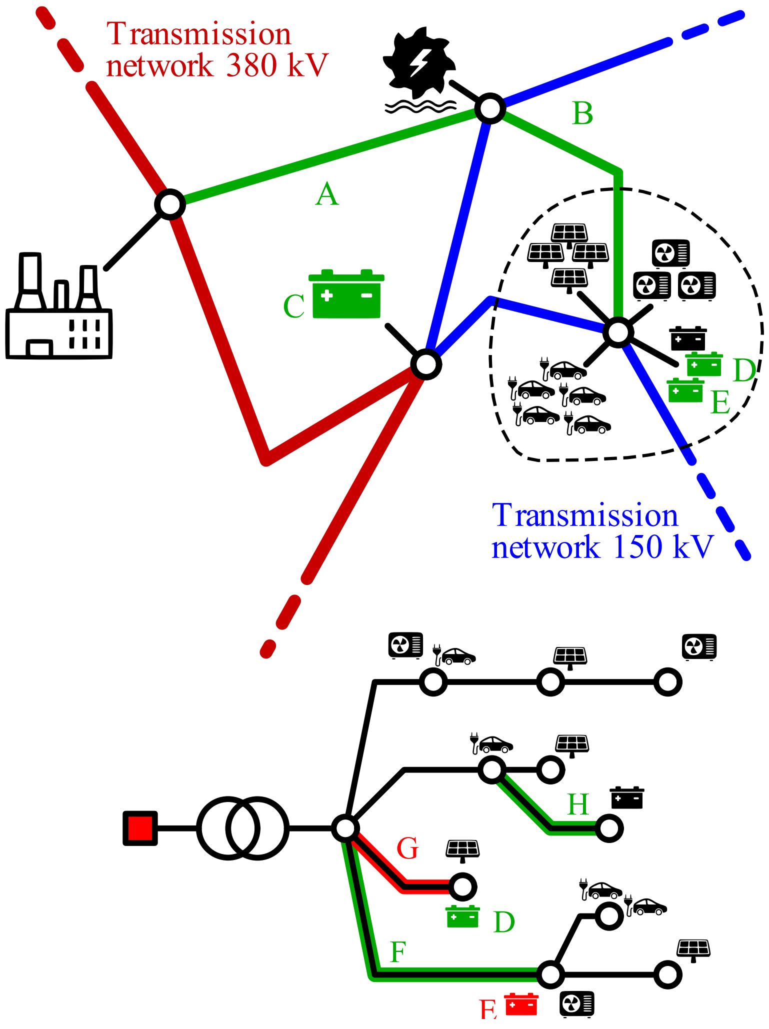
Flexible demand/generation/storage can provide a multitude of services and <u>transmission</u> system operators could exploit them as **alternative planning option** with respect to conventional grid reinforcement.

min **CAPEX+OPEX**

such that

- <u>transmission</u> grid constraints are respected
- <u>distribution</u> grid constraints are respected

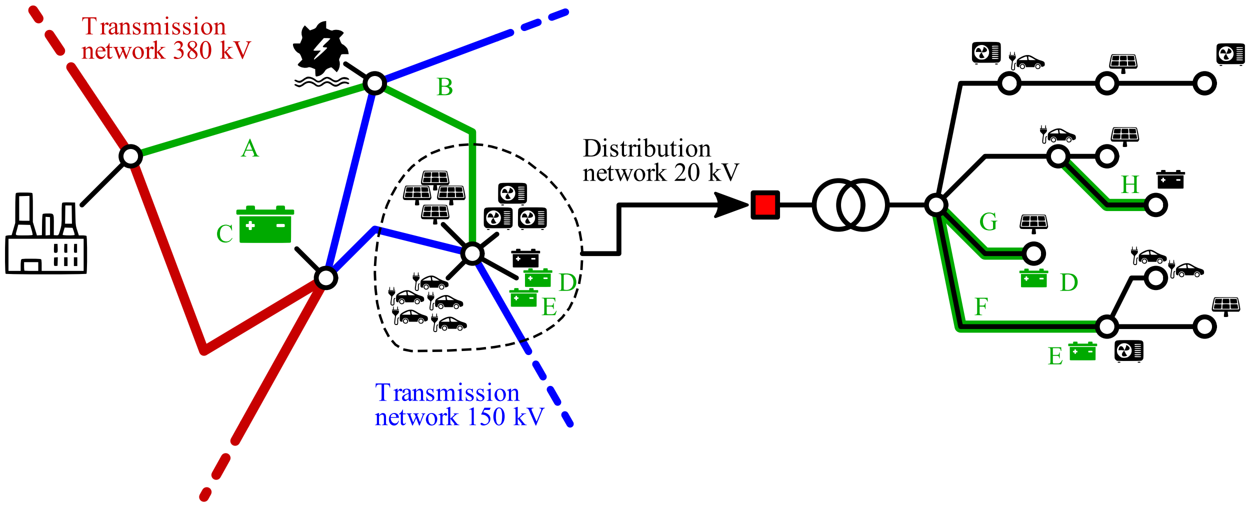
A large portion of the **available flexibility** is expected to be located at **distribution level**, and its exploitation for transmission services needs to consider also lower voltage systems.



Joint Transmission and Distribution Planning

FlexPlan

Optimal planning (for the entire system) needs the simultaneous consideration of both distribution and transmission requirements



⚠ Unbearable optimization problem for state-of-the-art of mathematical solvers

- Model complexity (DC+AC OPF)
- Dimension of the problem (number of variables and long-time horizons)

⚠ Lack of transparency and standards to exchange information among transmission and distribution system operators

Decomposition of the joint transmission and distribution planning

The Italian case

FlexPlan

Transmission network

The Italian regional case consists of a (simplified) transmission network which counts:

- 4160 AC buses
- 5165 AC lines
- 303 transformers
- 20 DC buses
- 26 DC lines (borders excluded)
- 2046 primary substations

(Synthetized) **distribution system**

- 3890 HV/MV transformers
- 774,739 AC buses and 774,738 AC lines

Sections of distribution network subject to overloading and/or voltage issues

- 2030 → overloading: 39% voltage issues: 0.10%
- 2040 → overloading: 55% voltage issues: 0.23%
- 2050 → overloading: 72% voltage issues: 2.39%

Reduction to only congested areas/feeders

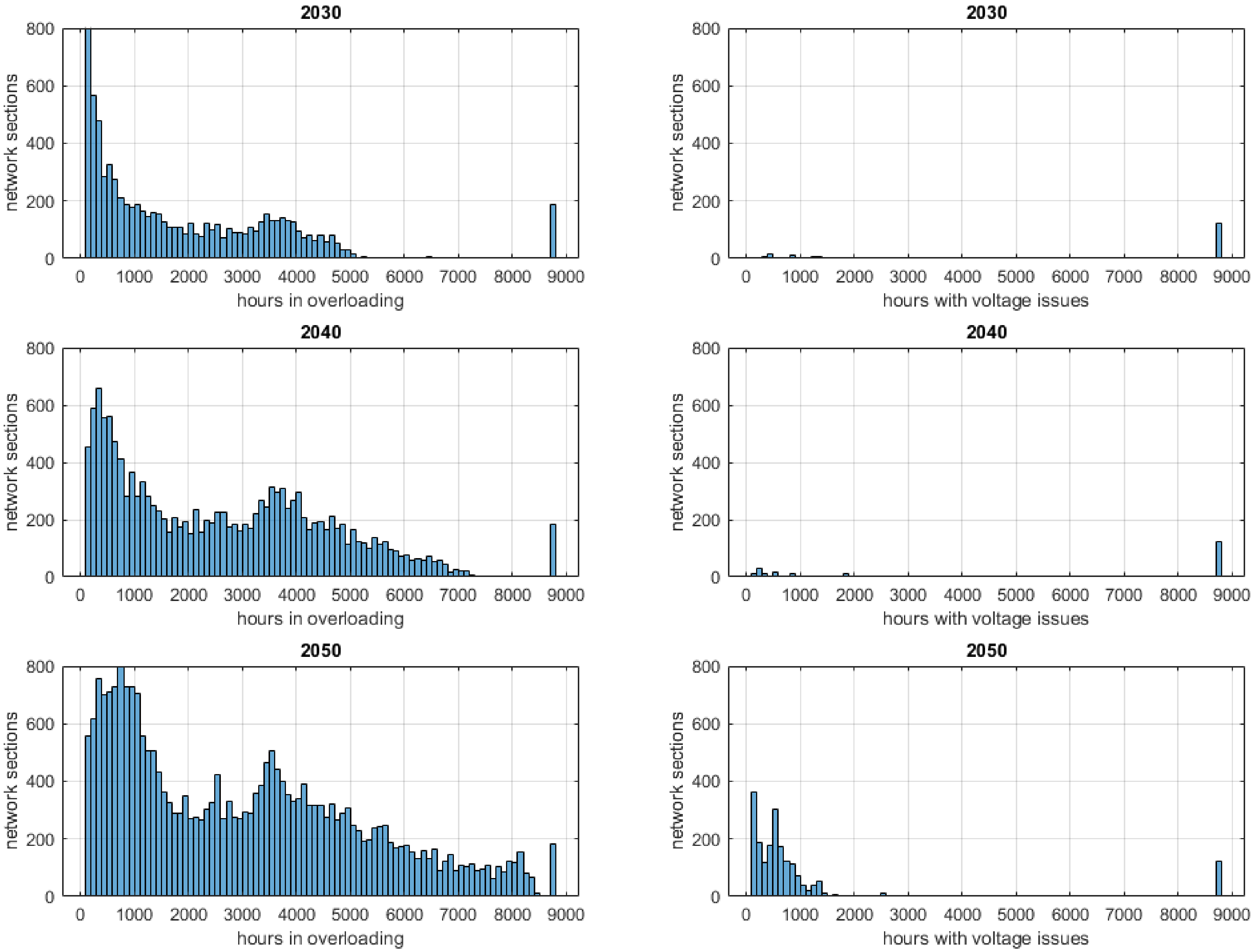
- 744,739 AC buses have been reduced to 68,297 AC buses (reduction to 8.82% of the original size)

The Italian case

Distribution network

Amount of expected congestions and their duration over the synthetized distribution system of Italy.

Thanks to the reduction, each transformer feeds averagely 18 MV nodes (200 before reduction)



Decoupled and collaborative T&D Planning

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Transmission and distribution **separation in planning routines** is still a requirement, but procedures can be updated in order to consider the <u>potential of power/energy flexibility outside of the planning perimeter</u>.

For what concerns **distribution network**, there is a **<u>planning conflict</u>**

Minimization of the distribution planning cost

min **CAPEX+OPEX**

such that

- distribution grid constraints are respected

Maximization of local flexibility for transmission services

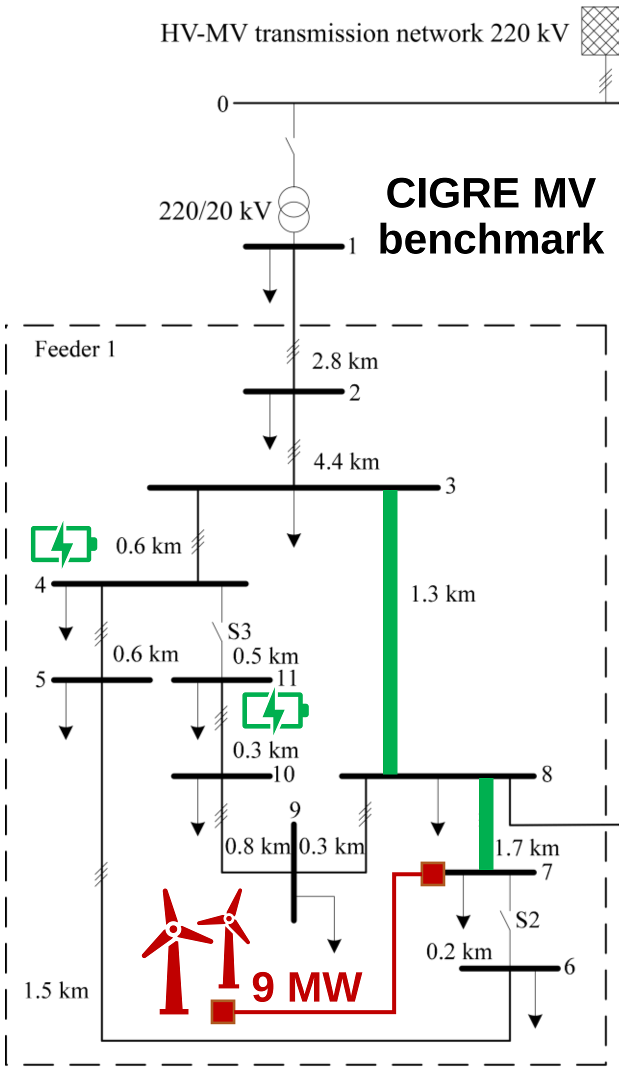
max **flexible power exchange btw. T&D**

such that

- distribution grid constraints are respected
- <u>CAPEX and OPEX are disregarded</u>

Two distribution planning options

FlexPlan

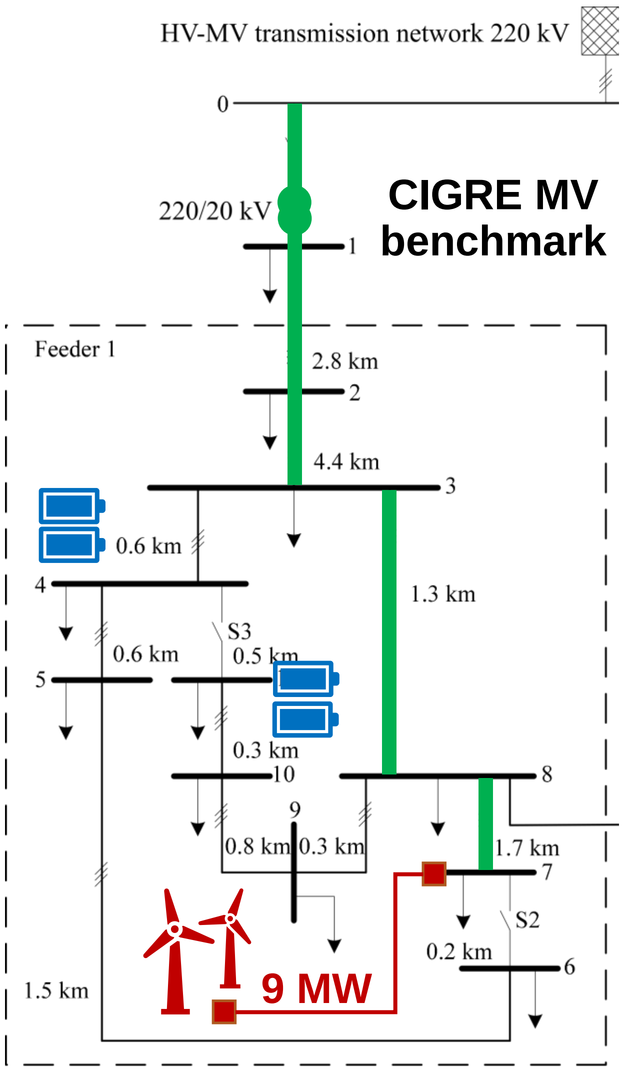


Minimization of the distribution planning cost

- 3 km reinforced lines
- Storage units provide local congestion management services
- CAPEX+OPEX = **691 k€**

Maximization of local flexibility for transmission services

- 10.2 km reinforced lines and substituted distribution transformer
- Local storage units **enhanced** and available for transmission services
- CAPEX = **2,792 k€** (OPEX=0)



More distribution planning options

FlexPlan

More options can be explored in order to determine **trade-offs** between minimum planning costs and maximum flexibility for transmission services

	Investment costs (on local network) [k€]	Operation costs (distribution services) [k€]	Equivalent storage flexibility for transmission services
✓	446	245	1.0 MW / 2.0 MWh
✓	1,006	245	2.0 MW / 4.0 MWh
✗	1,566	245	2.0 MW / 4.0 MWh
✗	1,706	245	2.0 MW / 4.0 MWh
✓	2,792	0	3.6 MW / 7.2 MWh

intermediate options

max **flexible power exchange btw. T&D**

such that

- distribution grid constraints are respected
- CAPEX <u>is limited</u>

Collaborative planning of transmission and distribution network

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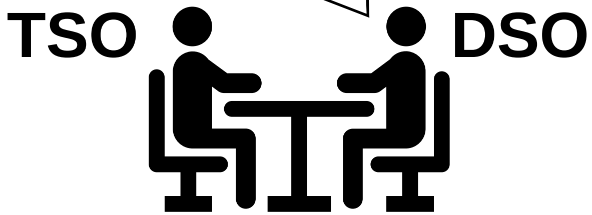
Investment costs (on distrib. network) [k€]	Equivalent storage flexibility for transmission services
446	1.0 MW / 2.0 MWh
1,006	2.0 MW / 4.0 MWh
2,792	3.6 MW / 7.2 MWh



Simple and efficient cooperation between system operators:

- The identified distribution planning options can be negotiated with a limited exchange of standard and non-sensitive information

Distribution network can be seen as an equivalent storage unit which can be exploited for services addressed to transmission system planning/operation.

The procedure can be repeated for any typology of flexibility resource (demand response, generation curtailment, etc.)

Collaborative planning of transmission and distribution network
Collaborative T&D Planning

Investment costs (on distrib. network) [k€]	Equivalent storage flexibility for transmission services
446	1.0 MW / 2.0 MWh
1,006	2.0 MW / 4.0 MWh
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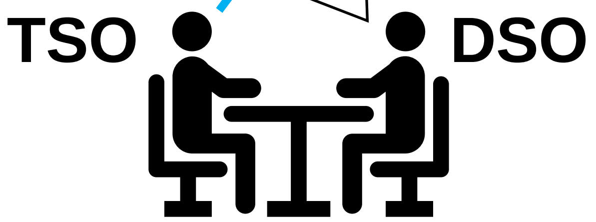

Transmission system operator can run its own planning routines (separately) by considering the proposed options and related costs.

min **CAPEX+OPEX**

such that

- transmission grid constraints are respected
- distribution grid planning options are considered

Collaborative planning of transmission and distribution network
Conclusion

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The procedure is currently under validation tests, is characterized by a non-negligible **complexity** and introduces **approximations**.

However, it offers **significant advantages** for a **global optimization** of distribution and transmission systems. It guarantees a **separated** (decoupled) **management** of the transmission and distribution planning problem

- Potential of distributed flexible resources maximally exploited
  - Not only local services, but lower voltage levels flexibility supports transmission network planning too
- Reduced computational burden
  - Possible solutions for distribution planning are managed separately from the transmission problem
- Simple and efficient **cooperation between system operators**
  - Procedure in line with EU directive 2019/944

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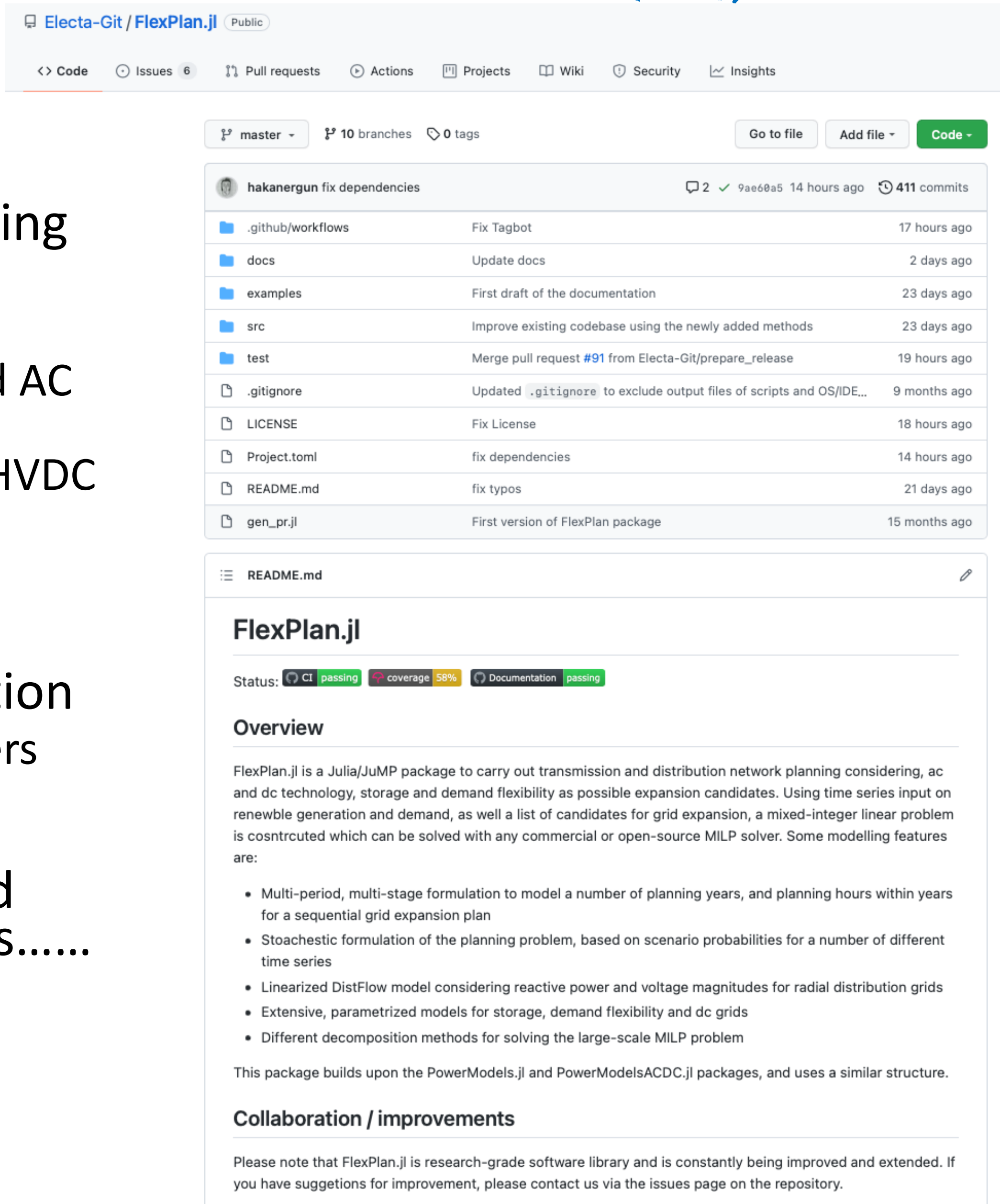
Summary

- A variety of different decompositions have been implemented and tested on proof-of-concept test cases
- The performance of the decomposition methods depend strongly on the analysed test cases
- Correct tuning of the optimization solvers are essential for single-shot or decomposed solution
- Temporal decomposition of the planning model, e.g., division in months / weeks as well as T&D network decomposition are inevitable for solving the problem for realistic networks

FlexPlan.jl released!

- Open-source Julia/JuMP implementation of the planning model, including:
  - A variety of different problem types
  - Two distinct network formulations for meshed AC/DC and AC radial distribution grids
  - Parametrised models for demand flexibility, storage and HVDC connections
  - Different model decompositions
- Serves as a testbed for the planning tool implementation
  - Easy to extend, easy to use a variety of optimisation solvers
- Current version v0.1.1, further improvements planned w.r.t. to tool documentation, problem types, examples……
- More information under: https://github.com/Electa-Git/FlexPlan.jl



Thank you…

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FlexPlan

RSE Ricerca Sistema Energetico
enel
e-distribuzione
Electricity Coordinating Center
ELES
KU LEUVEN
N-SIDE OPTIMIZING YOUR DECISIONS
R&D NESTER
REN
SINTEF
tecnalia Inspiring Business
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