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DYMASOS – Dynamic Management of Physically Coupled Systems of Systems

Technical work in WP2 and WP5

UNIZG-FER

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WP2 Work Plan (Task 2.4)

- Analysis of applicability and estimation of computational complexity of different uncertainty management strategies for SoS. (M15 – M20)
- Development of scenario-based robust dynamic management for SoS. (M18 – M24)
- Development of a stochastic methodology for the coordination of systems using SoS model subject to Gaussian distribution of uncertainties and disturbances. (M21 – M27)
- Development of a stochastic approach to the coordination of systems using SoS model subject to uncertainties and disturbances with arbitrary distributions, using both explicit and scenario-based approach. (M24 – M30)
- Development of methods for representation of the resulting SoS performance in stochastic sense, for merging with its neighboring systems. (M30 – M33)

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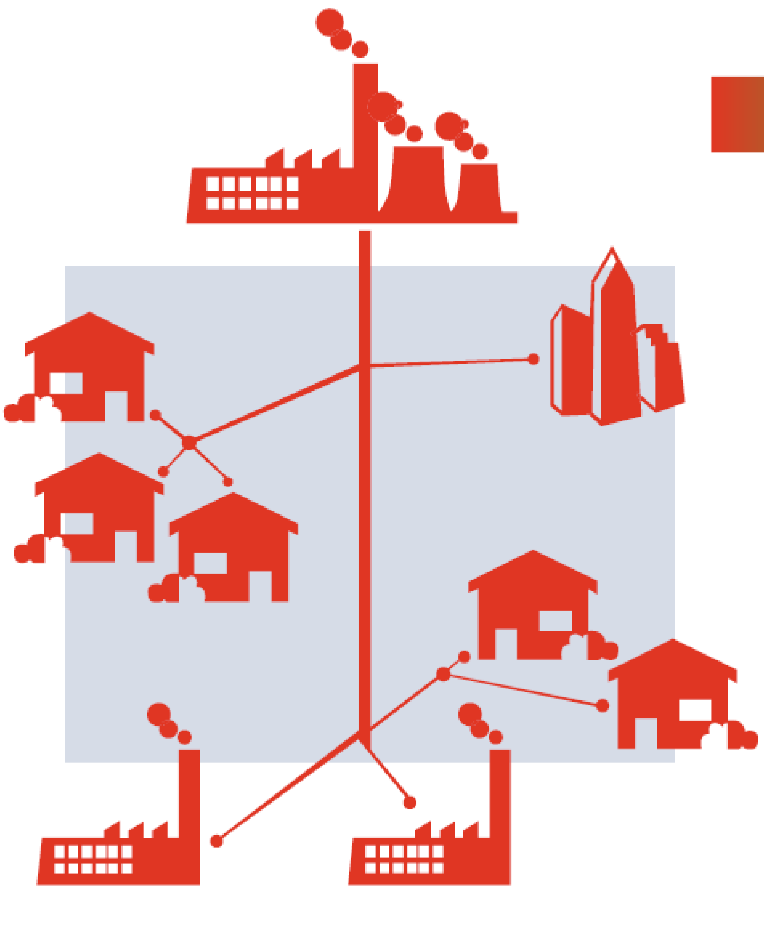
WP5 Work Plan (Task 5.2)

- Mathematical modeling of the case studies. (M07-M18)
- Implementation of the models. (M09-M18)
- Derivation of simplified models and implementation in MATLAB. (M12-M22)
- **Documentation. (M22-M24)**

Motivation



Simulation framework – a quick reminder

- Requirements:
  - MATLAB (tested on version 8.3.0.532, R2014a)
  - Windows (tested on Windows 8.1), should work on Mac OS X, Linux (e.g. Ubuntu), and older Windows (7, XP)
  - SimPowerSystems – standard Simulink toolbox for simulation of electrical power systems
  - For the OPF routines additional MATLAB packages are needed:
    - YALMIP
    - A dedicated solver (e.g. SeDuMi, SDPT3, Mosek, CPLEX)
- Advantages:
  - Out-of-box integration with MATLAB
  - Dynamic simulation of power system (phasor, continuous, discrete)
  - Many dynamic models already implemented in the toolbox

Simulation framework – key features

- Automatic generation of simulation models
  - The development of (large-scale) power network models is very tedious, time-consuming and prone to human error
  - A network is already described in a structured file format
  - Write MATLAB script/function that can interpret a network description and automate the creation of the simulation model
- Automatic initialization
  - Initialization of the dynamic simulation model of the network
  - Use OPF solution as an initial steady state operating point
- Full advantage of SimPowerSystems model libraries

Constraints and target (1)

- Objective: minimize total active power losses over a prediction horizon N

$$\sum_{t=0}^{N} \sum_{i \in \mathcal{V}} P_{i,t}^{I}$$

- Power balance constraints

$$P_{i,t}^{I} = P_{i,t}^{G} - P_{i,t}^{D} = \sum_{j \in N(i)} \delta_{ij,t} P_{ij,t} \,, \forall i \in \mathcal{V}$$

$$Q_{i,t}^{I} = Q_{i,t}^{G} - Q_{i,t}^{D} = \sum_{j \in N(i)} \delta_{ij,t} Q_{ij,t} \,, \forall i \in \mathcal{V}$$

$$P_{ij,t} = g_{ij} V_{i,t}^{2} - V_{i,t} V_{j,t} \left(g_{ij} \cos(\theta_{ij,t}) + b_{ij} \sin(\theta_{ij,t}) \right)$$

$$Q_{ij,t} = -b_{ij} V_{i,t}^{2} + V_{i,t} V_{j,t} \left(b_{ij} \cos(\theta_{ij,t}) - g_{ij} \sin(\theta_{ij,t}) \right)$$

Constraints and target (2)

- Voltage constraints

$$\underline{V} \leq V_{i,t} \leq \overline{V}, \forall i \in \mathcal{V}$$

- Current constraint

$$I_{ij,t}^2 = \delta_{ij,t}\left(g_{ij}^2 + b_{ij}^2\right)\left(V_{i,t}^2 + V_{j,t}^2 - 2V_{i,t}V_{j,t}\cos\left(\theta_{ij}\right)\right) \leq \overline{I}_{ij}^2$$

- Battery storage constraints

$$x_{i,t+1}^{BAT} = x_{i,t}^{BAT} - \eta_i P_{i,t}^{BAT},$$

$$\eta_i = \begin{cases} \eta_i^c, & P_{i,t}^{BAT} < 0 \; (charging) \\ 1/\eta_i^d, & otherwise \; (discharging) \end{cases}$$

Constraints and target (3)

- Battery storage constraints (cont'd)

$$\underline{X}_i \leq x_{i,t}^{BAT} \leq \overline{X}_i$$

$$\underline{P}_i^{BAT} \leq P_{i,t}^{BAT} \leq \overline{P}_i^{BAT}$$

$$\underline{Q}_i^{BAT} \leq Q_{i,t}^{BAT} \leq \overline{Q}_i^{BAT}$$

- Generator constraints

$$x_{i,t+1}^G = Ax_{i,t}^G + Bu_{i,t}^G$$

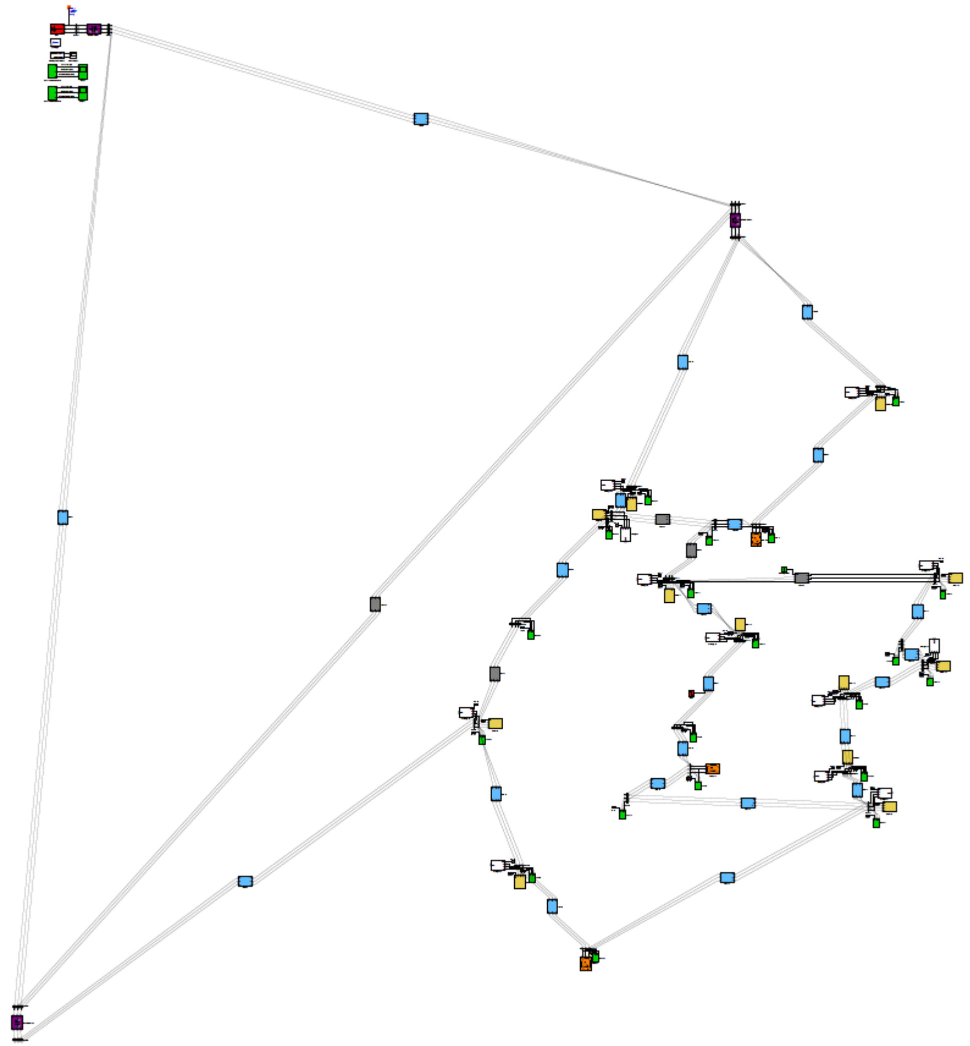
$$y_{i,t}^G = Cx_{i,t}^G + Du_{i,t}^G$$

$$\underline{P}_i^G \leq P_{i,t}^G \leq \overline{P}_i^G$$

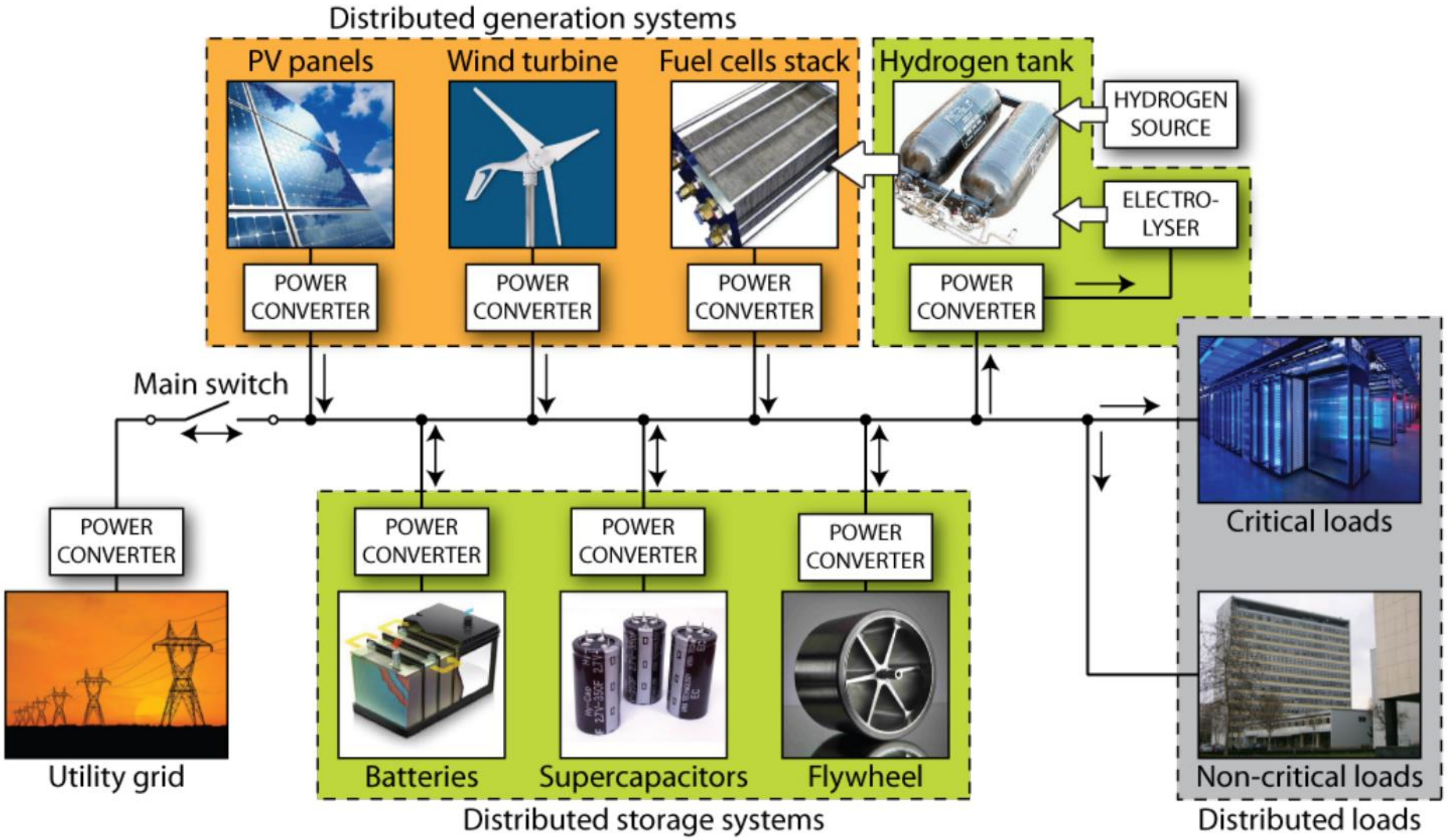
$$\underline{Q}_i^G \leq Q_{i,t}^G \leq \overline{Q}_i^G$$

Simulation scenarios

- Line fault
- Generator outage
- Major change of the overall system demand



Microgrid



Distributed generation systems
PV panels
Wind turbine
Fuel cells stack
Hydrogen tank
HYDROGEN SOURCE
ELECTRO-LYSER
POWER CONVERTER
POWER CONVERTER
POWER CONVERTER
POWER CONVERTER
Main switch
POWER CONVERTER
POWER CONVERTER
POWER CONVERTER
POWER CONVERTER
Critical loads
Utility grid
Batteries
Supercapacitors
Flywheel
Non-critical loads
Distributed storage systems
Distributed loads

Objective function and constraints

- Economic criterion

$$J(u, x_0, c, d) = -c_N \overline{x}_N + \sum_{k=0}^{N-1} c_k P_k^G \Delta T$$

$$c_N = \frac{p_{pct}}{100} \max_k c_k\,, \qquad t \leq k \leq t + N - 1$$

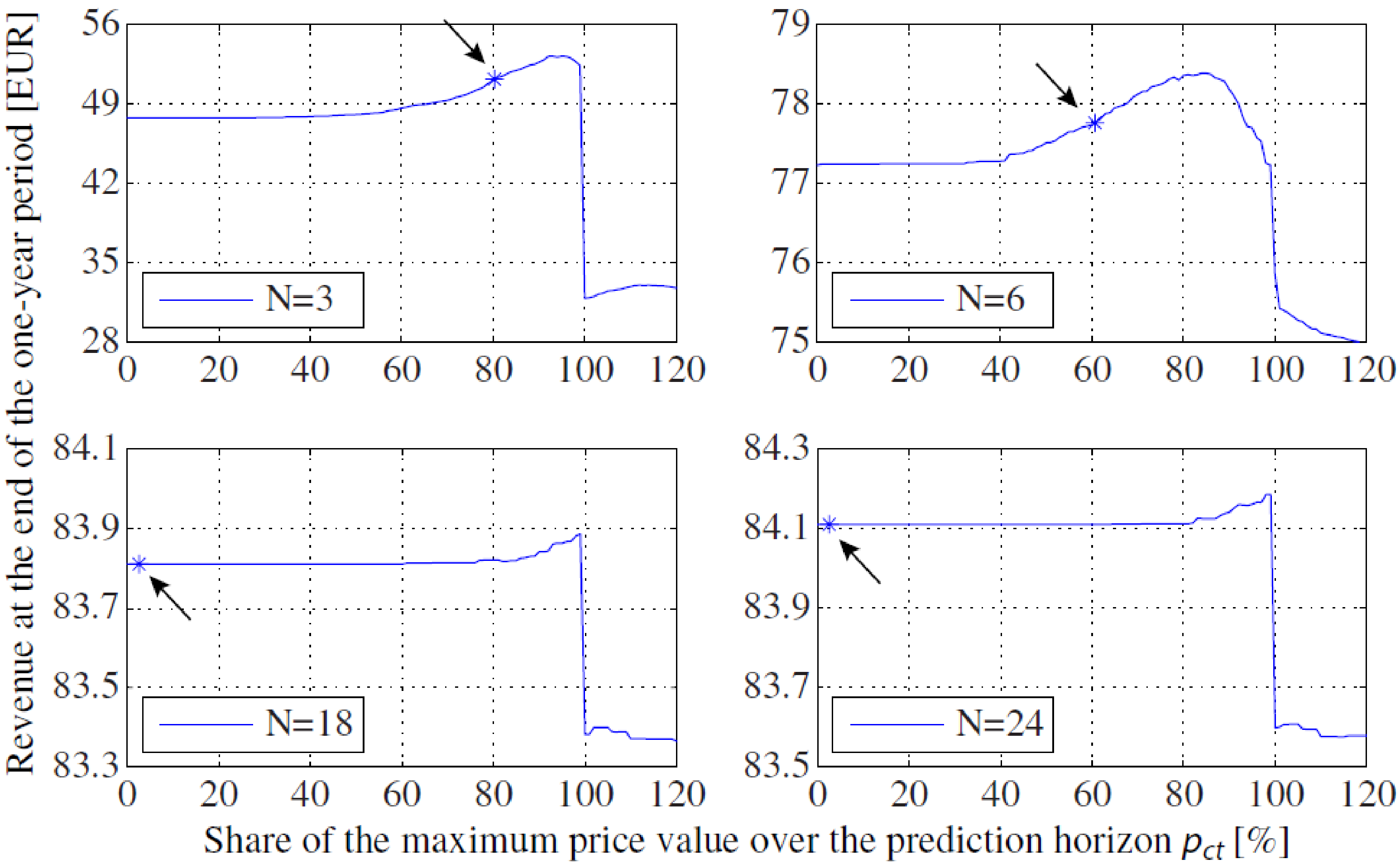
- Constraints

$$x_{min} \leq x_k \leq x_{max}$$
$$u_{min} \leq u_k \leq u_{max}$$
$$P_{min}^G \leq P_k^G \leq P_{max}^G$$

- LP formulation

$$\min_u \boldsymbol{f}^T \boldsymbol{u} + const$$
$$s.t.\, \boldsymbol{E}_x x_0 + \boldsymbol{E}_u \boldsymbol{u} + \boldsymbol{E}_d \boldsymbol{d} \leq \boldsymbol{g}$$

Penalization of residual storages state



Power distribution system

- Sources of uncertainty:
  - Power demand prediction
  - Uncontrollable generation prediction (e.g. wind, sun)
- Robust Optimal Power Flow (ROPF)
  - Compute optimal power references such that constraints are robustly satisfied for all possible realizations of uncertainty
- Objective
  - E.g. nominal objective (total system losses)
- Constraints
  - Must be satisfied for every realization of uncertainty

Exponential growth of num. of constraints

- Let $P_i^D = P_{i0}^D + \Delta P_i^D, \Delta P_i^D \in \left[\underline{\Delta P_i^D}, \overline{\Delta P_i^D}\right]$
- Then $\mathbf{P^D} = [P_1^D \quad P_2^D \quad \dots \quad P_n^D]^T \in \mathbb{W}_P^D$
  - $\mathbb{W}_P^D = \mathrm{co}\{\mathbf{P_1^D}, \mathbf{P_2^D}, \dots, \mathbf{P_m^D}\}$, where $\mathbf{P}_i^\mathbf{D}$ is one extreme realization of demand uncertainty
- The same goes for reactive power demand $\mathbf{Q^D}$
- Constraints must be satisfied for every combination of extreme realizations $\mathbf{P_i^D}$ and $\mathbf{Q_i^D}$!
- The number of constraints grows exponentially with number of nodes in the network!

Tube MPC (1)

- System dynamics:
  $$x^+ = Ax + Bu + w, \qquad (x, u) \in \mathbb{X} \times \mathbb{U}, \qquad w \in \mathbb{W}$$
- Idea: Separate control into two parts
  1. A portion that steers the nominal system to the origin
     $z^+ = Az + Bv$
  2. A portion that compensates for deviations from the nominal system $e^+ = (A + BK)e + w$
- The linear feedback controller K is fixed offline (such that $A + BK$ is stable)
- Keep “real” trajectory close to the nominal
  $$u_i = K(x_i - z_i) + v_i$$

Tube MPC (2)

- Bound maximum error (how far is the "real" trajectory from the nominal)
  - Compute **minimum** robust **positive invariant set** $\mathcal{E}$
  - $x_i \in z_i \bigoplus \mathcal{E}$
- Compute tightened constraints on nominal system
  - $z_i \in \mathbb{X} \ominus \mathcal{E}$
  - $v_i \in \mathbb{U} \ominus K\mathcal{E}$
- Formulate as convex optimization problem
  - Optimize the nominal system with tightened constraints
  - The cost is with respect to tube centers z_i
  - Choose terminal set and terminal objective function to ensure robust feasibility and stability

Scenario-based approach (1)

- Taking into account every possible combination of extreme uncertainty realization leads to an untractable optimization problem
- Scenario approach: take into account only N uncertainty realization scenarios (instead of all possible combinations of extreme uncertainty realizations)
- Constraint violation is tolerated, but with some probability level ε
  - E.g instead $x \in \mathbb{X}$ we have $\mathbb{P}\{x \in \mathbb{X}\} \geq 1 - \varepsilon$
- Additionally, we can discard k out of N scenarios in order to improve the objective value

Scenario-based approach (2)

- Theoretical guarantees that the solution obtained by inspecting N scenarios only is a feasible solution for the chance-constrained optimization problem with high probability $1-\beta$, provided that N and k fulfill the following condition:

$$\binom{k+d-1}{k}\sum_{i=0}^{k+d-1}\binom{N}{i}\varepsilon^{i}(1-\varepsilon)^{N-i}\leq\beta$$

  where d is the number of optimization variables.
- Choose N within the computational limit of the used solver, ε according to the acceptable level of risk, β small enough to be negligible (e.g. $\beta=10^{-10}$), and compute the largest k number of scenarios that can be discarded

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