A Multiagent System Approach to Schedule Devices in Smart Homes

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Feb, 2017
Home Automation

Fig. 1

Fig. 2

Nearly Zero-Energy Buildings = Niedrigstenergiegebäude nach EU (EPBD 2010)

Outline

• Background (DCOPs)

• Smart Homes Device Scheduling (SHDS)

• Results

• Conclusions and Future work
Distributed Constraint Optimization

\[ \langle X, D, F, A, \alpha \rangle:\]

- \( X \): Set of variables.
- \( D \): Set of finite domains for each variable.
- \( F \): Set of constraints between variables.
- \( A \): Set of agents, controlling the variables in \( X \).
- \( \alpha \): Mapping of variables to agents.

Constraint graph

Constraint (cost table)

<table>
<thead>
<tr>
<th>( x_a )</th>
<th>( x_b )</th>
<th>cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>( \infty )</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>
Distributed Constraint Optimization

\(<X, D, F, A, \alpha>:\)

\(• X: \) Set of variables.
\(• D: \) Set of finite domains for each variable.
\(• F: \) Set of constraints between variables.
\(• A: \) Set of agents, controlling the variables in \(X.\)
\(• \alpha: \) Mapping of variables to agents.

\(• \text{GOAL:} \) Find a cost minimal assignment.

\[ x^* = \arg \min_x F(x) = \arg \min_x \sum_{f \in F} f(x|_{\text{scope}(f)}) \]
**DCOP: Assumptions**

- Agents coordinate an assignment for their variables.
- Agents operate distributedly.

**Communication:**
- By exchanging messages.
- Restricted to agent’s local neighbors.

**Knowledge:**
- Restricted to agent’s sub-problem.
- Privacy preserving.
Smart Home Device Scheduling (SHDS)

A SHDS problem is composed of:

- $H$: A neighborhood of smart homes.
- $Z_i$: A set of smart electric devices within each home $h_i$.
- $H$: A time horizon for the device scheduling.
A **SHDS** problem is composed of:

- $\mathcal{H}$: A neighborhood of **smart homes**.
- $\mathcal{Z}_i$: A set of **smart electric devices** within each home $h_i$.
- $H$: A time horizon for the device scheduling.
- $\theta$: A pricing function expressing cost per kWh of energy consumed.

<table>
<thead>
<tr>
<th>Time (min.)</th>
<th>[0-60]</th>
<th>[60-120]</th>
<th>[120-180]</th>
<th>[180-240]</th>
<th>[240-300]</th>
<th>[300-360]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTP ($/kWh$)</td>
<td>0.172</td>
<td>0.161</td>
<td>0.191</td>
<td>0.145</td>
<td>0.149</td>
<td>0.174</td>
</tr>
</tbody>
</table>
Smart Home

A smart home $h_i$ has:

- A set of smart devices $Z_i$ it can control.

\[ h_i \rightarrow Z_i \]
Smart Home

A smart home $h_i$ has:

- A set of smart devices $Z_i$ it can control.
- $L_i$ A set of locations (e.g., living room, kitchen)
Smart Home

A smart home $h_i$ has:

- A set of smart devices $Z_i$ it can control.
- $L_i$ A set of locations (e.g., living room, kitchen)
- $P_H$ A set of state properties (e.g., cleanliness, temperature)
Smart Devices (Actuators)

A smart device is defined with a

- **Location**, defining the place where the device can act (e.g., living room)
- The possible **actions** it can perform (clean, charge, stop) and the power consumption associated to them
- The set of **state properties** it affects (e.g., cleanliness, battery_charge)

<table>
<thead>
<tr>
<th>Action</th>
<th>State property</th>
<th>Power (kW/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>run</td>
<td>cleanliness</td>
<td>0.0</td>
</tr>
<tr>
<td>charge</td>
<td>battery charge</td>
<td>0.26</td>
</tr>
<tr>
<td>stop</td>
<td></td>
<td>0.0</td>
</tr>
</tbody>
</table>
Smart Devices (Sensors)

- We associate a *predictive model* to each home sensor.
- It describes the transition of a state property from a state $s$ and time $t$ to time $t+1$, when affected by a set of actuators.

<table>
<thead>
<tr>
<th>Heater</th>
<th>Oven</th>
<th>Current State</th>
<th>Next State</th>
</tr>
</thead>
<tbody>
<tr>
<td>off</td>
<td>off</td>
<td>12 C</td>
<td>11 C</td>
</tr>
<tr>
<td>off</td>
<td>bake</td>
<td>12 C</td>
<td>13.8 C</td>
</tr>
<tr>
<td>on</td>
<td>off</td>
<td>12 C</td>
<td>17.5 C</td>
</tr>
<tr>
<td>on</td>
<td>bake</td>
<td>12 C</td>
<td>19.3 C</td>
</tr>
</tbody>
</table>

Effect of the environment
Smart Device Schedules

Scheduling Rules

- **Simple syntax to express scheduling rules:**
  \[<location> <state property> <relation> <state> <time>\]

- **Active rules:** specify user-defined objectives on a desired state of the home. E.g.,
  
  \[living\_room\_cleanliness \geq 75\ \text{before} \ 1800\]

- **Passive rules:** define implicit constraints on devices. E.g.,
  
  \[z_v \ battery\_charge \geq 0\ \text{always}\]
  
  \[z_v \ battery\_charge \leq 100\ \text{always}\]
Smart Device Schedules

Schedule: A sequence of actions for the home devices.

<table>
<thead>
<tr>
<th>Device Schedule</th>
<th>Cleanliness (%)</th>
<th>Battery Charge (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>0</td>
<td>65</td>
</tr>
<tr>
<td>R</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>R</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>55</td>
</tr>
<tr>
<td>R</td>
<td>45</td>
<td>30</td>
</tr>
<tr>
<td>R</td>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>R</td>
<td>60</td>
<td>25</td>
</tr>
<tr>
<td>C</td>
<td>75</td>
<td>0</td>
</tr>
</tbody>
</table>

**Background**

**SHDS**

**Results**

**Conclusions**
**Smart Home Device Scheduling (SBDS)**

- **SHDS objective:**

  \[
  \min_{\xi, z_{\pi \to H}} \alpha_c \cdot C_{\text{sum}}^{\text{opt}} + \alpha_e \cdot E_{\text{diff}}^{\text{opt}}
  \]

  Aggregated monetary cost of the homes schedules

  Energy consumption peaks across all homes

  Homes’ devices schedules

  subject to:

  \[
  \forall h_i \in H, R_p^{[t_a \to t_b]} \in R_i : \xi^{[t_a \to t_b]} \Phi_p^{[t_a \to t_b]} = R_p^{[t_a \to t_b]}
  \]

  All scheduling rules must be satisfied
### DCOP mapping

#### SBDS
- A home $h_i \in \mathcal{H}$.
- A device $z_j$ (in building $h_i$)
- Action $j$ for device $z_j$.
- Schedule costs for a device $z_j$
- Device scheduling feasibility
- Energy peak consumption

#### DCOP
- Agent $a_i \in \mathcal{A}$
- Variable $x_i \in \mathcal{X}$ (controlled by $a_i$)
- j-th value in domain $D_i$ of variable $x_i$
- Local soft constraint
- Local hard constraint
- Global soft constraint
Solution Approach

SH-MGM: Adaptation of a local search DCOP algorithm (MGM).
1. Agents independently search for a feasible schedule for their local devices.

\[ c_i : \text{schedule cost} \]
\[ E_i^t : \text{energy consumption} \]
Solution Approach

SH-MGM: Adaptation of a local search DCOP algorithm (MGM).

1. Agents independently search for a feasible schedule for their local devices.
2. Schedule costs and energy consumption are broadcasted to all other agents.
Solution Approach

SH-MGM: Adaptation of a local search DCOP algorithm (MGM).

3. Upon receiving all other agents costs and energy consumptions:

- $c_i$: schedule cost
- $E_j^t$: energy consumption
Solution Approach

SH-MGM: Adaptation of a local search DCOP algorithm (MGM).

3. Upon receiving all other agents costs and energy consumptions:
   • Computes the objective cost with its current schedule.
**Solution Approach**

SH-MGM: Adaptation of a local search DCOP algorithm (MGM).

3. Upon receiving all other agents costs and energy consumptions:
   - Computes the objective cost with its current schedule.
   - Within a time limit, it finds a new solution to its local subproblem that is no worse than the current solution.

\[
\alpha_c \cdot c_i(\hat{\xi}_{Z_i}^{[0 \rightarrow H]}) + \alpha_e \cdot \hat{E}^{\text{diff}} \leq \alpha_c \cdot c_i(\xi_{Z_i}^{[0 \rightarrow H]}) + \alpha_e \cdot E^{\text{diff}}
\]

- \(c_i\): schedule cost
- \(E_i^t\): energy consumption

**Conclusions**
Solution Approach

SH-MGM: Adaptation of a local search DCOP algorithm (MGM).

3. Upon receiving all other agents costs and energy consumptions:
   - Computes the objective cost with its current schedule.
   - Within a time limit, it finds a new solution to its local subproblem that is no worse than the current solution.
   - It computes the gain $G_i$ between its current and new solutions, and broadcast it to all other agents.

\[
G_i = \left( \alpha_c \cdot c_i(\xi_{Z_i}^{[0 \rightarrow H]} ) + \alpha_e \cdot E_{\text{diff}} \right) \\
- \left( \alpha_c \cdot c_i(\hat{\xi}_{Z_i}^{[0 \rightarrow H]} ) + \alpha_e \cdot \hat{E}_{\text{diff}} \right)
\]

- $c_i$: schedule cost
- $E_t^i$: energy consumption
Solution Approach

SH-MGM: Adaptation of a local search DCOP algorithm (MGM).

4. Upon receiving all other agents’ gains $G_k$, it checks if the agent has the largest gain among all those received. If so, it updates its schedule to the new schedule, otherwise it retains its old schedule.

5. The process repeats until convergence (all gains = 0) or a fixed number of iterations.
Evaluation: Settings

- 7 Raspberry Pis connected via a LAN.
- Each controlling 9 smart actuators.
- Communication and coordination of the MAS is implemented via the JADE framework.
- Each agent uses an internal CP solver (JaCoP) to solve its local scheduling problem.
Evaluation

Settings:
- $H = 12 \text{ (step = 30 min)}$
- Realistic device consumptions and environment settings
- CP timeout = 10 sec

Main Results:
- SH-MGM finds better solutions than a simple uncoordinated approach.
- Solution quality increases with the number of cycles.

![Graph showing comparison between SH-MGM and Uncoordinated approach]
Conclusions and Future Work

• We formalized the Smart Home Device Scheduling Problem and cast it as a DCOP.

• We propose SH-MGM, a local search-based algorithm to solve SHDS problems.

• Some results:
  • SH-MGM finds better solutions than a simple uncoordinated method.
  • Feasibility established for using a local search-based approach implemented on hardware with limited storage and processing power.

• Future work:
  • More realistic setting for the SHDS agents and devices.
  • Taking account user preferences for the scheduling rules.
Thank You!

References:

Fig. 1: http://goo.gl/5znqip
Fig. 2: goo.gl/dqwUz2
Fig. 3: goo.gl/WFzMhv