Multi-Agent Cooperative Voltage Stability Control of Smart Grid

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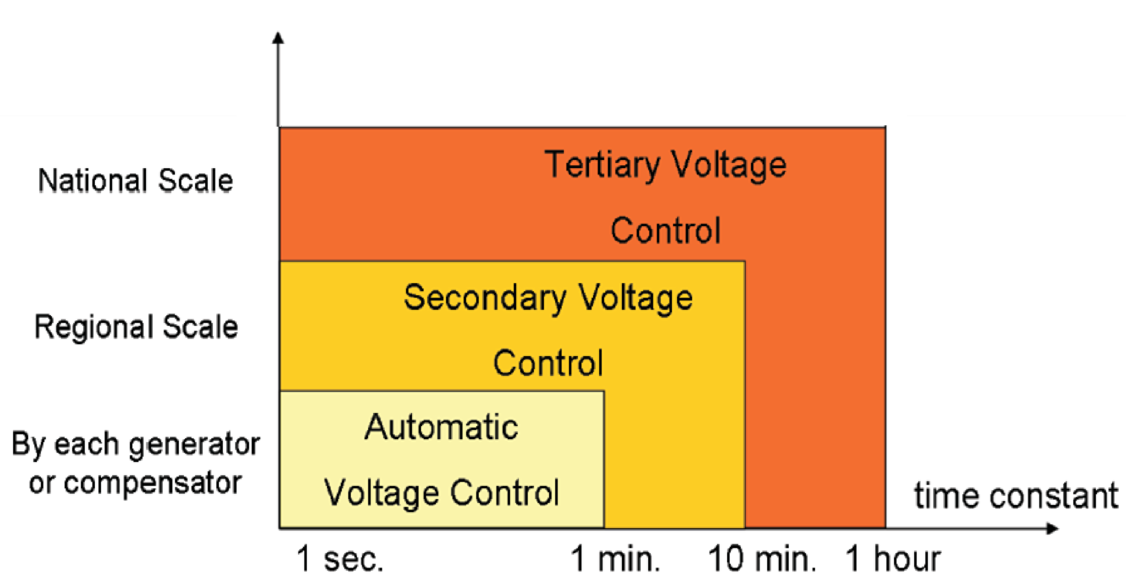
Consider the problem of voltage stability control and reactive power scheduling in a multi-area power system (possibly) controlled by independent transmission system operators.

A major issue is to coordinate, with a high level of robustness, the control actions of the interconnected areas with respect to their operational objectives and constraints.

We propose an agent-based cooperative approach to this issue. Each control area is treated as an intelligent agent that pursues small-scale, self-owned objectives, assuming that each area is capable to properly communicate with its own entities and to stably govern them in a centralized or decentralized manner.

It is shown that while each agent pursues its local goals, the multi-agent control scheme stabilizes the large-scale system and achieves the global goals of an adaptive voltage control function through neighborhood active interactions.

Modern practices in voltage control



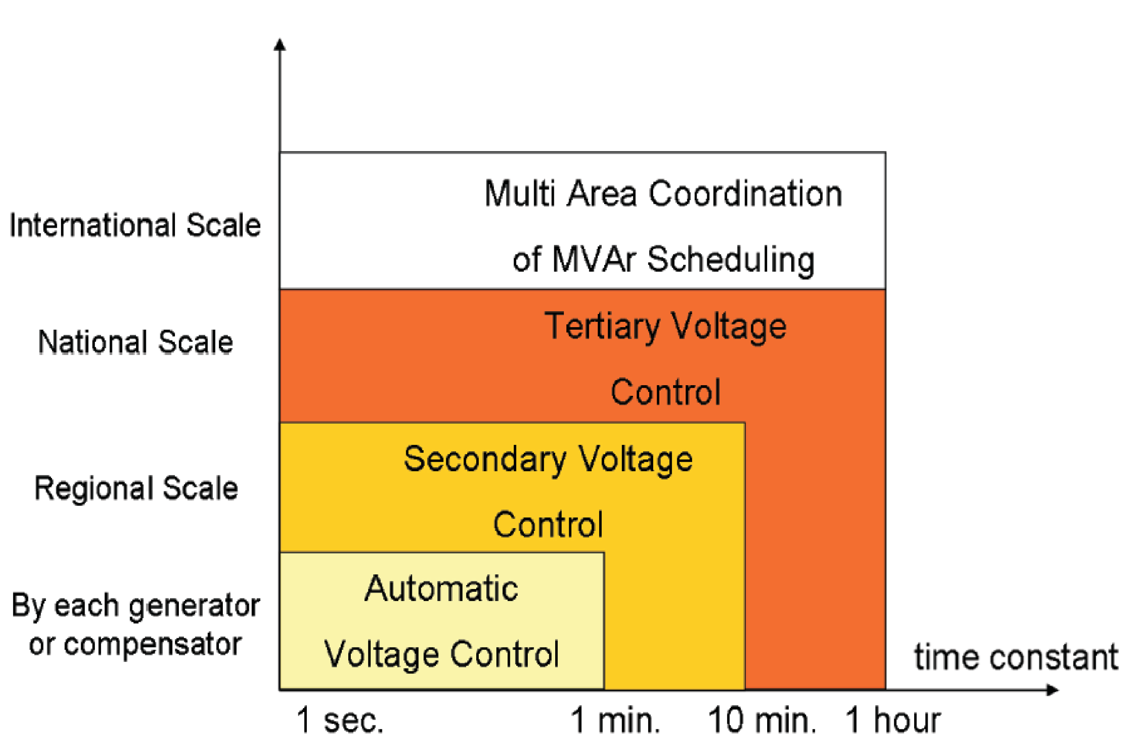
Automatic Voltage Control (AVR): It manages a fast response to fast voltage changes by maintaining the bus voltage at its expected value. It sets the reactive power injection of generators, synchronous condensers, and fast static VAr compensators with the response of 1 ms to 1 min.

Secondary Voltage Control (SVC): The AVR alone cannot assure a steady-state equilibrium. So a regional closed-loop control maintains the pilot bus voltage at its reference value with the time constant 1-15 min. It sets a reference for AVR, slower equipment such as synchronous condensers and static VAr compensators, and controls load/transformer taps.

Tertiary Voltage Control (TVC): Also called reactive power scheduling, refreshes the reference values of bus voltages and reactive power injections based on the scheduled operating conditions (load demand, active power generation pattern, and network topology). It consists a steady-state optimization often run every 15 to 30 min, or when events occur.

- **Control variables:** voltage amplitude at every generating unit or compensation device, and tap settings.
- **State variables:** voltage amplitude and angle at every bus.
- **Objective function:** short-term voltage stability, operation cost, transmission capacity, and/or long-term voltage stability.
- **Constraints:** load flow equations, bus voltage and reactive power limit ranges, and line capacities.

Need for a higher level of voltage control



- In very large interconnected power systems, poorly coordinated operation may increase the risk of blackouts.
- Interconnected independent TSOs may choose different optimization functions, which can significantly increase the costs of the interconnected utilities.
- Lack of coordination among TSOs can increase reactive power flows in interconnection lines, which limits the transmission capacities and stresses the entire power system.
- It is customary to assume that there is no reactive power flow between TSOs when they schedule their power dispatch, but in practice, the exchange of reactive power is rarely negligible.

Centralized Coordination: Each TSO (Transmission System Operator) transfers its prerogatives to a center which builds consensus among different areas through a specific multi-party optimization scheme.

- With ever larger area of interconnected operators, this formulation is neither feasible in computation nor reliable in communication.
- Every TSO may preserve some prerogatives of its power system.

Decentralized Coordination: With no information exchange between TSOs, each control area assumes an external network equivalent in place of its neighbor areas and optimizes its own objective function regardless of its impact on the others.

- It does not lead to an optimal performance in large and can not guarantee a secure operation, as satisfying the objective of a single TSO may adversely affect other TSOs.
- Conflicting local strategies reduces TSOs' performance.

Negotiation makes our multi-agent design distinct from a conventional decentralized scheme. Intelligent agents do not respond to predefined requests from specific agents, but they negotiate and interact in a cooperative manner to reach a global agreement.

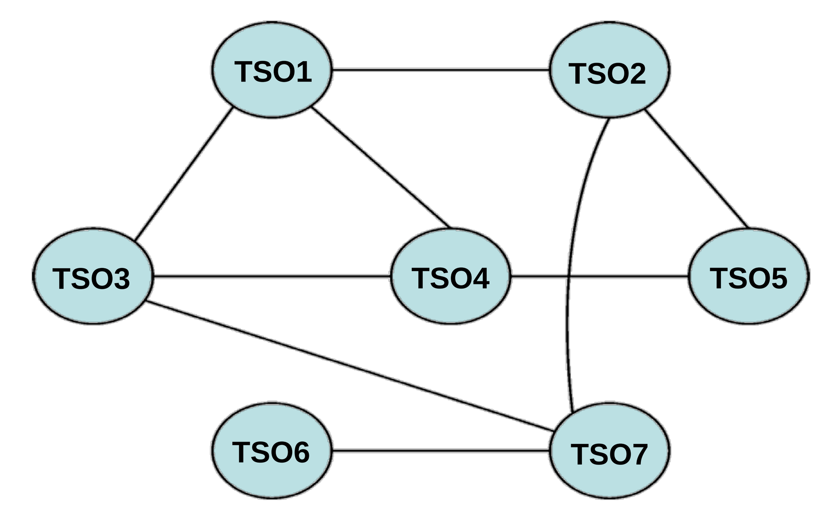
Adaptation, Optimization, Reconfiguration, Fault tolerance

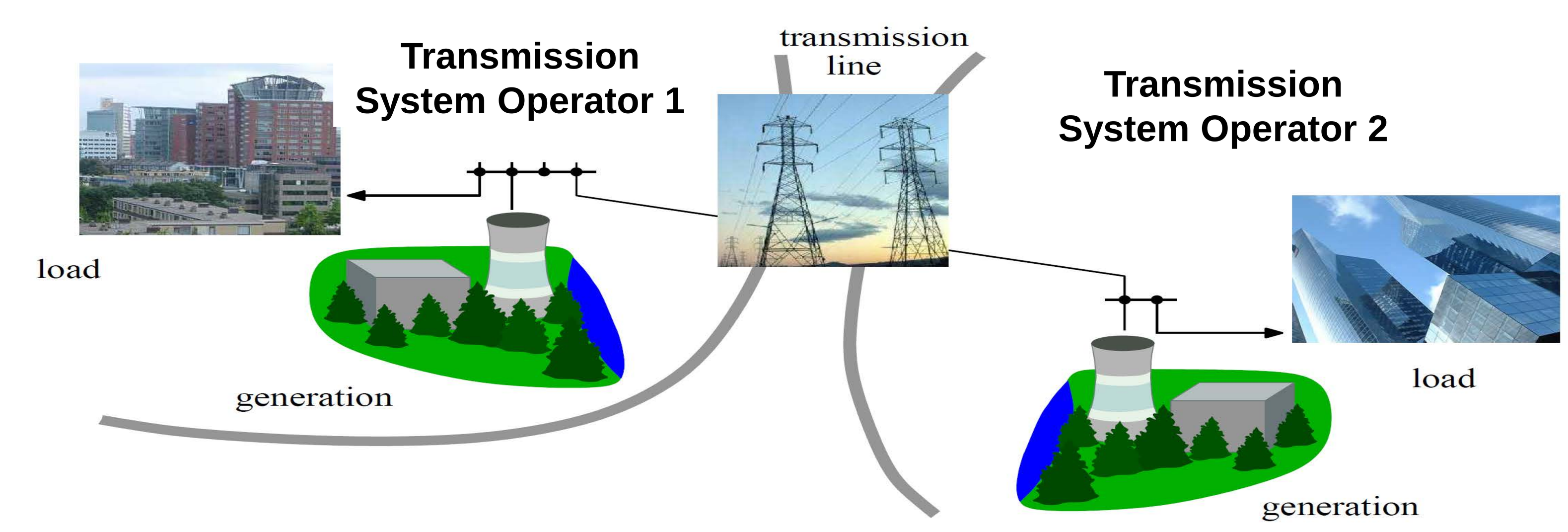
Extra degree of uncertainty is introduced by negotiation due to general difficulty of predicting the future state of an agent to guarantee a real-time performance.

Distributed model predictive control is used in which each agent knows a local model of its own area as well as reduced-order quasi-steady-state approximations of its neighbor areas.

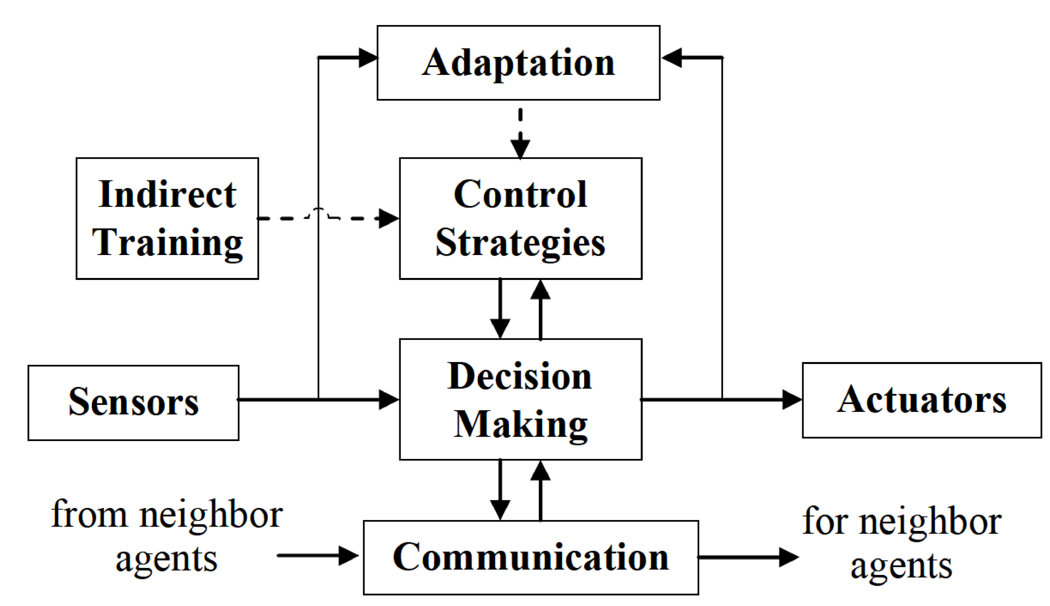
Active interaction-based distributed control approaches are highly promising in the light of access to wide-area synchronized PMUs and resilient high-speed communication networks in the future smart grid.

A large-scale multi-area power system is represented by an undirected graph





Agent Architecture



Communication enables the agent to negotiate with other agents for the coordinated execution of proper tasks.

Sensors perceive local data and estimates the voltage level and reactive power generation within the TSO.

Actuators execute the tasks by sending commands to tap positions, generators, FACTS devices, shunt capacitors, and/or load shedding procedure.

Decision making evaluates the current operating state using endogenous data from the sensors and exogenous data from neighbor areas.

Control strategies provides the **decision making** module with a proper control and optimization algorithm from its database, based on the system operating state.

Adaptation: As long as the control strategy has not changed, the **decision making** module dynamically adjusts its behavior in accordance with the information provided by the **sensors** and **communication** modules. Meanwhile, the **adaptation** module continuously evaluates the control policy performance and accordingly updates the model parameters and objective functions in the **control strategies** data-base.

To meet voltage control requirements, the control agent should take different control strategies and algorithms under different conditions.
In this work we consider only two state modes: **● Normal Mode ● Emergency Mode**

Normal Mode Operation based on Distributed Model Predictive Control approach

In a steady-state practice, each TSO uses a general dynamic model of its own area as well as a reduced-order QSS model of its neighbors, exchanged at each **time-slot**.

Every **time-step** k, the continuous-time linearization of local DAE equations is obtained in the "decision making" module.

$$x_i(k+1)=A_{ii}x_i(k)+\sum_{j\sim i}A_{ij}x_j(k)+B_iu_i(k)+g_i$$

$$v_i(k)=C_{ii}x_i(k)+\sum_{j\sim i}D_{ij}u_j(k-1)+h_i \qquad (1)$$

This discrete-time approximation is employed as a prediction model in:

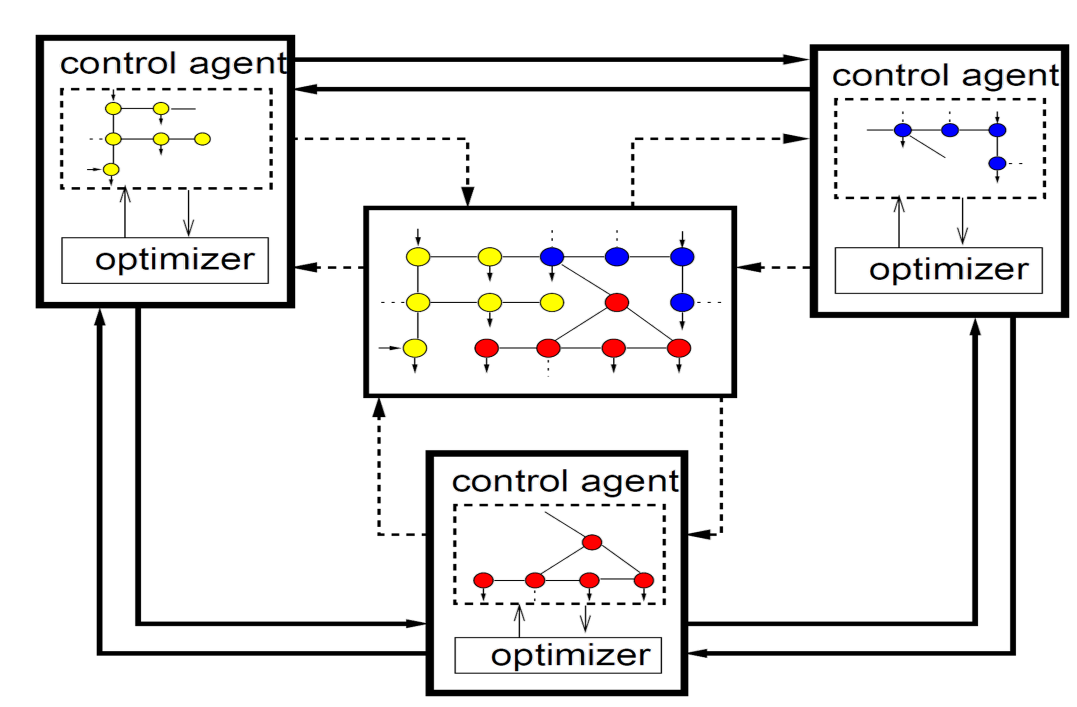
$$\min_{X_i(k),\,U_i(k)} J_i\big(X_i(k),\,U_i(k)\big)$$

Subject to: 1) equality constraints (1)
2) inequality constraints on the inputs

$$X_i(k)=\{x_i(k+1|k),\,\dots,\,x_i(k+m|k)\}$$

$$U_i(k)=\{u_i(k|k),\,\dots,\,u_i(k+m-1|k)\}$$

This performance index represents the measure of the difference between the predicted behavior and the desired future behavior: The lower the value, the better the performance.

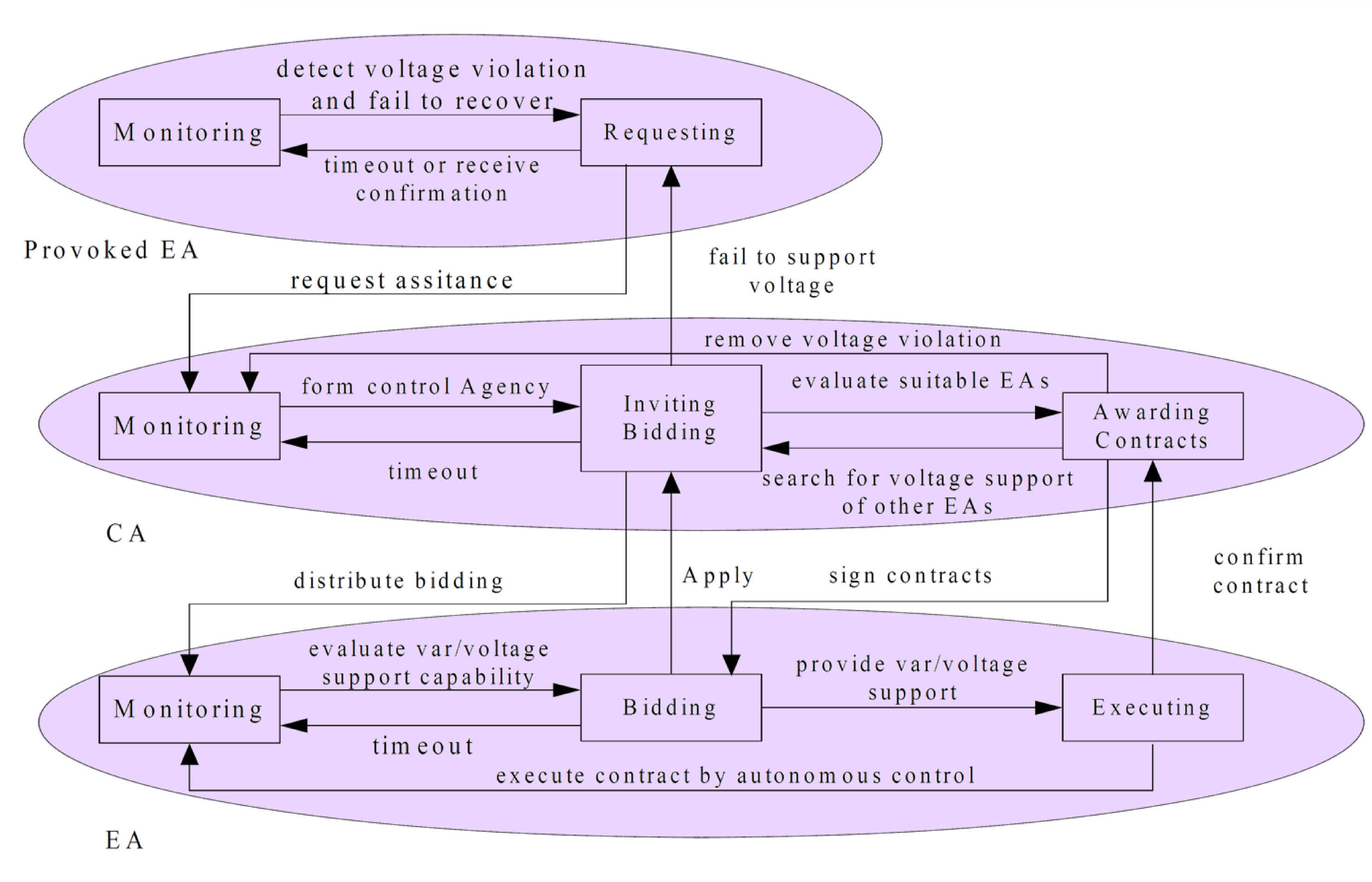


The variables $x_i(k+m|k)$ and $u_i(k+m|k)$ are respectively the predicted state and the predicted control of agent i at time-step $k+m$ given the information at the step k.

The optimization scheme produces an open-loop optimal control sequence in which only the first control value is applied to the system: $u_i(k)=u_i(k|k)$
The controller waits for the next time-step to repeat this process.

Each agent uses the predictions of neighbor agents at the previous time-step to estimate the influence of neighbor TSOs.

Coordination in Emergency Mode Operation based on Contract Net Protocol (CNP)



In emergency resulting from a large disturbance, it is necessary to manage a fast, dynamic response for providing the bus where voltage violation occurs with reactive power support.

The TSO first makes its own decision to change the settings of reactive power injection through its own entities for rapidly restoring the abnormal voltage back to its allowable range.

If voltage violation cannot be removed by the agent itself, it sends request for voltage control assistance to neighbor areas.

For the coordination of neighbor TSO agents in recovering the violated voltage, we use CNP (Contract Net Protocol), that is a negotiation-based protocol to establish efficient cooperation among agents, very similar to the broadcasting protocol in communication networks.

If one agent discovers a problem that is not able to solve it alone, it announces this problem to the rest of the agents. Some other agents will reply to the corresponding agent to provide help for solving the problem through a bidding and contract application.