Modeling Disaster Response Using Multi-Agent Systems: Snowstorm Simulation Framework

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Research Problem

Traditional disaster management systems struggle to respond quickly and adapt to changing conditions, especially in snowstorms where real-time decisions are critical. The 2019 snowstorm in Western New York exposed how delays and poor coordination can lead to serious disruptions. Inspired by Vereshchaka and Dong's work **[1]** on multi-agent resource allocation, this project explores a decentralized, adaptive approach using agent-based modeling to simulate more efficient and responsive disaster management.

Goals

- Design and implement a real-time snowstorm simulation using GIS data and the GAMA platform
- Develop adaptive snowplow and rescue agents using decentralized coordination and BDI-inspired decision-making
- Evaluate system performance through response time, road clearance efficiency, and realistic agent behavior metrics

Multi-Agent Systems

Multi-Agent Systems consist of independent agents that make decisions based on their local surroundings while interacting with others in a shared environment.
This decentralized approach is well-suited for disaster scenarios that require fast, adaptive responses.

In this simulation:

Snowplows and rescue vehicles act autonomously, reacting to road and weather conditions

Agents collaborate without a central authority, improving flexibility and responsiveness

MAS allows the system to realistically model the complexity of real-time emergency operations

GAMA: A Platform for Simulating MAS Behavior

GAMA is a simulation platform designed for spatially-explicit agent-based models. It was chosen for this project due to its ability to integrate GIS data for realistic maps, support real-time agent interaction, and provide visual feedback. GAMA also allows the implementation of custom algorithms, enabling agents to adapt their behavior and make decentralized decisions in response to changing conditions**[2].**

BDI Architecture for Agent Decision-Making

Agents in this simulation follow a simplified **Belief-Desire-Intention (BDI)** model:

- **Beliefs**: local knowledge (e.g., snow levels, road status)
- **Desires**: goals like clearing roads or reaching emergencies
- **Intentions**: chosen actions to achieve those goals

This structure allows agents to make adaptive, goal-driven decisions in real time, improving coordination and responsiveness.

Methodology

The simulation was developed in stages using the GAMA platform.
The first model developed is **baseline random model**, where snowplows and rescue vehicles moved without coordination. This served as a reference for performance comparison

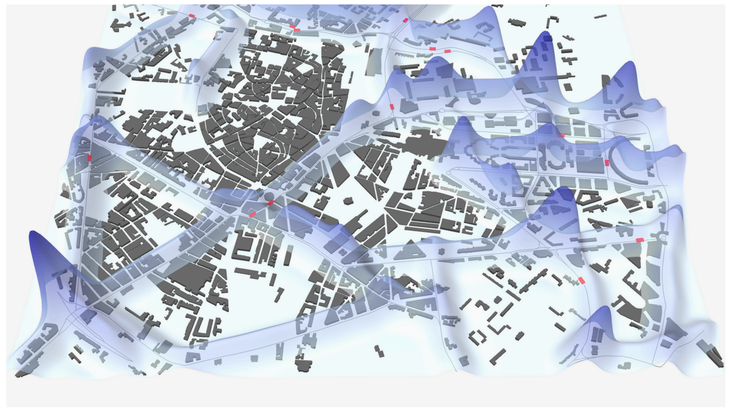

Figure 1: Real-Time 3D Visualization of Snow Accumulation Using Mesh Rendering

The final model uses a **scoring system** to help snowplows prioritize roads based on **snow levels**, **distance**, and **road importance**.
Plows target the highest-scoring roads, while rescue vehicles adapt their speed to current road conditions.
This coordination leads to faster, more efficient responses in dynamic snowstorm scenarios.

$$finalScore = snowFactor + (distanceFactor \times 0.2) + priorityScore - distancePenalty$$

Figure 2: Scoring Formula for Route Evaluation

Road Condition	Snow Level Range	Speed Multiplier
Heavy Snow	> 10 units of snow	0.25× base speed
Moderate Snow	5 – 10 units of snow	0.5× base speed
Light Snow	1 – 5 units of snow	0.75× base speed
Cleared or Slightly Covered	≤ 1 units of snow	1.0× base speed

Figure 3: Speed Adaptation System Based on Snow Level

Results

The structured model using a scoring-based decision system significantly outperformed the baseline random model.
Snowplows prioritized roads by **snow level**, **distance**, and **road importance**, leading to faster and more efficient snow removal.
The performance graph shows that structured plowing results in consistently higher snow cleared over time.

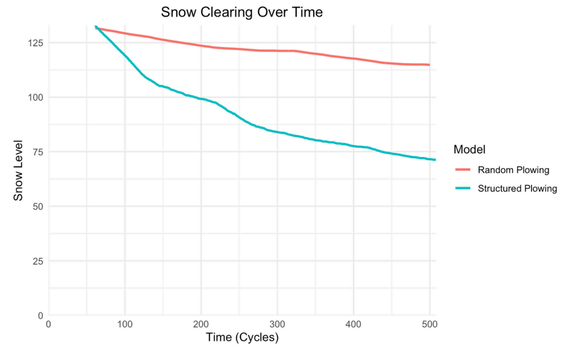

Figure 4: Comparative Snow Clearing Efficiency: Structured vs. Random Plowing

Rescue vehicles in the final model **adapted speed** based on snow levels, unlike the base model with fixed speeds.
Vehicles reached their targets **25–30% faster** in most cases under structured plowing, thanks to earlier and more targeted snow clearing.
Smooth progress curves in the structured model highlight **uninterrupted and efficient routing**.

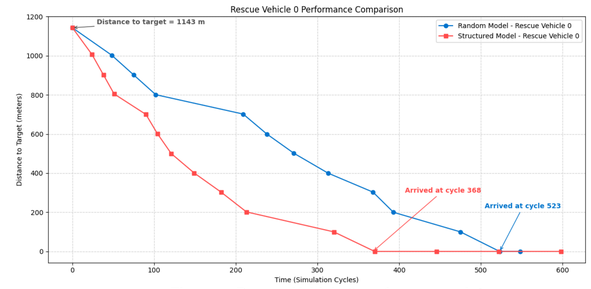

Figure 5: Rescue Vehicle 0 performance plot.

Conclusion

This project transformed theoretical models into a working snowstorm simulation using GAMA and multi-agent systems.
Agents evolved from random behavior to coordinated decision-making through scoring-based logic and adaptive speed.
The final model shows that decentralized, real-time coordination significantly improves snow clearing and rescue response, demonstrating the power of agent-based systems for disaster management.

References

[1] Vereshchaka, A., & Dong, W. (2019).Dynamic Resource Allocation During Natural Disasters Using Multi-agent Environment.
[2] P. Taillandier et al. "Building, Composing and Experimenting Complex Spatial Models with the GAMA Platform". In: (2019). url: https://doi.org/10.1007/s10707-018- 00339-6