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Modeling and simulation of Complex Interdependent Systems: a federated agent-based approach

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Agenda

- Research goal
- Federated ABMS concept
- Federated ABMS model
- The interdependencies model
- A case study
- Implementation Issues
- Remarks

Research Goals

- This research, part of the CRESCO project, aims to face the problem of modeling and simulation of interdependent critical infrastructures proposing an approach based on discrete agent-based modeling and simulation and federated simulation (Federated Agent-based Modeling and Simulation - Federated ABMS).

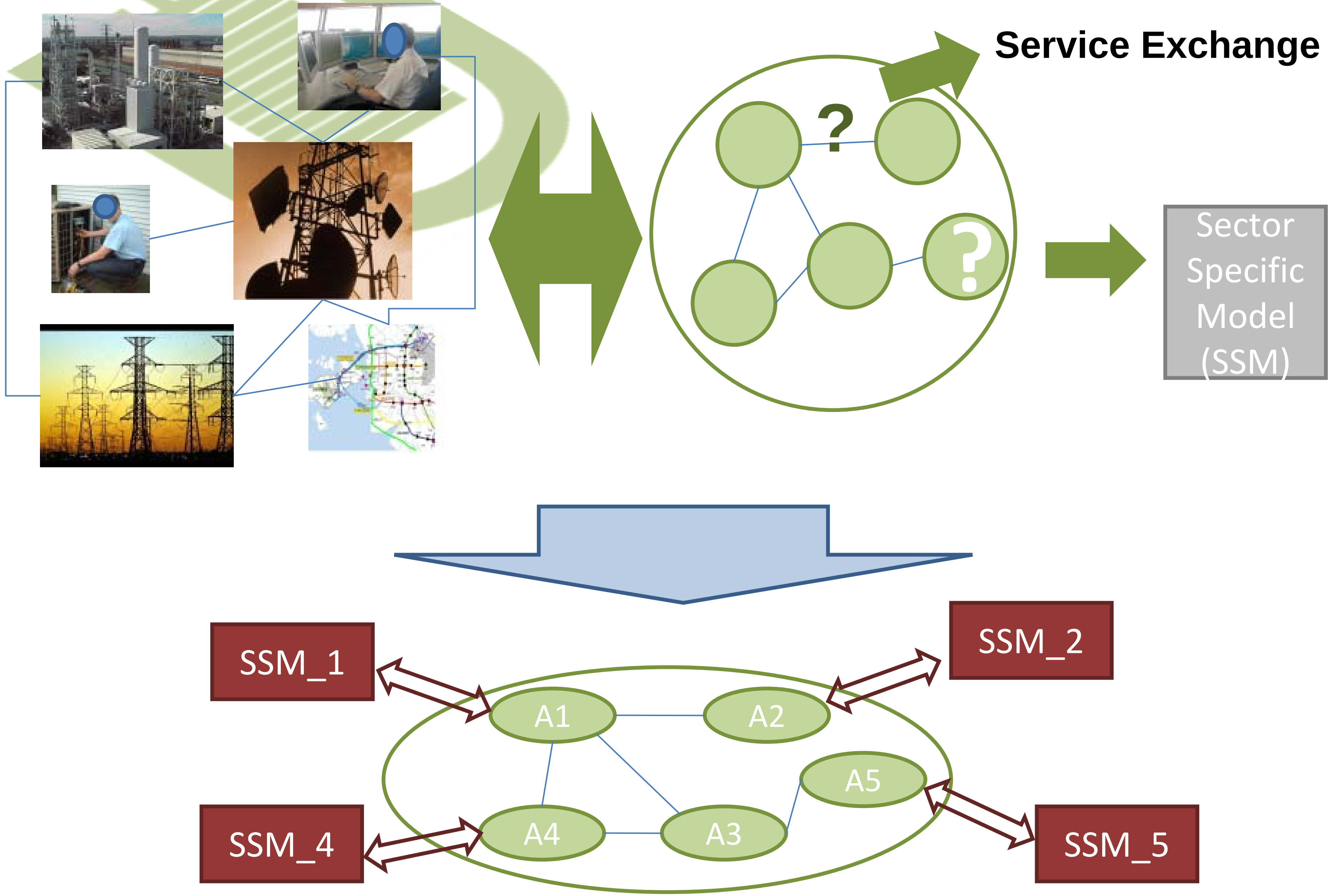
Federated ABMS concept

The idea behind Federated ABMS is the following. A compound complex system, composed of interacting complex systems, can be modeled as a set of interacting agents. The behavior of each agent is modeled by a sector-specific model.

Then, the whole model for the compound complex system is obtained federating the agent-based models and the sector specific models. The abstraction introduced by Federated ABMS relieves the modeler of the details of the complex system models (viewed as a black-box), allowing to concentrate her/his attention on the modeling of the compound complex system and on interdependencies modeling.

Another advantage of Federated ABMS is the possibility to simulate with greater detail the agent behavior re-using sector specific simulation models.

The concept behind Federated ABMS



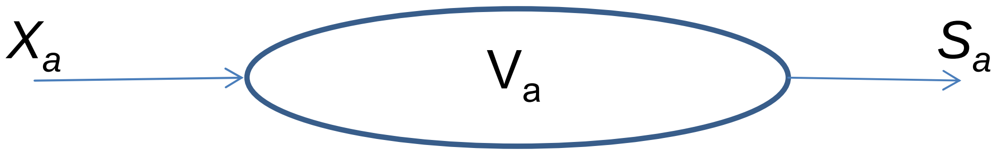
Research contribution

- We formalize the concept of federated agent based modeling, providing a formalism to model compound complex systems, composed of interacting systems.
- The introduced formalism allows:
  - to abstract the functional aspects of the infrastructure behavior, modeled in greater depth re-using existing sector specific models;
  - to model physical and cyber interdependencies as service exchange among infrastructures;
  - to model geographical and logical interdependencies as infrastructure perturbations.

Federated Agent-based model

An agent a is described by the tuple (V_a, S_a, X_a) where:

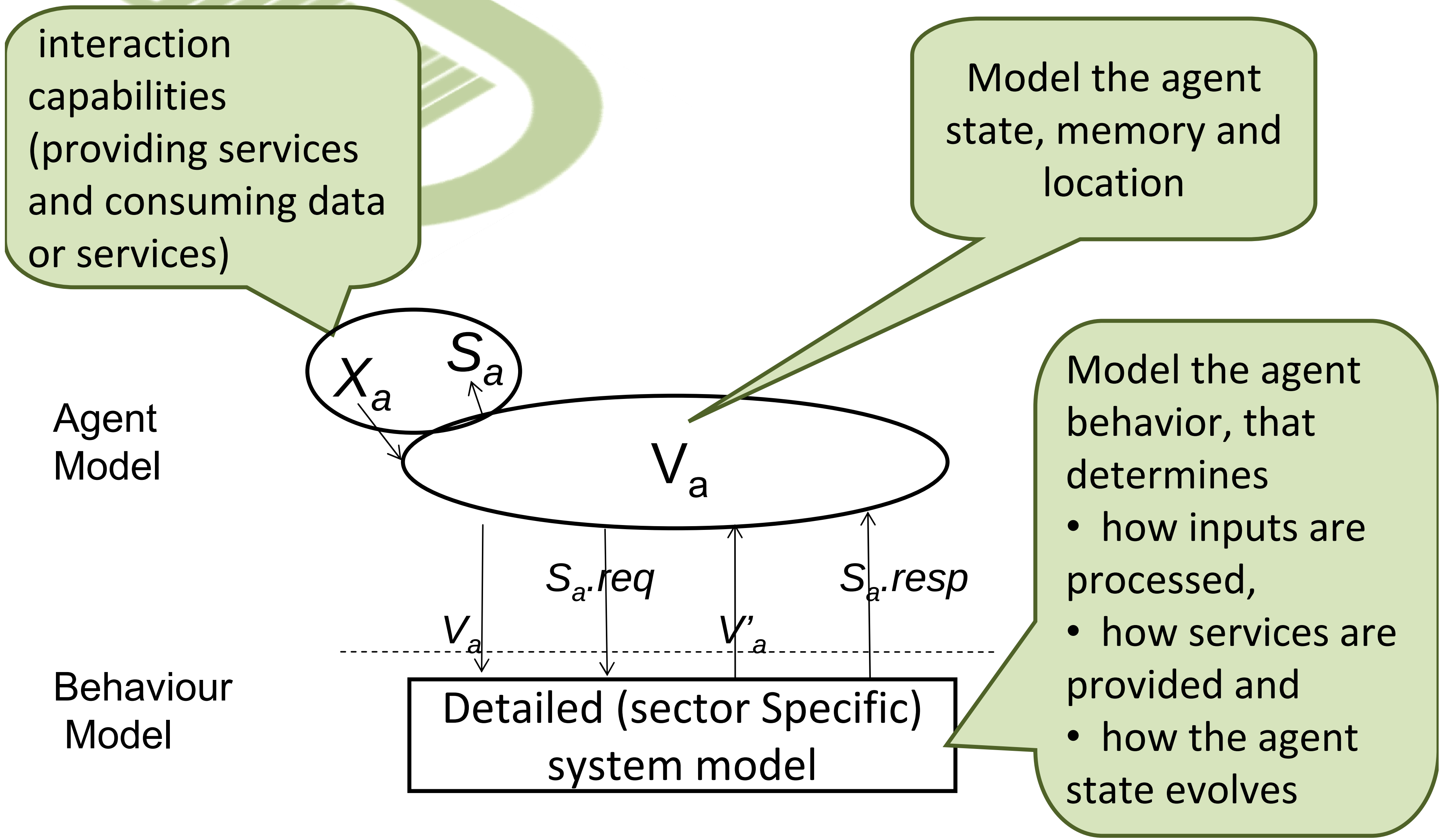
$V_a = \{v_1^a, \ldots, v_{N_v^a}^a\}$, $v_i^a \in \mathscr{V}_i^a$ and $|V_a| = N_v^a$. V_a is the set of the agent attributes and $\mathscr{V}_i^a$ is the domain of the agent attribute i. The values assumed by the agent attributes at time t represent the state of the agent.



$S_a = \{s_1^a, \ldots, s_{N_s^a}^a\}$, $|S_a| = N_s^a$, is the set of services that the agent a provides to other agents. In our model agents interact exchanging services.

$X_a = \{x_1^a, \ldots, x_{N_x^a}^a\}$ $(|X_a| = N_x^a)$ is the set of inputs of the the agent a. Inputs can be services produced by other agents or perturbations. A perturbation is an unpredictable event that modifies the agent state and alters the behavior of the agent a, reducing the a's capabilities to provide services. An input is characterized by the tuple $x_i^a = (t_x, x)$ where $x \in \mathscr{X}_i^a$ is the value of the input, $\mathscr{X}_i^a$ the set of possible values for the i^{th} input of agent a, and t_x the time at which the value x is available ($t_x \in, \mathbb{R}^+$ or $t_x \in, \mathbb{N}^+$ if we consider continuous or discrete time respectivelly).

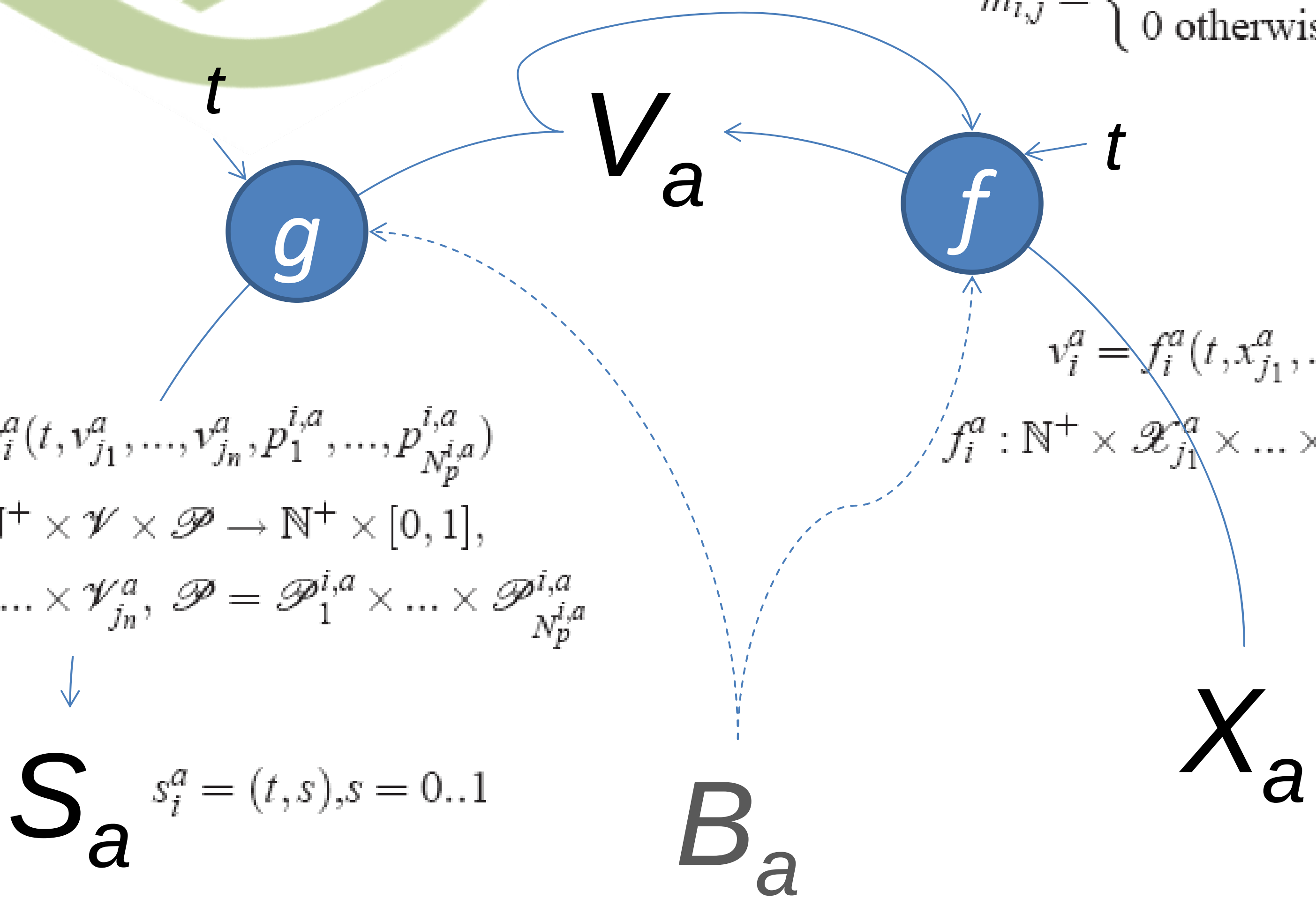
Agent definition vs FederatedABMS



Relationship among attributes, services and inputs

$$M_a = \{m_{i,j}\}^{N_x^a \times N_v^a}$$

$$m_{i,j} = \begin{cases} 1 \text{ if } x_i^a \in dom(f_j^a) \\ 0 \text{ otherwise} \end{cases}$$



$$v_i^a = f_i^a(t, x_{j1}^a, \ldots, x_{jn}^a),$$

$$f_i^a : \mathbb{N}^+ \times \mathscr{X}_{j1}^a \times \ldots \times \mathscr{X}_{jn}^a \rightarrow \mathscr{V}_i^a.$$

$$s_i^a = g_i^a(t, v_{j1}^a, \ldots, v_{jn}^a, p_1^{i,a}, \ldots, p_{N_p^{i,a}}^{i,a})$$

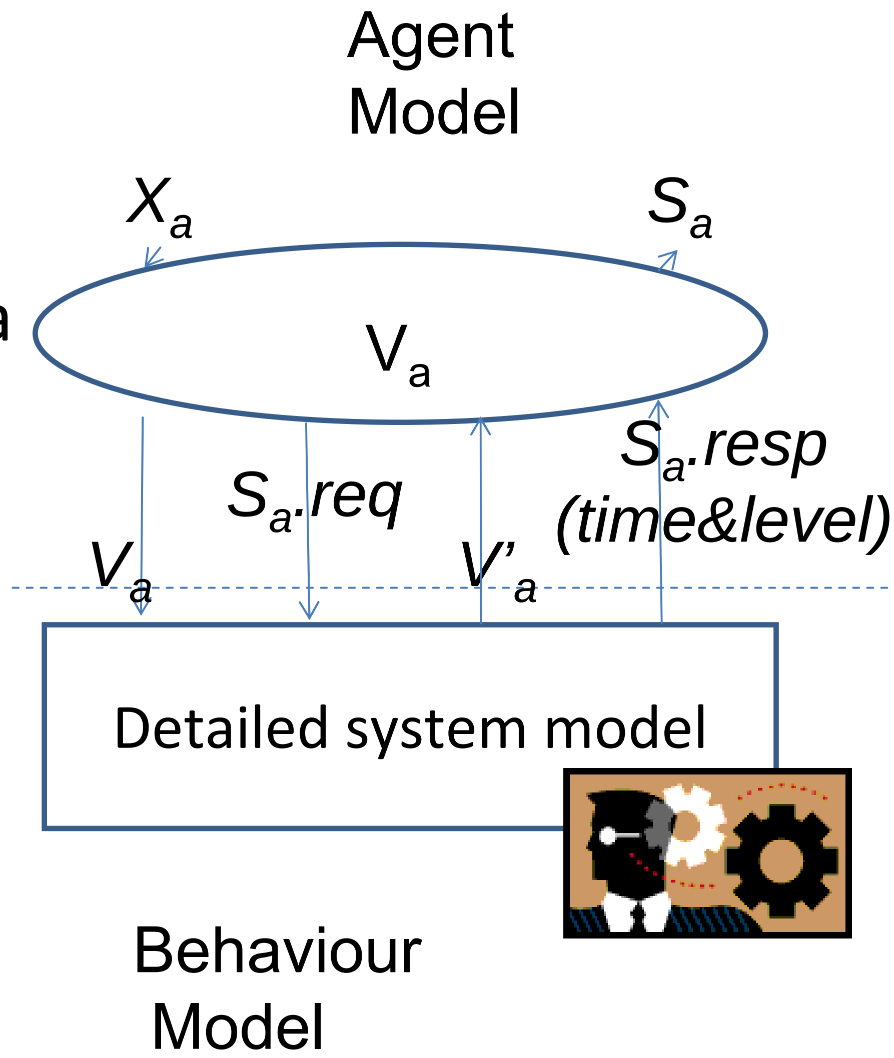
$$g_i^a : \mathbb{N}^+ \times \mathscr{V} \times \mathscr{P} \rightarrow \mathbb{N}^+ \times [0,1],$$

$$\mathscr{V} = \mathscr{V}_{j1}^a \times \ldots \times \mathscr{V}_{jn}^a, \ \mathscr{P} = \mathscr{P}_1^{i,a} \times \ldots \times \mathscr{P}_{N_p^{i,a}}^{i,a}$$

$$s_i^a = (t, s), s = 0..1$$

How to model Agent state evolution and service delivery

- **Solution: A detailed model of the target complex system**
- The detailed system model is a black-box, controlled by the agent model
  - Compute the new system state
  - Compute the service delivery time
  - Compute the service level

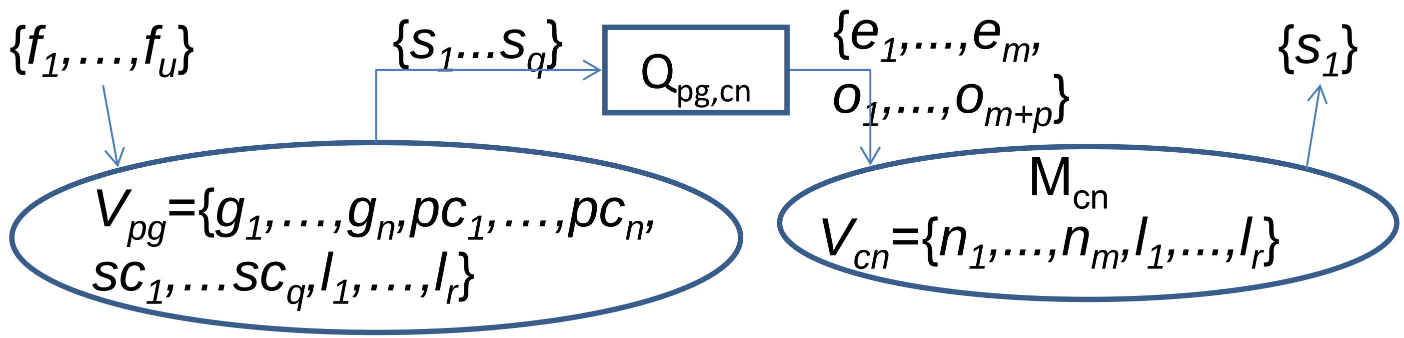


The interdependencies model

- Physical and cyber interdependencies are modeled as service exchange
- Geographical and logical interdependencies are modeled as perturbations

$$Q_{a,b} = \{q_{i,j}\}^{N_s^a \times N_x^b},\ q_{i,j} = \begin{cases} 1 \text{ if } s_i^a = x_j^b \\ 0 \text{ otherwise} \end{cases}$$

$$M_b = \{m_{i,j}\}^{N_x^b \times N_v^b},\ m_{i,j} = \begin{cases} 1 \text{ if } x_i^b \in dom(f_j^b) \\ 0 \text{ otherwise} \end{cases}$$



The Fed ABMS methodology

1. Identification of the simulation study goals.
2. Identification of the complex systems (e.g. infrastructures) that compose the compound complex system under study.
3. For each component system identified in step 2, identify:
   1. the set of variables that are representative of the system state;
   2. the set of services that allow to represent the interaction of the complex system with the other component systems, with the environment and with human beings;
   3. the set of perturbations and inputs that influence the component system behavior;
   4. the relationship among agent inputs and agent state variable.

supported by interviews

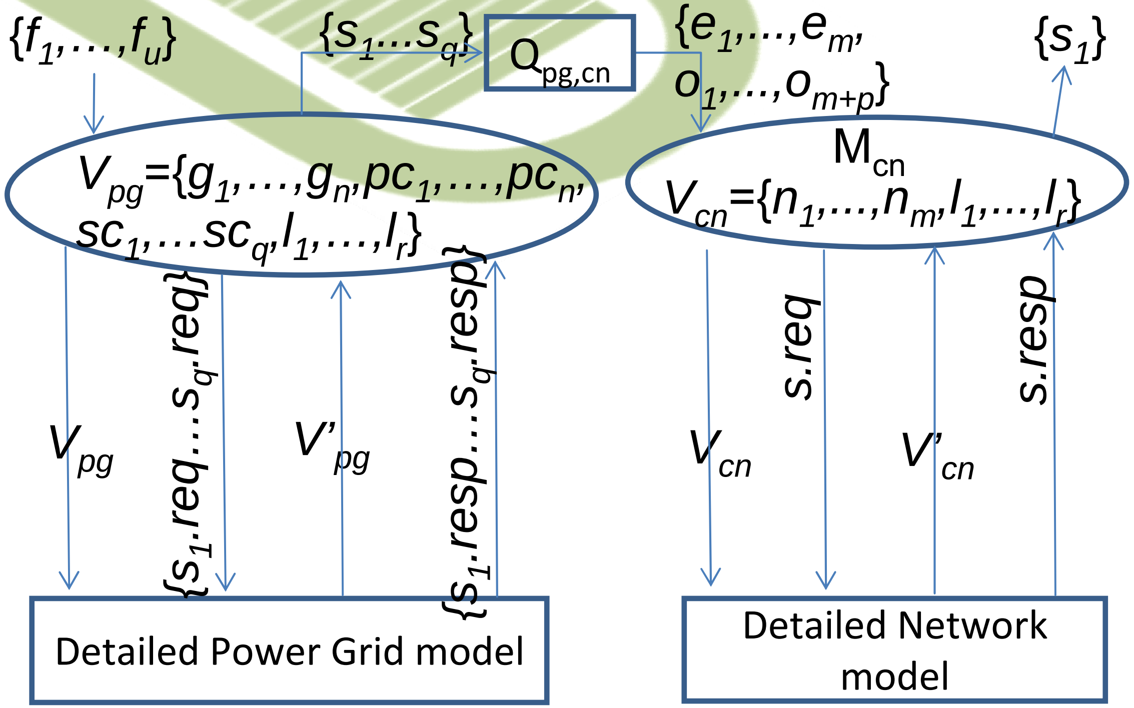
4. Associate an agent *a to each system identified in step 3 and define the related* agent model (*Va, Xa, Sa) and Ma. Va, Xa Sa and Ma are determined in steps 3.1*-3.4 respectively.

The Fed ABMS methodology

5. For each agent defined in the previous step identify the sector-specific simulation model useful to simulate the infrastructure behavior.
6. Identify the system interdependencies, for example using interviews of infrastructure experts.

- For each couple of infrastructures *a and b (a 6= b) define the interdependencies* matrix *Qa,b.*

An example: An IP network (cn) and a Power Grid (pg)



$$M_{cn} = \begin{array}{c|ccc} & n_1,\ldots,n_m, & l_1,\ldots,l_p \\ \hline e_1 & & \\ \vdots & I_m & 0_p \\ e_m & & \\ o_1 & & \\ \vdots & & I_{m+p} \\ o_{m+p} & & \end{array}$$

$$f_{pg} = \begin{cases} v_i = 1 \text{ if } y_i = 1, \ \forall t \\ v_i = 0 \text{ otherwise}, \ \forall t \end{cases}$$

$$f_{cn} = \begin{cases} n_i = 0 \text{ if } (e_i = 0) \text{ or } ((e_i = 1) \text{ and } (o_i = 1)), \ \forall t \\ l_i = 0 \text{ if } o_i = 1, \ \forall t \\ n_i = 1, l_i = 1 \text{ otherwise}, \ \forall t \end{cases}$$

$$M_{pg} = \{m_{i,j}\}^{u \times u} = I_{u \times u}$$

$$Q_{pg,cn} = \{q_{i,j}\}^{N_s^{pg} \times N_x^{cn}}, \quad q_{i,j} = \begin{cases} 1 \text{ if } s_i = e_j \\ 0 \text{ otherwise} \end{cases}$$

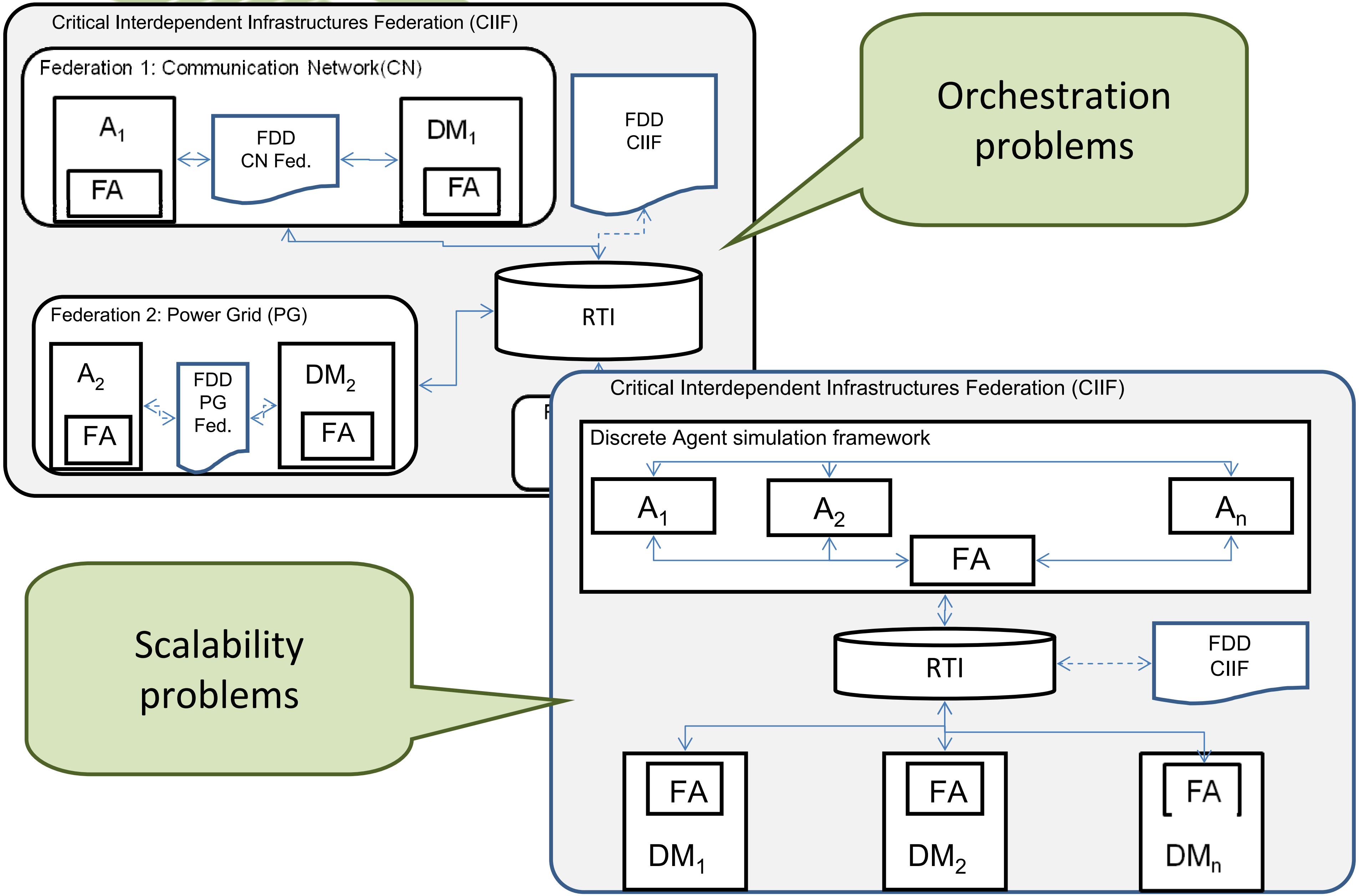
Implementation Issues

1. Implementation of agents
2. Federation of agent-based model(s) and sector specific models
3. Interaction between the agent model and the sector specific model
4. Orchestration of the Federated agent-based simulation model

Implementation of agents

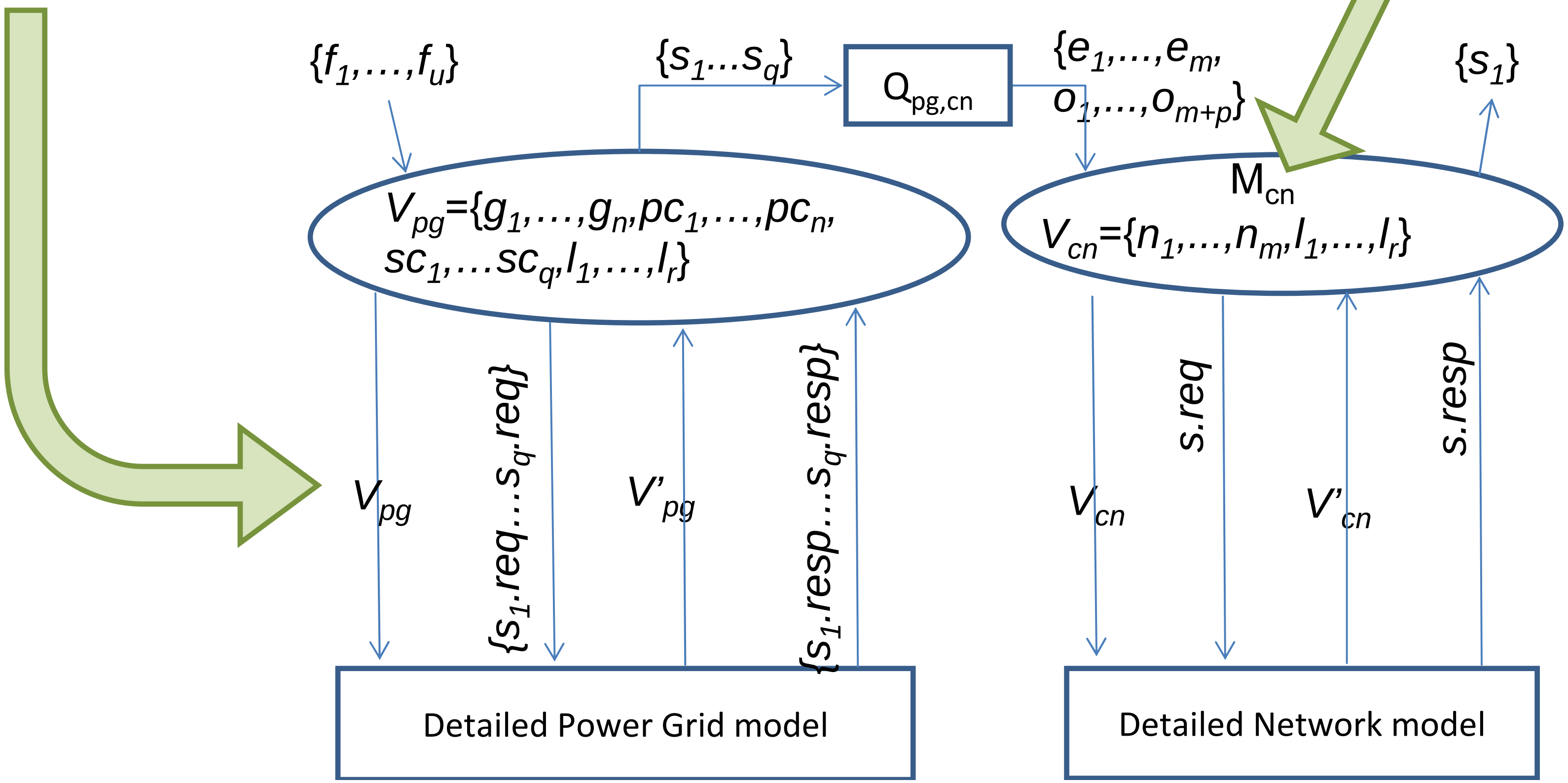
- Agent and multi-agent simulation
- Distributed Agents
  - JadeSIM
  - SIM_AGENT
- "Centralized" agents
  - RePast
- FederatedABMS is technology independent
  - In our prototype we have used a centralized approach based on RePast.

Federation of the ABM and SSM



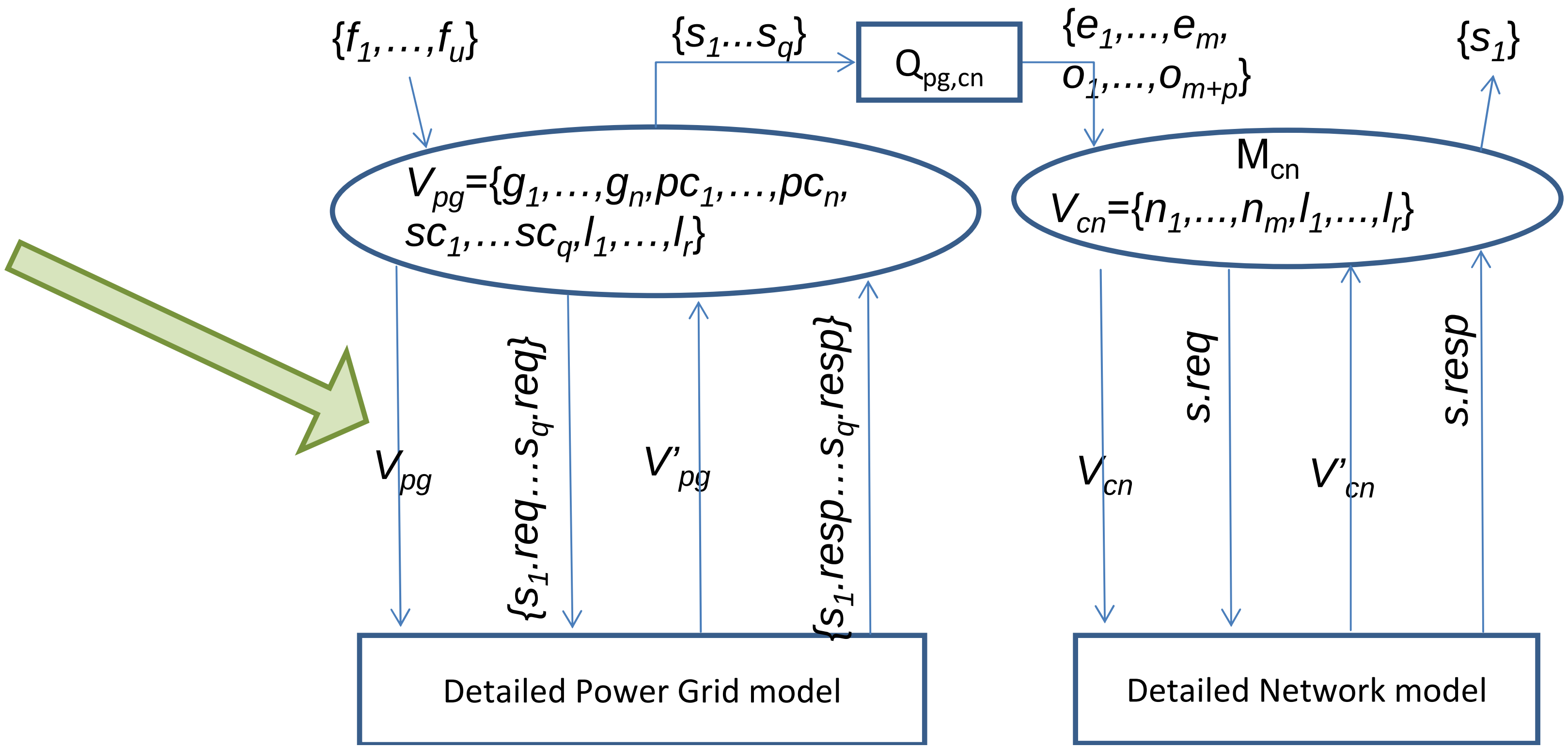
Interaction between ABM e SSM

- Two implementation problems:
  - logical relationship between the agent state and inputs (*Va and Xa) as well as the state variable and parameters of the d*etailed simulation models.
  - physical interaction between models;



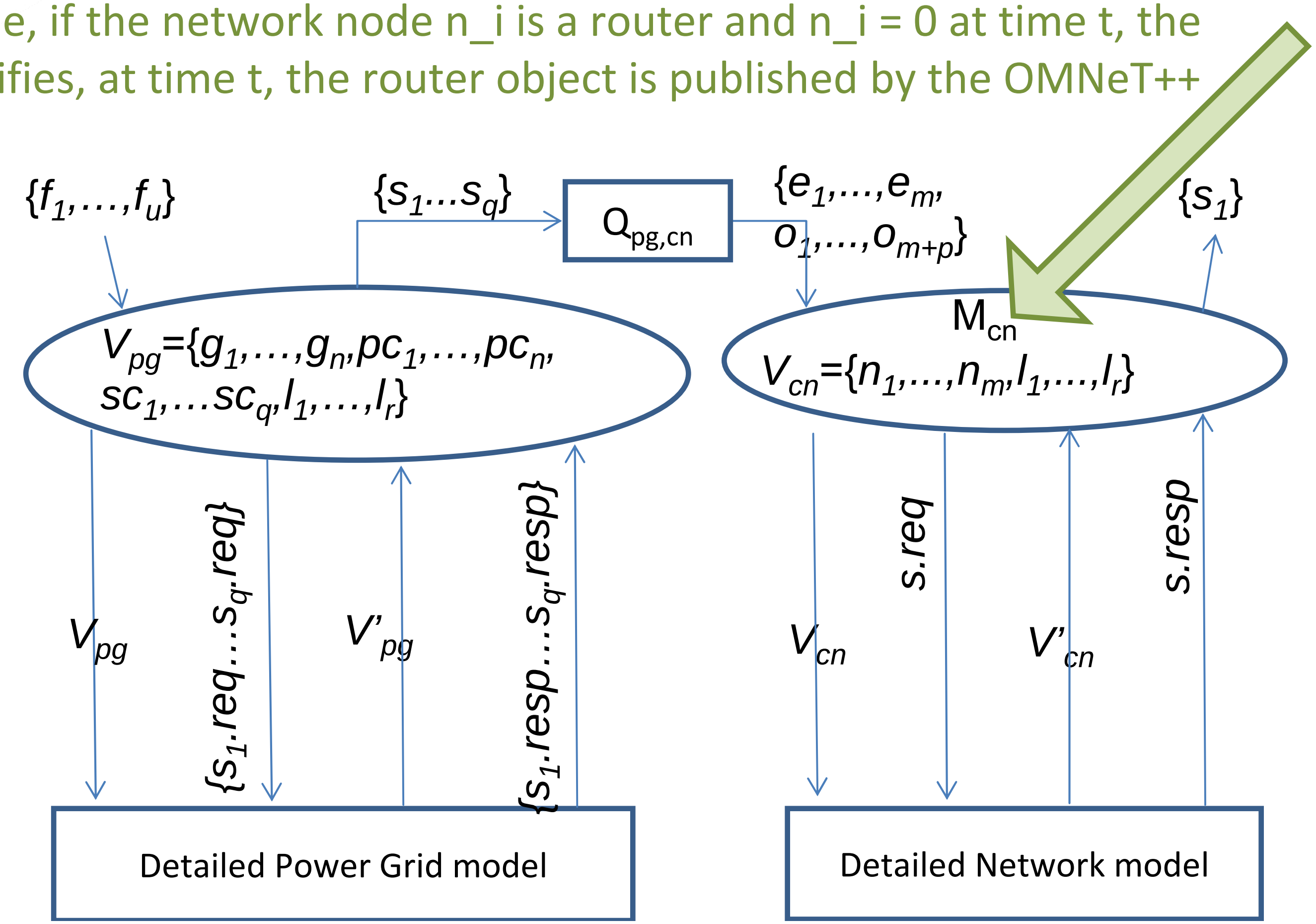
Interaction between ABM e SSM

- The physical interaction is defined by the FOM.
  - The agent model publishes, as objects, the inputs Xa and the state variables Va
  - The sector specific model publishes V'a as an object and Sa as an interaction.



Interaction between ABM e SSM

- The logical relationship is implemented on the agent side.
  - The agent implements the function f_a and the mapping M_a.
  - Each time an agent state variable changes its value, the agent model changes the value of the related sector specific model variable.
    - For example, if the network node n_i is a router and n_i = 0 at time t, the agent modifies, at time t, the router object is published by the OMNeT++ federate



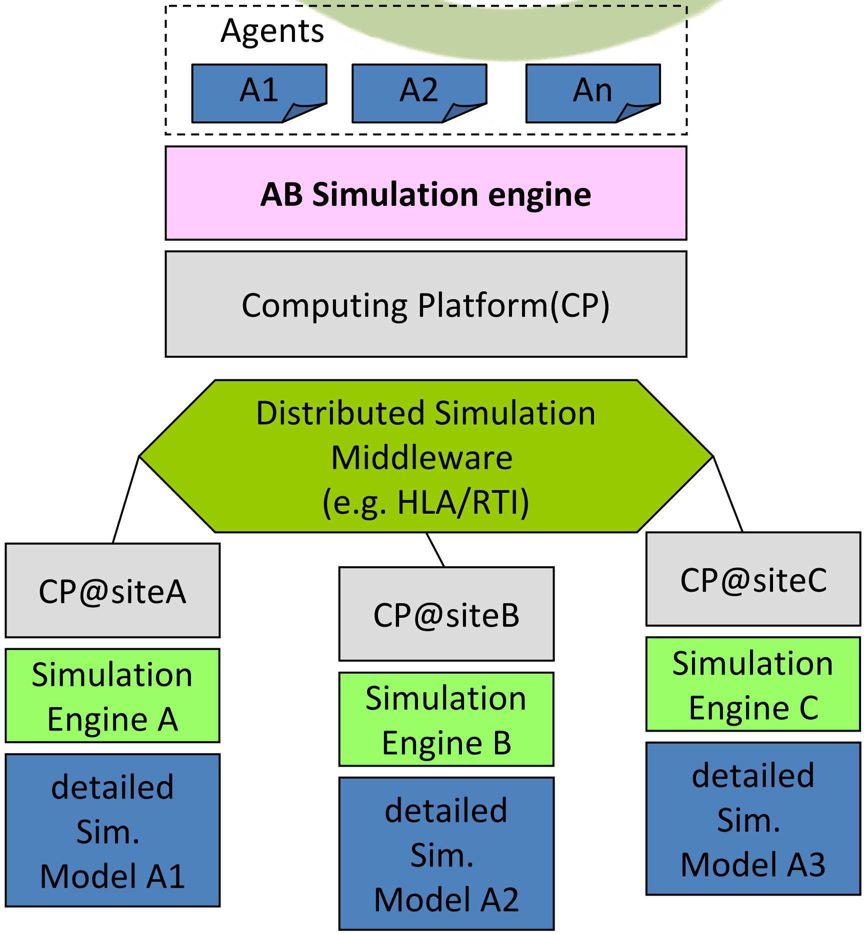
Orchestration of the Federated ABM

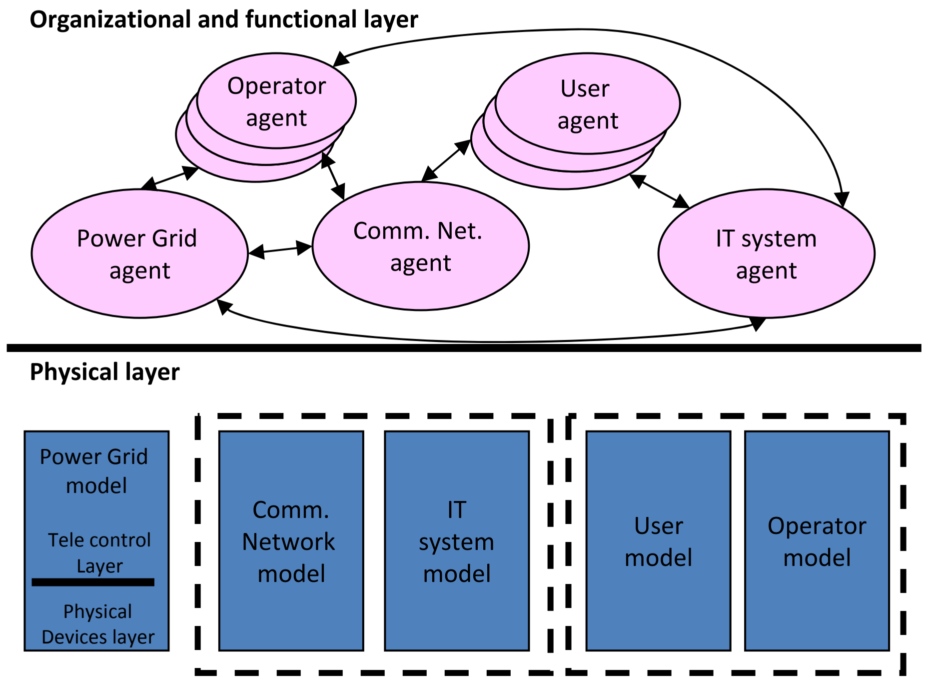
- In federated agent-based modeling and simulation, the agent model plays the natural role of the simulation orchestrator.
  - If a centralized agent based simulation framework is used, the simulation orchestrator can be easily implemented
  - If distributed agents are used, a specific agent that works as simulation orchestrator have to be designed.

Concluding Remarks

- The proposed methodology is intended as an aid to whom design a simulation framework for interdependent complex systems analysis
- With Federated ABMS a modeler can define an abstract model of the target compound complex system ignoring the details of the component system models (that are used as black-box).
- There are some unsolved problems:
  - Scalability
  - Validation
  - Geographical and logical interdependencies modeling

Federated ABMS





Questions?
Thank you

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