KINSHIP INFRASTRUCTURE DESIGN: LEVERAGING BIOLOGICAL INSPIRATION TO CREATE RESILIENT SYSTEMS

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Abstract

Facing the challenge of planning for disasters without knowing all the details in advance, this study introduces a new, nature-inspired method called Kinship Infrastructure Design (KID). Drawing from how bees and other social animals share strong family ties, we propose that similar "kinship" ideas can improve disaster response strategies, making them more efficient and robust. We tested this by simulating a forest fire scenario and evaluating 60 different plans for fighting the fire, each based on varying levels of kinship ideas. Our tests found a sweet spot, termed the "Goldilocks Zone" of kinship, between 0.5 and 0.75, where disaster responses were most effective, saving an extra seven percent of forest with the same budget compared to other methods. This discovery confirms that KID is a valuable approach for early disaster response planning, offering a fresh way to think about allocating resources in emergencies. By borrowing the concept of kinship from nature, we suggest a shift from traditional planning to a more flexible, stronger system design inspired by the natural world.

Research Question

How can the concept of kinship coefficients observed in eusocial animals, such as honeybees, be applied to disaster response infrastructure to optimize its efficiency and resilience without detailed pre-fault analysis?

Purpose

- Utilize the concept of kinship coefficients observed in eusocial animals as a model for organizing and optimizing disaster response systems.
- Develop and test the KID methodology to determine its effectiveness in improving the efficiency and resilience of disaster response infrastructures without the need for detailed pre-fault analysis
- Propose a shift from traditional, detailed fault analysis to a more adaptive, resilient approach based on the natural dynamics of kinship observed in the animal kingdom.

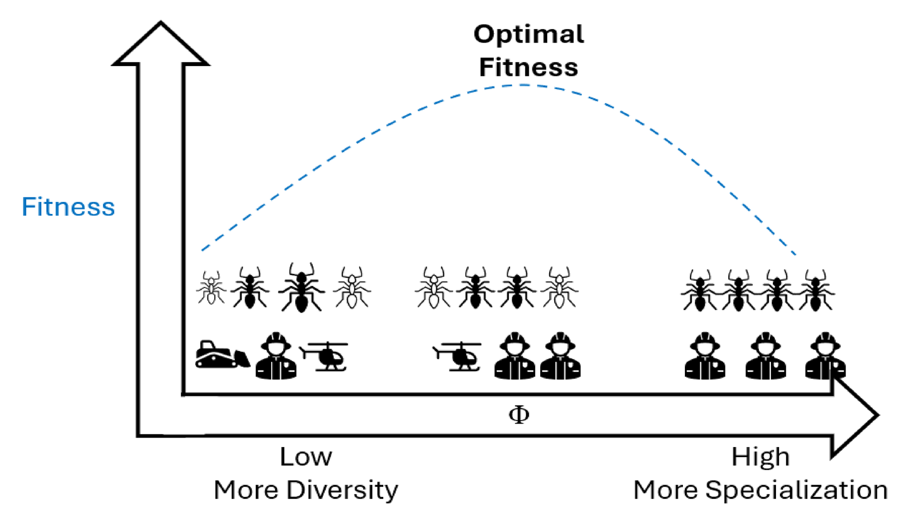

Figure 1: In natural systems, optimal fitness is found in a "goldilocks zone" of diversity (ϕ=.75 for ants). Our Hypothesis is that using ϕ can provide insight during the initial design phase for infrastructure systems. Note, that the blue dashed line is an approximation for illustration purposes.

Hypothesis

Applying kinship coefficients, inspired by the social structures of eusocial animals, to disaster response infrastructure design—termed Kinship Infrastructure Design (KID)—will identify a 'Goldilocks Zone' where resource allocation is optimized for both efficiency and resilience, significantly improving outcomes in simulated wildfire disaster scenarios compared to traditional planning methods.

Methods

- **Case Study Setup**: Focused on a 30 square mile forest at risk of wildfire, with a budget of $30,000 per day for different firefighting resources including teams, trucks, bulldozers, construction crews, and helicopters.
- **Calculating the Kinship Coefficient**: $\phi = \frac{\sum_{n=1}^{N} P\left(G_i(n) == G_{j,j \neq i}(n)\right)}{N}$ (1)

Where *G(n)* represents the allele for the n^{th} position in an individual's gene and the subscript *i*, *j* indicate the ith or jth individual. For example, consider the colony shown in the following genes (Equations 2 -4), with each gene represented as a horizontal array with three alleles.

- **Resource Costs**: Estimated costs for each resource were drawn from cited sources to ensure comparisons were made between infrastructures with equivalent budgets.
- **Kinship Coefficient Assignment**: Resources were allocated based on kinship coefficients ranging from 0.05 to 1.0, to assess diversity in resource distribution and its effect on wildfire management effectiveness.
- **Simulation Model**: Developed in AnyLogic 8.8.6, utilizing a grid to simulate the forest, initialized with lumber levels and incorporating roads acting as natural firebreaks.
- **Wildfire Introductions**: Simulated over a seven-day period with ignition times based on a Triangular distribution, evaluating the response of the firefighting resources.
- **Experiment Design**: Generated 1435 candidate infrastructures using a Python script, with three randomly selected for each kinship coefficient value. 50 Monte Carlo simulations captured stochastic elements such as unit positions and lumber levels.
- **Data Analysis**: Evaluated based on the percentage of forest area saved, with the goal of identifying a potential "Goldilocks Zone" for kinship coefficients.

TABLE 1: Firefighting Equipment Genome Values

Equipment	Speed	Travel Limit	Firebreak Ability	Watering Capacity	Flight
Firefighter Team	2	3	1	2	1
Construction Crew	1	2	2	1	1
Bulldozer	2	2	3	1	1
Helicopter	3	3	1	3	3
Firetruck	3	1	1	3	1

Table1: Basis for genome design

Results

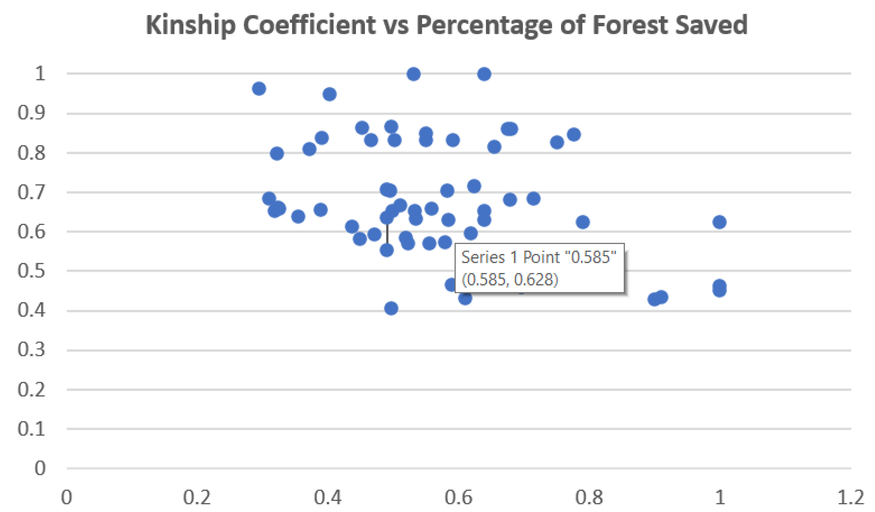

Figure 2: Kinship Coeficient (Φ) versus Percentage of Forest Saved

- A cluster of data points within the intermediate range of kinship coefficients hints at the potential existence of an optimal efficacy zone, albeit with a degree of variability.
- The presence of several higher-performing instances within the mid-range of kinship coefficients implies the potential existence of a "Goldilocks Zone".
- The spread of the data points across the graph suggests a subtle relationship between kinship coefficients and the percentage of forest saved during wildfires.

Simulation

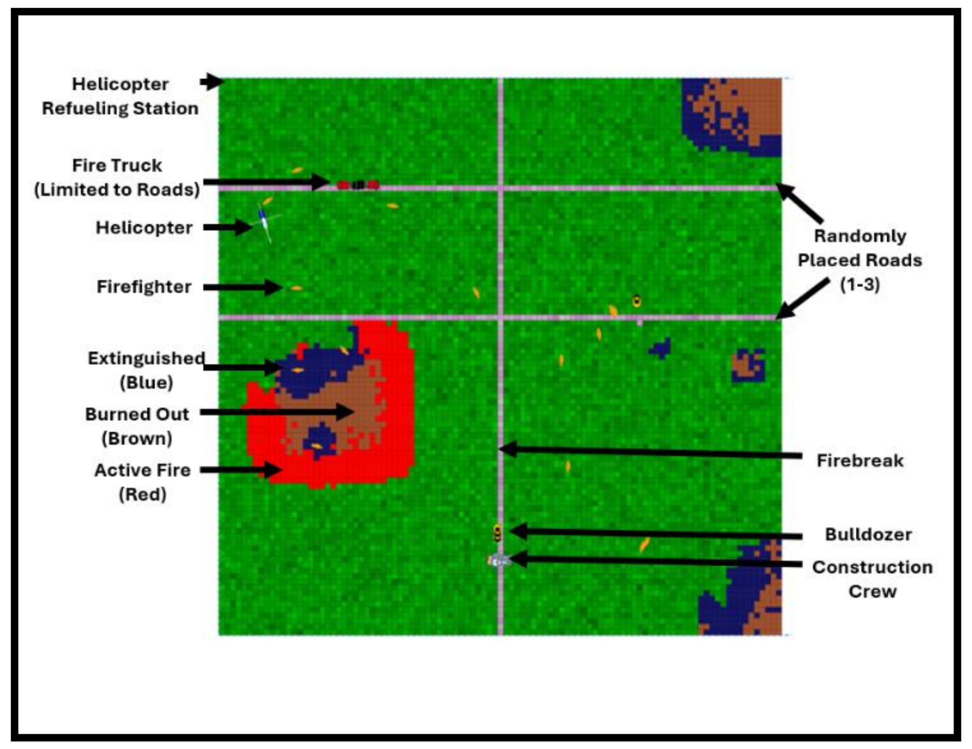

Figure 3: Example Simulation Run with Points of Interest

Conclusion

- •Kinship coefficients inspired by social animals enhance disaster response efficiency.
- •Data backs the "Goldilocks Zone" hypothesis for optimal resource allocation, acknowledging other influencing factors.
- •Confirms the value of bioinspired designs in complex systems and disaster resilience strategies.
- •Indicates a move towards adaptive emergency management that prioritizes efficiency.
- •The "Goldilocks Zone" informs better disaster response designs, confirming KID's effectiveness.

Future Work

- Test KID for floods and earthquakes to see how it works for different emergencies.
- Compare KID's costs and benefits to traditional methods for economic value.

Citations

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Biologically Inspired Design-for-Resilience Lab