Introduction

• Post-disaster restoration planning for a water supply system is important but very difficult.

• Difficulties in restoration planning:
  1. Situation awareness in dynamic and uncertain situation → Technical problem
  2. Prioritization in restoration process → Socio-technical problem

• Great need for a high-fidelity simulation of water supply system restoration for testing and comparing various prioritizations
1. To develop a high-fidelity simulation of water supply system restoration
   – Considering multiple interdependencies underlying urban systems
   – Implementing a realistic restoration task
   – Considering hydrodynamic behavior of water distribution system
   – Using the actual city data

2. To apply this simulation to practical decision-making support
   – Restoration planning reflecting the priority in restoration process
Modeling Framework

## Multiple Interdependencies

<table>
<thead>
<tr>
<th>Dependence Of</th>
<th>Civil Life</th>
<th>Industry</th>
<th>Lifeline</th>
</tr>
</thead>
</table>
| Civil Life    | 1) Between civil life  
|               | ● Means-ends  
|               | ● Resource conflict  
|               | ● Geographical  
| Industry      | 2) Civil life on industry  
|               | ● Supply  
|               | ● Geographical  
| Lifeline      | 3) Civil life on lifeline  
|               | ● Supply  
|               | ● Geographical  
| Civil Life    | 4) Industry on civil life  
|               | ● (Labor) Supply  
|               | ● Geographical  
| Industry      | 5) Between industry  
|               | ● Supply  
|               | ● Demand  
|               | ● Alternative  
|               | ● Geographical  
| Lifeline      | 6) Industry on lifeline  
|               | ● Supply  
|               | ● Geographical  
| Civil Life    | 7) Lifeline on civil life  
|               | ● Demand  
|               | ● (Labor) Supply  
|               | ● Geographical  
| Industry      | 8) Lifeline on industry  
|               | ● Demand  
|               | ● Supply  
|               | ● Geographical  
| Lifeline      | 9) Between lifeline  
|               | ● Supply  
|               | ● Demand  
|               | ● Alternative  
|               | ● Geographical  

4
Simulation Model

• Agent-based model
  – Citizen: daily activity
  – Company: production process
  – Restoration Squad: restoration process

• Network model
  – Lifeline Infrastructures
  – Power grid, **water supply**, sewage, gas, **road**, waste disposal, telecommunication, etc.
Restoration Task

- **Restoration procedure**
  1. Get the resources for restoration from the warehouse
  2. Move to the damaged pipeline
  3. Repair by using the resources

- **Realistic restoration operations**
  - Operate valves
  - Use a heavy machinery
  - Partition the affected area and repair in block units
  - Distribute water tank trucks
  - Receive the support from outside the city
Hydrodynamic Behavior

• Hydrodynamic Analysis API (EPANET)
  – Calculate the water demand, flow, pressure, and so on
  – Evaluate the water availability of each residence / company
  – https://www.epa.gov/water-research/epanet
City Model

- Target area under this study
  - Arao city
  - In Kumamoto prefecture, Japan
  - With a population of about 50,000 people

- City model considering:
  - Population and its distribution
  - Number of companies
  - Location of important facilities such as hospitals and evacuation centers
  - Road network topology from OSM
  - Water supply network topology
Optimization of Restoration Plan

• Genetic Algorithm (GA)
  – Chromosome: restoration plan
    • the order of restoration for damaged pipelines
    • the squad in charge of the restoration

\[
\text{fitness} = \alpha \times \text{fitness}_L + \beta \times \text{fitness}_I + \gamma \times \text{fitness}_C
\]

- \text{fitness}_L (Lifeline)  Restoration rate
- \text{fitness}_I (Industry)  Operation rate
- \text{fitness}_C (Civil Life)  Quality of life

– Weight coefficients \((\alpha, \beta, \gamma)\) = the priority of each subsystem
Simulation

- Simulation Procedure
  
  **start**
  
  initialize agents and networks
  
  initialize damage on water pipelines
  
  run recovery simulation
  
  evaluate fitness
  
  final generation?
  
  **end**

- Simulation Setting

<table>
<thead>
<tr>
<th>Network (*1)</th>
<th>Nodes</th>
<th>173</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Links</td>
<td>199</td>
</tr>
<tr>
<td></td>
<td>Damaged Links (*2)</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Agent</th>
<th>Company</th>
<th>153</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Residence</td>
<td>257</td>
</tr>
<tr>
<td></td>
<td>Citizen / Worker (*3)</td>
<td>1540</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GA</th>
<th>Population</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Generations</td>
<td>10000</td>
</tr>
<tr>
<td></td>
<td>Selection Rate</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Crossover Rate</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Mutation Rate</td>
<td>0.1</td>
</tr>
</tbody>
</table>

(*1) only the central part of Arao city
(*2) estimated by potential earthquake damage
(*3) 1 agent representing approx. 11 people
Simulation Results (1)

- As the number of generations increases, the fitness value becomes higher.
- The optimized plan was 5 days shorter than non-optimized plan.
- GA optimization works appropriately.
• We can observe and evaluate the restoration process of each three subsystem.
Simulation Results (3)

<table>
<thead>
<tr>
<th>Objective Function</th>
<th>Lifeline</th>
<th>Industry</th>
<th>Civil Life</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>α:β:γ=1:1:1</td>
<td>70.85</td>
<td>94.60</td>
<td>82.28</td>
<td>247.73</td>
</tr>
<tr>
<td>α:β:γ=1:0:0</td>
<td>69.85</td>
<td>106.94</td>
<td>91.03</td>
<td>267.82</td>
</tr>
<tr>
<td>α:β:γ=0:1:0</td>
<td>80.40</td>
<td>87.13</td>
<td>98.80</td>
<td>266.33</td>
</tr>
<tr>
<td>α:β:γ=0:0:1</td>
<td>71.86</td>
<td>108.89</td>
<td>83.18</td>
<td>263.93</td>
</tr>
</tbody>
</table>

- The different objective functions provide slightly different results.
- We can compare the optimized restoration under various prioritizations.
Conclusion

• A high-fidelity simulation of water supply system restoration was developed.
  – Considering multiple interdependencies underlying urban systems
  – Implementing a realistic restoration task
  – Considering hydrodynamic behavior of water distribution system
  – Using the actual city data

• Optimization of restoration plan using GA was conducted.
  – GA optimization works appropriately.
  – We can observe the restoration process of each three subsystem.
  – We can compare the optimized restoration under various prioritizations.
Thank You!

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