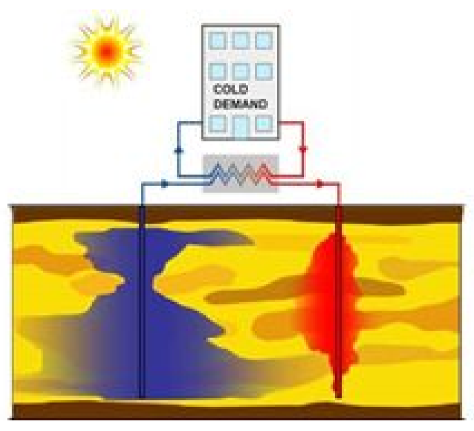
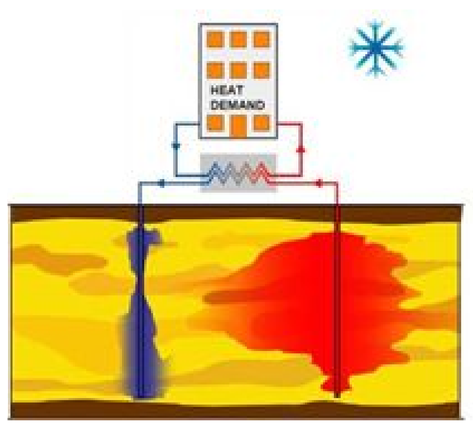
ATES System in Smart Thermal Grids

Distributed Stochastic Model Predictive Control

Aquifer Thermal Energy Storage (ATES)

- A large-scale natural subsurface storage for thermal energy
- An innovative method for thermal energy balance in smart grids





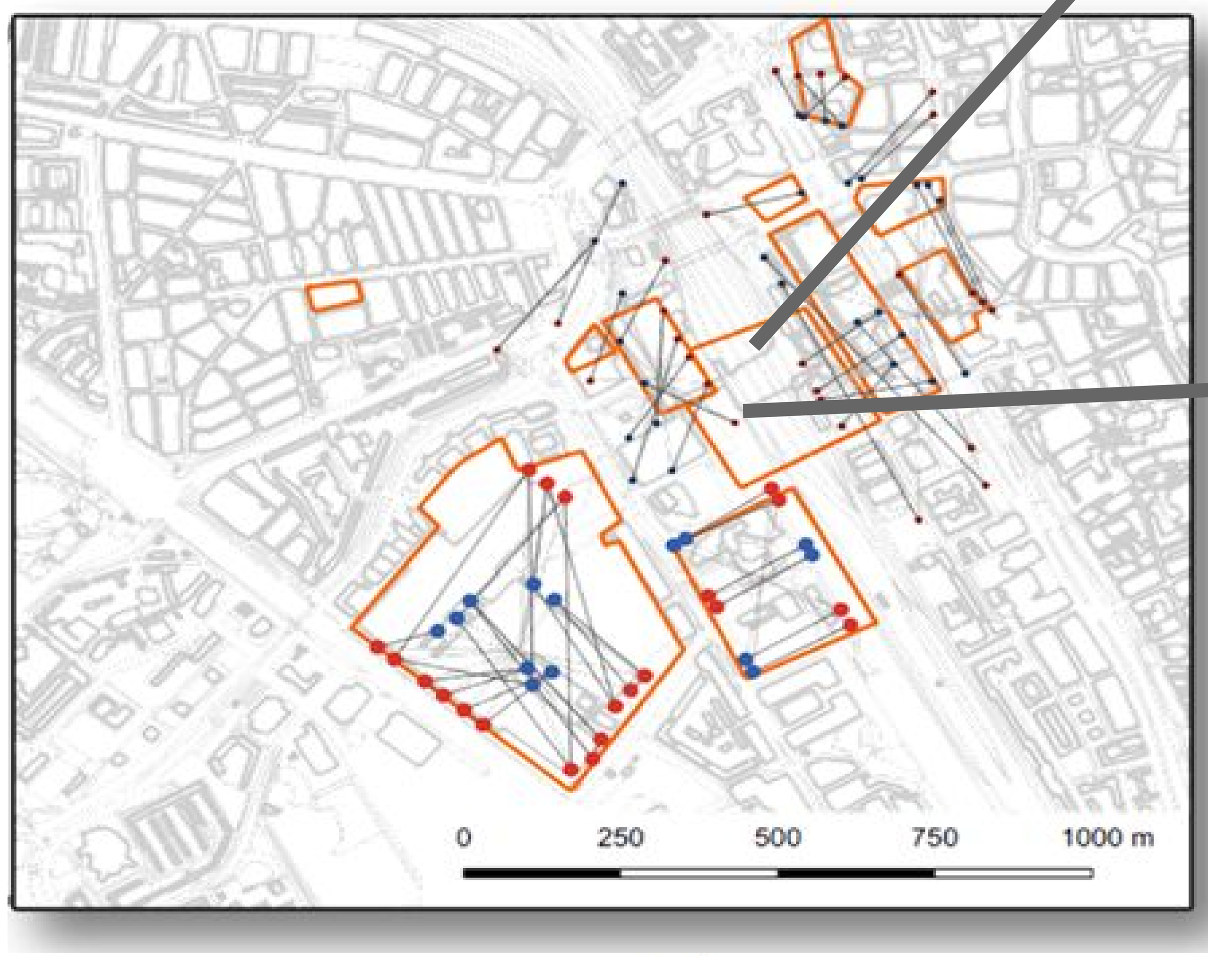
Warm season:

- The building requests thermal energy for the cooling purpose
- Water is injected into warm well and is taken from cold well
- The stored water contains warm thermal energy for next season

Cold season:

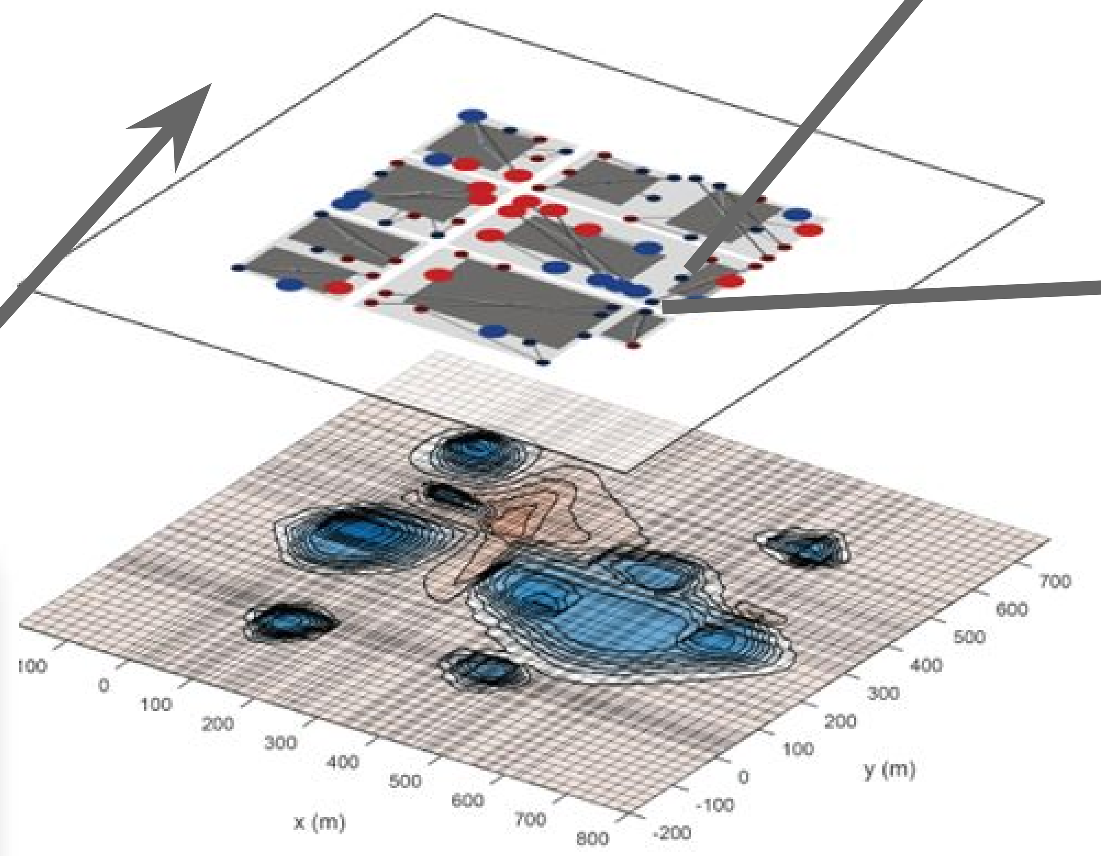
- The building requests thermal energy for the heating purpose
- Water is injected into cold well and is taken from warm well
- The stored water contains cold thermal energy for next season

- ATES systems act as seasonal energy storage buffers and can self-organize subsurface space use to increase efficiency

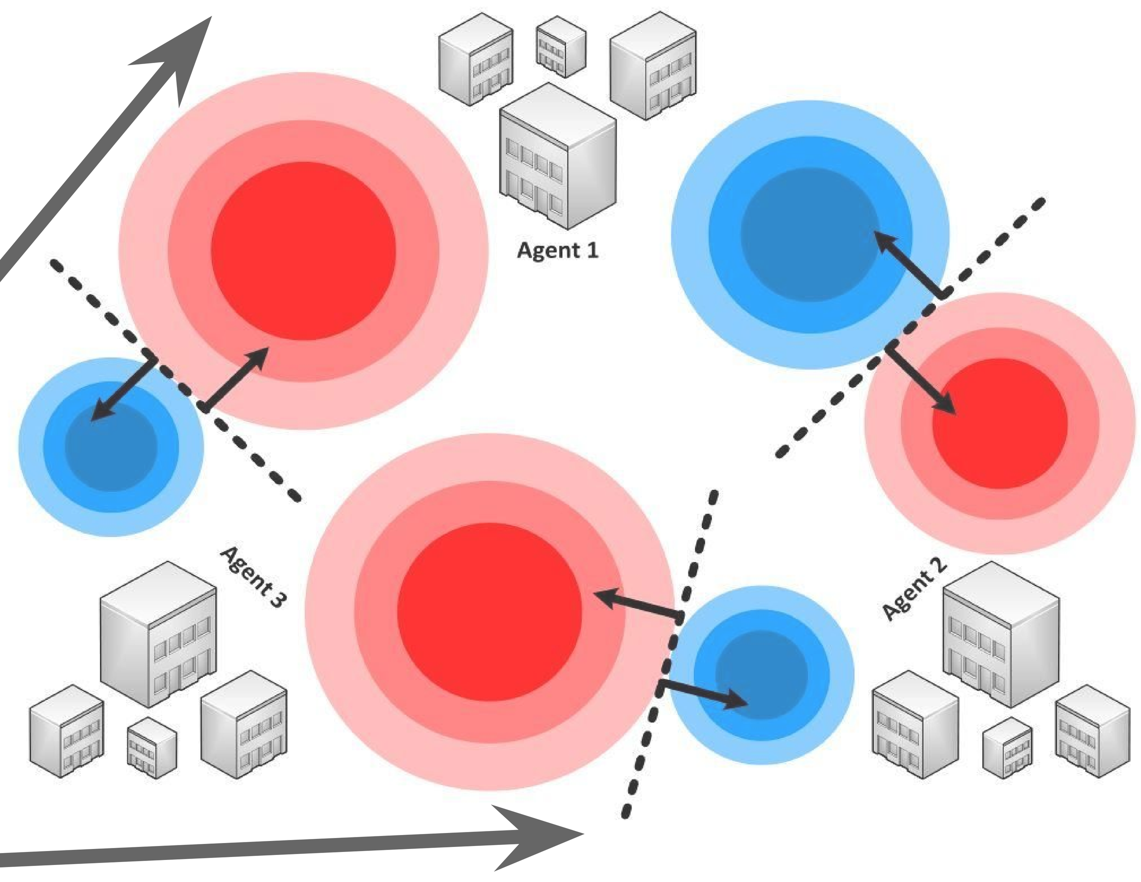


Problem Statement

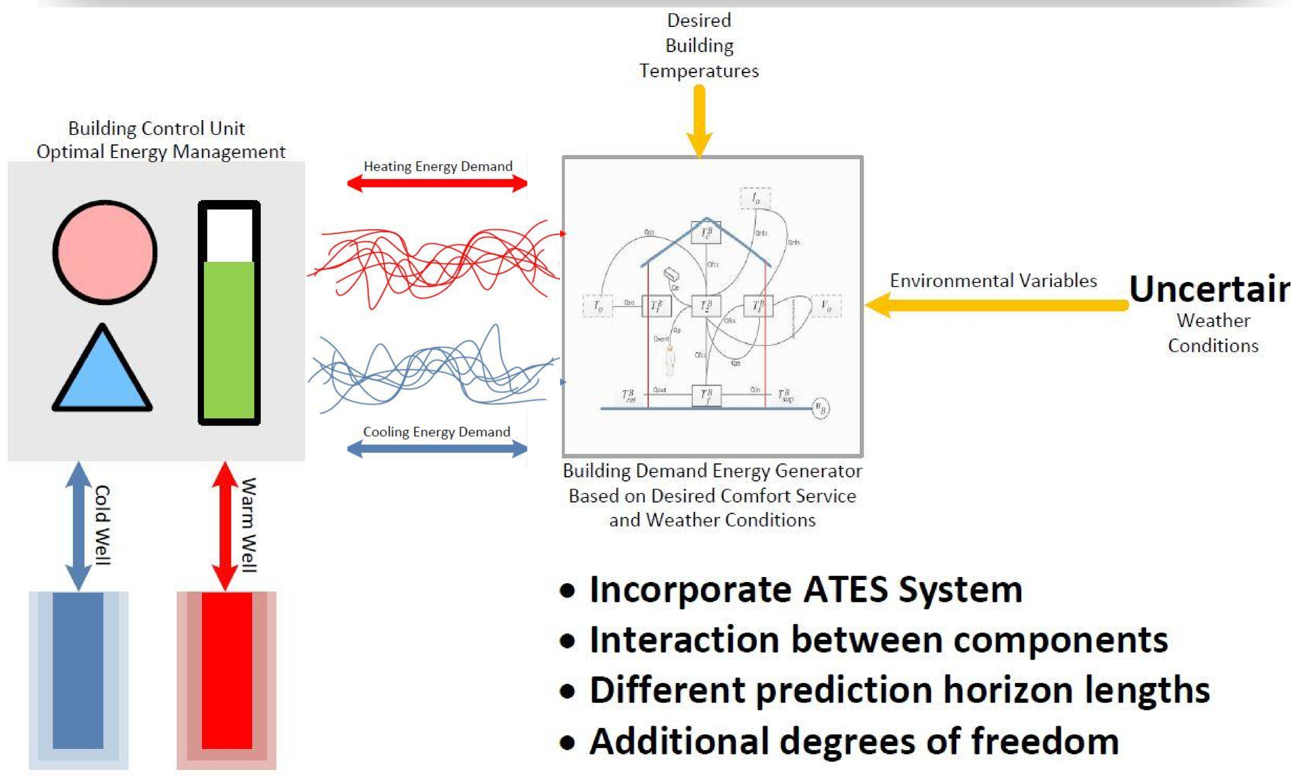
- How can we develop a self-organizing system that adapts to the operational experience in a networked of interconnected ATES systems?
- How do the idealized dynamics manifest in realistic conditions under operational uncertainties?
- What kind of control framework is the best for such a network of buildings using interconnected ATES subject to the local (private) and common uncertainty sources?



ATES in Uncertain STGs



- How can we deal with such a spatially distributed system, complex multivariable, switching, nonlinear behavior when coupled with building climate controllers together with strong exogenous disturbances, stochastic uncertainty?
- The most efficient way to reduce uncertainty is to communicate (cooperate) between neighboring systems
- Investigate cooperative control schemes that allow a distributed solution of the underlying stochastic control problem



- **Incorporate ATES System**
- **Interaction between components**
- **Different prediction horizon lengths**
- **Additional degrees of freedom**

Thermal Energy Demand Profile:

- Complete and detailed building dynamical model
- Desired building temperatures (local controller unit)
- In uncertain conditions, uncertain demand profiles are generated

Building Control Unit:

- Main components: Boiler, HP, HE, micro-CHP, Storage Tank
- **ON/OFF status** together with **production schedule** as decisions
- **Control Objective:** thermal **energy balance** for the overall systems

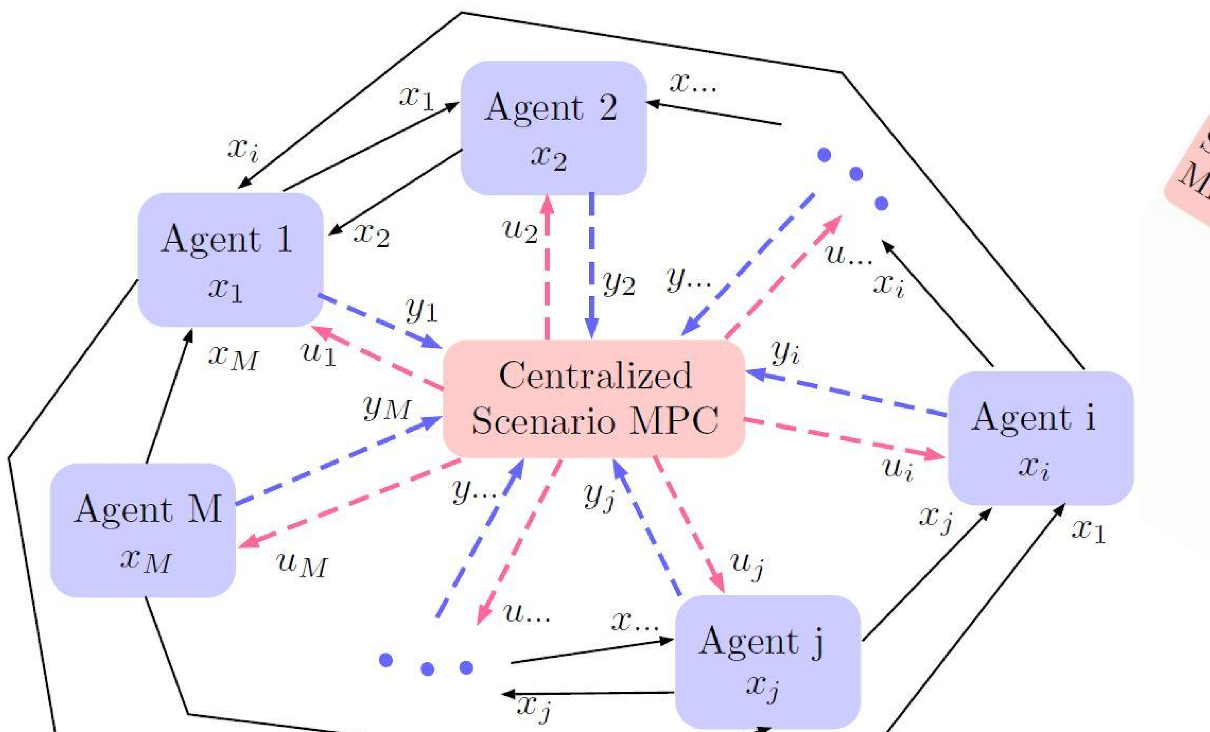
Distributed Scenario MPC (Plug-and-Play Framework)

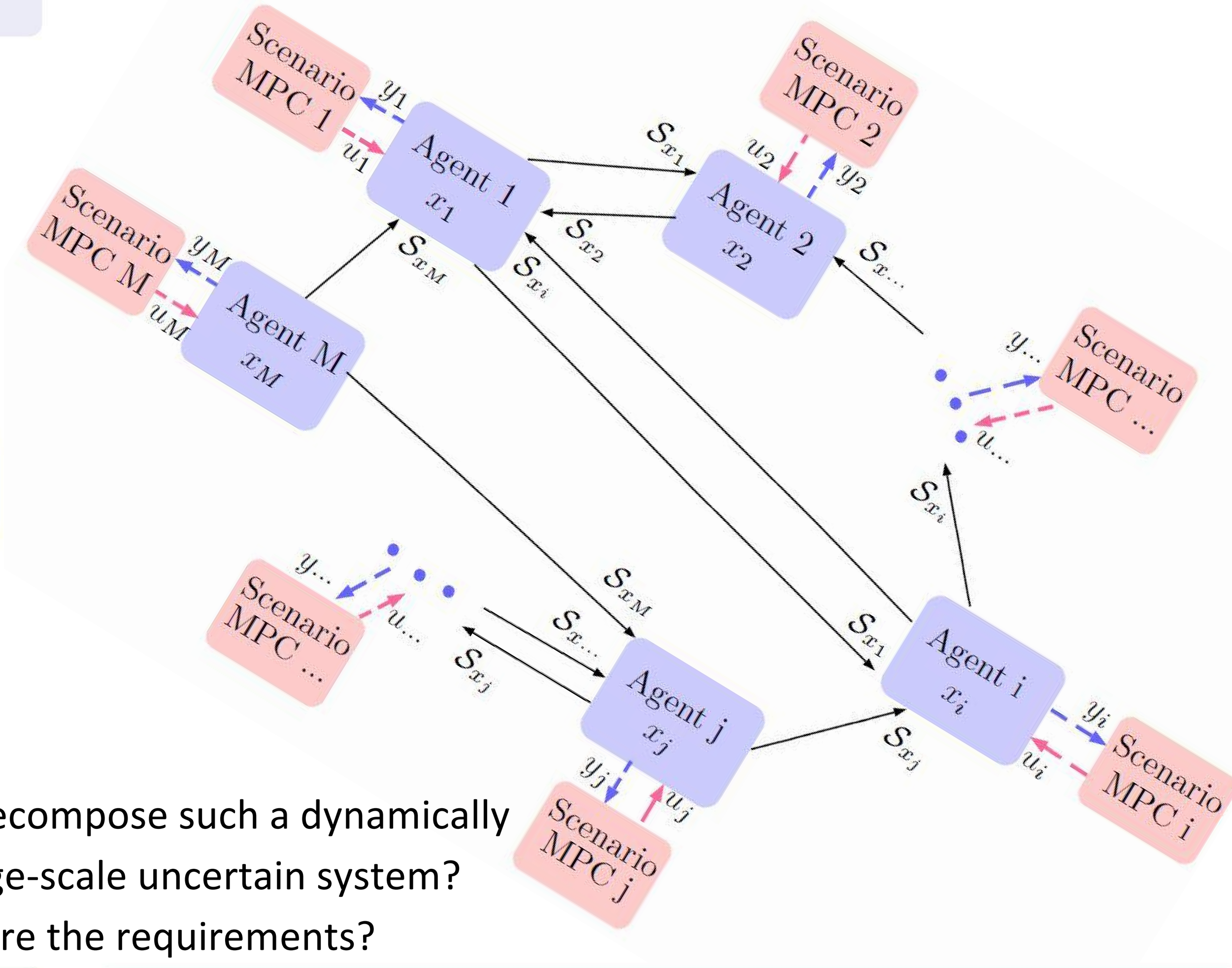
Centralized Scenario Program

$$\begin{aligned}\min_{\{u_i\}_{\forall i\in\mathcal{N}}}\quad & \sum_{i\in\mathcal{N}} f_i(x_{i,k},u_{i,k})\\ \text{s.t.}\quad & x^{(i)}_{i,k+1}=A_{ii}x^{(i)}_{i,k}+B_iu_{i,k}+C_i\delta^{(i)}_{i,k}+\sum_{j\in N_i}A_{ij}x^{(i)}_{j,k}\ ,\ x^{(i)}_{i,k}=x_{i,0}\\ & x^{(i)}_{i,k+\ell}\in\mathcal{X}_i\ ,\quad \forall\ell\in\mathbb{N}_+\ ,\quad \forall\delta^{(i)}_{i,k}\in\mathcal{S}_{\delta_i}\\ & u_{i,k}\in\mathcal{U}_i\ ,\quad \forall k\in\mathcal{T}\ ,\forall i\in\mathcal{N}\end{aligned}$$

Distributed Scenario Program

$$\begin{aligned}\min_{\{u_{i,k}\}_{\forall k\in\mathcal{T}}}\quad & f_i(x_{i,k},u_{i,k})\\ \text{s.t.}\quad & x^{(i)}_{i,k+1}=A_{ii}x^{(i)}_{i,k}+B_iu_{i,k}+q^{(i)}_{i,k}\ ,\ x^{(i)}_{i,k}=x_{i,0}\\ & x^{(i)}_{i,k+\ell}\in\mathcal{X}_i\ ,\quad \forall\ell\in\mathbb{N}_+\ ,\quad \forall q^{(i)}_{i,k}\in\mathcal{S}_{q_i}\\ & u_{i,k}\in\mathcal{U}_i\ ,\quad \forall k\in\mathcal{T}\end{aligned}$$





- How can we decompose such a dynamically coupled large-scale uncertain system?
- What are the requirements?

Probabilistic Feasibility for Multi Agent Problem*

If $\varepsilon=\sum_i\varepsilon_i\in(0,1)$, $\beta=\sum_i\beta_i\in(0,1)$ and given $\mathcal{S}$, then

$$\mathbb{P}^{|\mathcal{S}|}\left(\mathcal{S}\in\Delta^{|\mathcal{S}|}\ :\ \mathbb{P}\Big(\delta\in\Delta\ :\ x^*_{\mathcal{S}}\notin\prod_i\mathcal{X}_i(\delta_i)\Big)\le\varepsilon\right)\ge 1-\beta$$

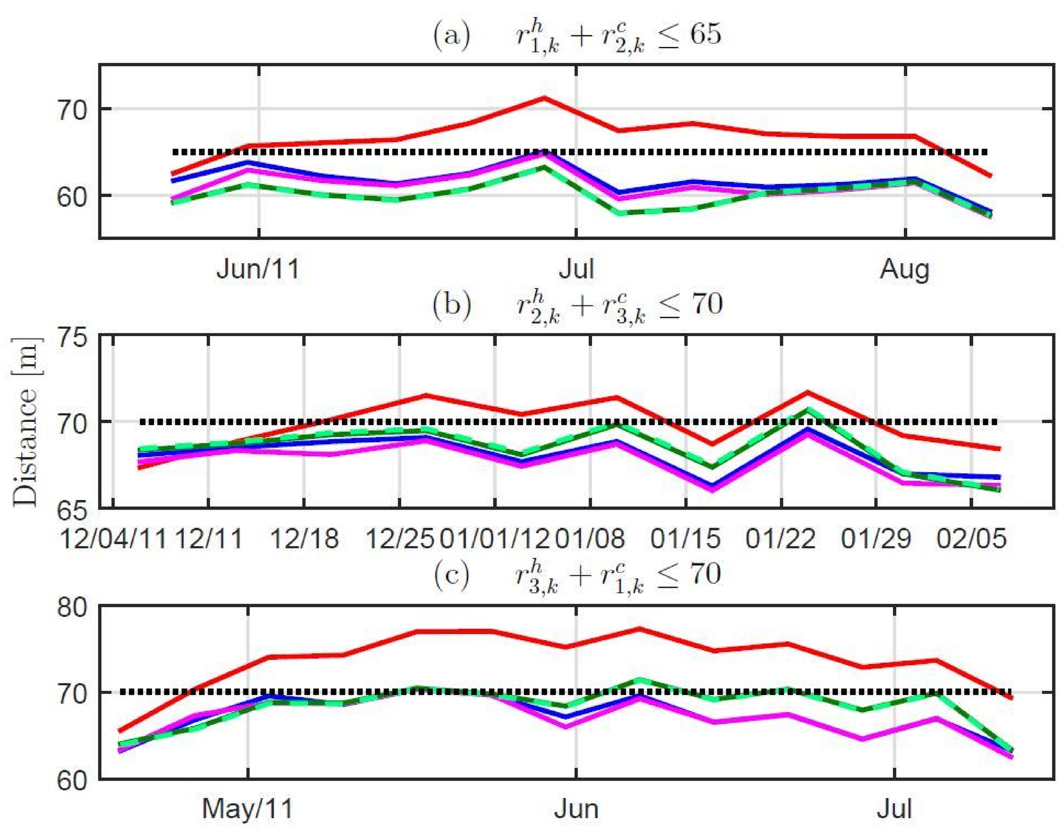
Requirements

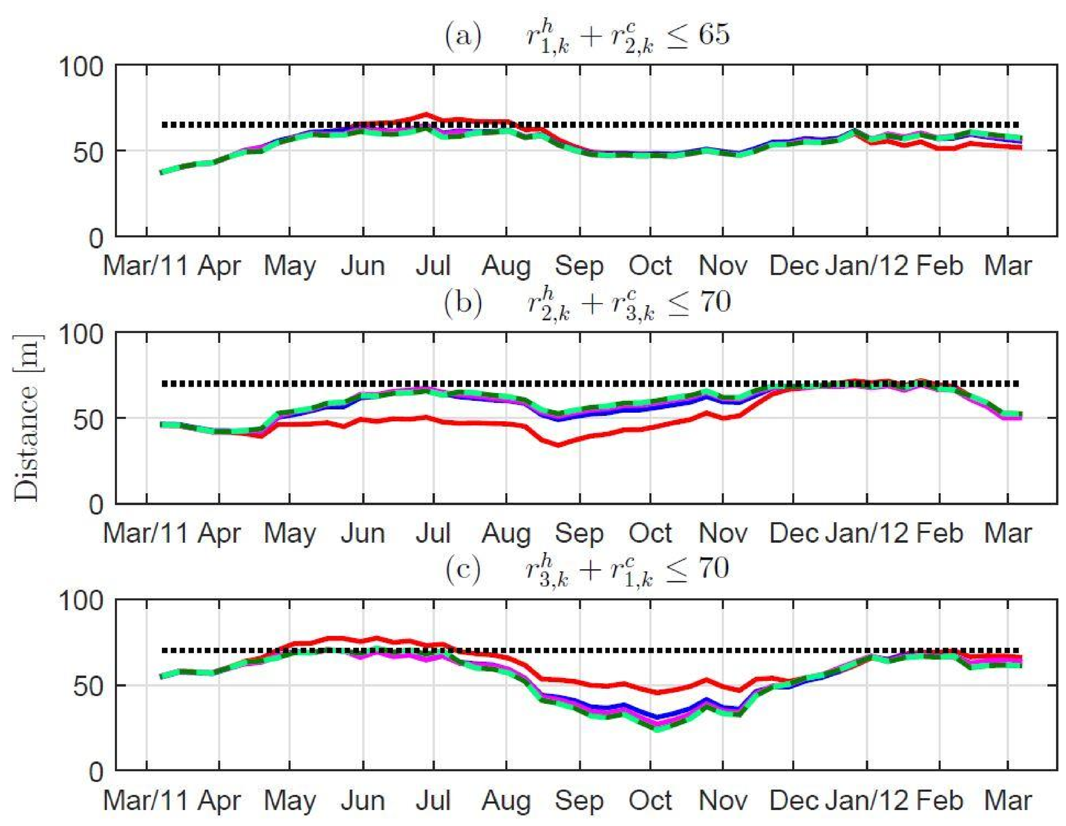
$$\mathcal{S}_{q_i}=\left\{q^{(i)}_{i,k}\ :\ q^{(i)}_{i,k}=C_i\delta^{(i)}_{i,k}+\sum_{j\in N_i}A_{ij}x^{(i)}_{j,k}\ ,\ \forall\delta^{(i)}_{i,k}\in\mathcal{S}_{\delta_i}\ ,\ \forall x^{(i)}_{j,k}\in\mathcal{S}_{x_j}\right\}$$

Simulation Study

Case Study: three-building in Utrecht city with real parameters together with registered weather condition data from 2010-2012

- Decoupled SMPC
- Centralized SMPC
- Distributed SMPC
- DSMPC—0.85
- DSMPC—0.50





Conclusions

Remarks:

- Distributed randomized optimization to deal with private (local) uncertainty source over a network of dynamically coupled systems
- Soft communication scheme with an extension of probabilistic feasibility guarantee
- Application to energy management of smart thermal grids (STGs) with aquifer thermal energy storage (ATES) system

What comes next:

- Preserving privacy of individual agents in a network

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