CSE475 Project

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Abstract

The purpose of this project is to run a simulation with a simple agent design, the overarching objective being to achieve coherent behavior amongst the agents. The environment is designed to provide a rough simulation of how a real fire would spread through a two-dimensional area. The firefighter agents are all identical. They are designed to be mostly reactive due to the dynamic nature of fighting fires and for simplicity of coding. A series of simulations were run with varying numbers of firefighters, fires started, and visibility ranges of the firefighters. The data is presented in various tables and graphs. Following the presentation of the simulation data, observations are made about trends and whether the original hypotheses from the beginning of the project held true. Justifications for the trends observed follow the justifications section, then the implications of these observations are presented.

1 System Design

1.1 Environment

The environment in this project consists of an $L \times L$ grid, a maximum fire strength, S_{max}, a maximum flammability, F_{max}, and a maximum fuel level, G_{max}. The spaces in the grid are all of equal size, however the size is an arbitrary value. As such, an unlimited number of firefighters are allowed to occupy any given space at a time. Each space in the grid is assigned a random flammability value, $F \leq F_{max}$. This value determines both how likely the space is to start on fire, as well as how a fire responds once it is started in the space. This value on each space remains fixed throughout the simulation.

In addition, each space is assigned a random fuel level, $G \leq G_{max}$, which is systematically consumed as a fire burns on the space. At every tick, n, in the simulation, each space, i, in the environment is examined and its fire strength, S_i, and fuel level, G_i, are updated.

$$
S_{i_n} = \begin{cases} 0 & \text{if } S_{i_{n-1}} = 0, \text{ and } \sum S_{i_{neighbors}} < F_{max} - F_i \\ 1 & \text{if } S_{i_{n-1}} = 0, \sum S_{i_{neighbors}} \geq F_{max} - F_i, \\ & \text{and a random probability of } P \\ S_{i_{n-1}} + \frac{{F_i}^2}{F_{max}} & \text{if } S_{i_{n-1}} > 0, S_{i_{n-1}} < S_{max}, \text{ and } G_{i_{n-1}} > 0 \\ S_{max} & \text{if } S_{i_{n-1}} \geq S_{max} \\ S_{i_{n-1}} - \frac{{F_i}^2}{F_{max}} & \text{if } S_{i_{n-1}} > 0, \text{ and } G_{i_{n-1}} = 0 \\ S_{i_{n-1}} + 1 & \text{if } S_{i_{n-1}} < 0 \end{cases} \tag{1}
$$

$$
G_{i_n} = \begin{cases} G_{i_{n-1}} & \text{if } S_{i_{n-1}} \leq 0 \\ G_{i_{n-1}} - \frac{S_{i_{n-1}}}{S_{max}} & \text{if } S_{i_{n-1}} > 0 \end{cases} \tag{2}
$$

These equations are ultimately what control the state of the environment. Once a space starts on fire, it can only affect its immediate neighbors (not counting diagonals). This is how a fire is able to spread across the environment.

Ignition

At each tick, any space can have a fire ignited if there is no fire already present, there is still fuel, and the sum of the fire strength of all of the space's neighbors is higher than $F_{max} - F_i$, where F_i is the flammability level of the space. Once these conditions are met, the chances of a fire igniting are determined by the ignition probability variable, P. If a fire is to be started, S_i is set to 1 (Eq. 1).

This model allows for a space with a high flammability value to ignite more readily than a space with a low flammability. In other words, a space with a low flammability requires its neighbors to have a higher total fire strength in order to ignite.

Fire Lifespan

Once a space is on fire, the strength of that fire increases at every tick until either the maximum fire strength, S_{max}, is reached or until the fuel level of that space, G_i, reaches zero. The number of ticks needed for a fire to reach S_{max} depends on the flammability, F_i, of the space. A fire on a space with a higher flammability grows faster than a fire on a space with a lower flammability (Eq. 1).

If a fire's strength, S_i, reaches the maximum fire strength, S_{max}, it remains there until either the fuel level of the space, G_i, reaches zero, or the fire strength, S_i, is reduced due to being sprayed by a firefighter agent. Once the fuel level, G_i, reaches zero, the fire starts to burn out at the same rate that it grew when it ignited (Eq. 1).

When $S_i \leq 0$, the fire has been extinguished. If the fire is extinguished due to burning out its fuel, there is no chance of a new fire re-igniting on the space. If the fire was extinguished by a firefighter, and there is still fuel in that space ($G_i > 0$), a new fire can still be re-ignited in that space. Also, if a fire is extinguished by a firefighter, S_i can be less than zero. This indicates that the space is wet, and needs to dry before it can be re-ignited. Once $S_i = 0$, it remains there until the space re-ignites (Eq 1).

Fuel Consumption

As a fire burns on a space, i, it consumes the fuel in that space, G_i. How quickly the fuel burns depends on how strong the fire is, S_i (Eq. 2). Once the fuel level of a space reaches zero, a fire in that space begins to die down. Once the fire dies, the space is not able re-ignite.

Due to a glitch in the program that was not caught in time, G_i can become negative. This occurs every time that a fire burns itself out, because it does not start the burn-out process until G_i already equals zero. So, for every step that the fire is burning out, G_i becomes more negative. Fortunately, due to the large amount of total fuel in the environment, this glitch is not believed to have significantly changed the outcome of the experiments.

1.2 Firefighter Agents

The firefighter agents are designed to be as autonomous as possible while achieving coherent behavior. In order to achieve this, the logic required to make a firefighter able to maximize his well-being was designed first. Then, the blackboard communication protocol was designed to allow the firefighters to inform each other of the locations of new fires.

Intelligent Design

The firefighters were designed to be reactive agents in order to keep the design simple. The only history that a firefighter stores is the locations he has visited for the purpose of navigating through the environment towards a task. For all other information, the firefighter just makes observations of the environment.

A firefighter is allowed to move one space and shoot at one space in each step. He can only shoot the space he occupies or a space immediately adjacent to that space. The decision to allow two actions per step was justified by arguing that there is no reason that a real firefighter would not be able to shoot and move simultaneously.

With this restriction in mind, a firefighter goes through a series of decisions to determine the best course of action at each step (See Figure 1):

Decision 1: A firefighter first tests to see whether the space he currently occupies is on fire. If it is not on fire, the firefighter can move on to another problem, but if it is on fire, he must determine the best course of action to minimize the amount of damage received, and ultimately, to keep himself alive.

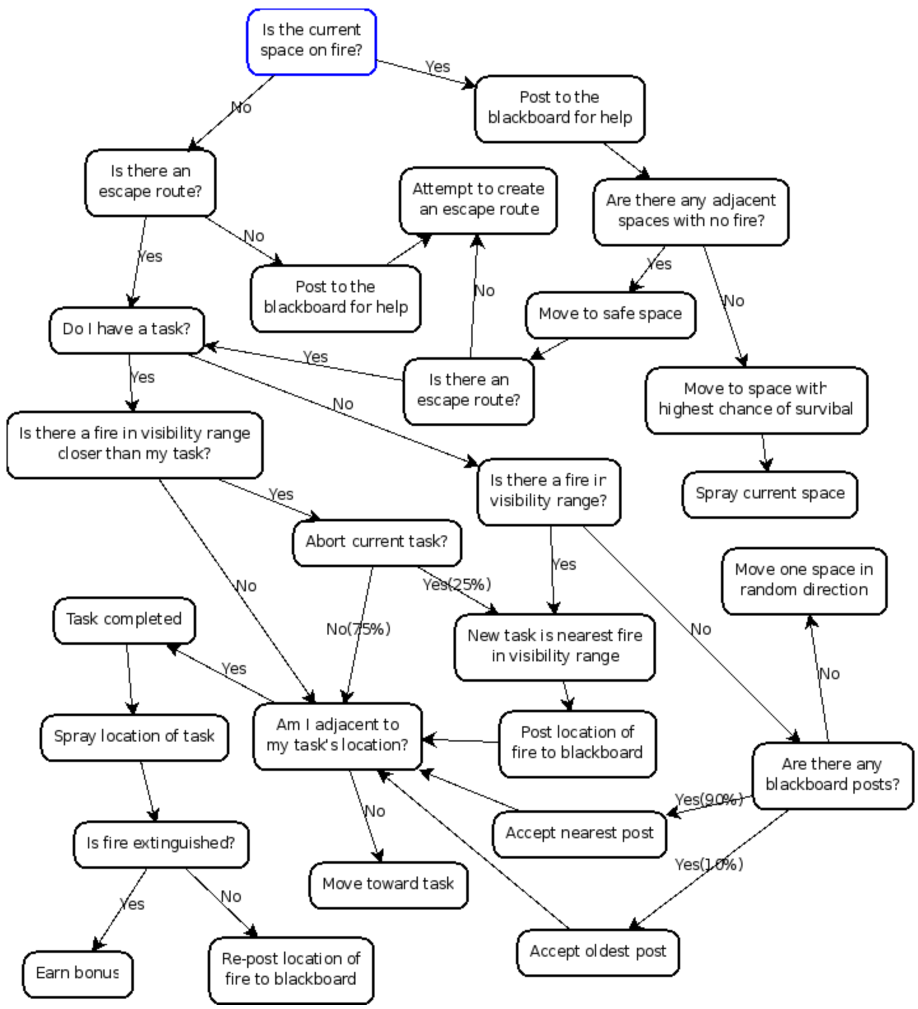

Figure 1: Firefighter Decision Tree

Staying Alive: Part 1

It is assumed that a space with no fire is safer than a space with fire. It is also assumed that a space with a lower flammability is safer than a space with higher flammability. A firefighter takes these two assumptions into account when he finds himself on a space that is on fire, and is trying to decide the best course of action. He first checks all of the spaces immediately adjacent to the space he currently occupies, and if there are one or more that are not on fire, he moves to the one that has the lowest flammability. Once he is in a safe location, he then moves on to decide which space to shoot.

Staying Alive: Part 2

If a firefighter is completely surrounded by fire, and the space he currently occupies is also on fire, his top priority is to get to the safest space. The safest space is considered to be the space that will cause the least amount of damage to the firefighter.

In this situation, the first thing he does is estimate how strong he believes the fire will be at each adjacent space in the next tick. This estimation is done based on the current fire strength, the flammability, and the amount of fuel on each of these spaces. The space with the lowest result is considered to be the safest.

Once the safest space has been determined, the firefighter moves to that space and immediately shoots it. By doing so, he is not only moving to the space that will cause the least amount of damage, but he is also reducing that amount of damage by weakening the fire there.

Decision 2: In an attempt to prevent ever having to act on the first decision, the firefighter always looks for an escape route. An escape route is simply an adjacent space that is currently not on fire. This means that the firefighter has somewhere to move to if the space he occupies starts on fire. If the firefighter finds such a space, he moves on to the next decision point, otherwise the firefighter finds the adjacent space that will be easiest to reduce the fire strength to zero of and shoots it.

Decision 3: After a firefighter ensures that he is not on fire and has an escape route, he tries to find a fire to extinguish. First, he checks to see if there is a fire within visibility range. Then, if he has already accepted a blackboard post that is farther away than the fire he spotted, he must choose whether to continue toward his task, or to abort and move toward the fire. This decision is based on a random probability, where there is a 75% chance that he will continue toward his task, and a 25% chance that he will abort and move toward the fire.

If a firefighter does not have a task at hand and there is no visible fire, he checks the blackboard for new posts. While searching the blackboard, only the tasks that a firefighter is capable of helping with are considered.

That is, if a firefighter has low energy, he will not accept a post for a fire that has a high intensity. Also, among the tasks being considered, there is a 90% chance that he will accept the task that is closest to his current location, and a 10% chance that he will accept the oldest post on the blackboard.

If there are no posts on the blackboard, and there are no fires in his visibility range, a firefighter chooses a random direction to move.

Communication

The firefighters are capable of communicating with each other by means of a simple blackboard system. The messages that are posted to the blackboard simply contain coordinates, and the strength of the fire there, if it is known. The blackboard maintains the messages in the order that they are received. Also, when a response to a message is received, that message is removed from the blackboard to prevent multiple responses to a message.

A firefighter posts a message to the blackboard in various situations. Every time a firefighter finds a fire, and decides to move toward it, he posts the location and intensity of the fire. If a firefighter finds himself on a space that is on fire, he posts a message to the board, essentially asking for help. Likewise, if a firefighter ever finds himself without an immediate escape route, he posts to the board for help.

A firefighter checks the blackboard when he does not have a task, and there are no fires in his visibility range. While searching the blackboard, there is a 90% chance that the firefighter will choose to respond to the message with the closest coordinates to his current location, and a 10% chance that he will choose to respond to the oldest message on the board.

The purpose of the blackboard system is to help the firefighters find fire when they do not have an immediate task to take care of. Because of this, it is safe to say that local decision-making is preserved. To ensure the firefighters keep their autonomy, they still search for fires on their approach to the location of the task they remove from the blackboard. If a fire is found closer to the firefighter than the location of the task, there is a 25% chance that the firefighter will abandon the task taken from the blackboard to extinguish the closer fire.

Learning

The firefighters are not capable of any form of advanced learning. That is, they do not make any decisions based on anything they have encountered in the past. However, when a firefighter earns the bonus from extinguishing a fire, that bonus is then applied to how well a firefighter can fight the next fire. So, as a firefighter extinguishes more fires, he is able to put out later fires with greater ease. While this is not technically "learning" in a MAS point of view, it is quite obvious that the firefighters are quicker to put out fires later in the simulation.

1.3 Definitions

Effectiveness: The effectiveness of the system is measured by comparing the percentage of fuel remaining in the environment at the end of the simulation against the baseline percentage of fuel remaining after running the simulation with no firefighters. If the percentage is higher than the baseline, the system is considered to be effective. The higher the percentage, the more effective the system is.

Efficiency: The efficiency of the system is determined by the total amount of firefighter health remaining at the end of a simulation. If the total amount of health reaches zero, that means that all of the firefighters were killed, and the system is not considered to be efficient at all.

Coherence: The system is considered to reach coherence if both effectiveness and efficiency are reached on some level. That is, at least one firefighter must survive, and the remaining fuel level must be higher than what it would have been if there were no firefighters.

1.4 Hypotheses

Hypothesis 1: The effectiveness of the team of firefighter agents is proportional to $\frac{N}{K}$. However, if $N \ll K$, then the effectiveness becomes nonexistent, and the fire will end up burning up most of the available fuel in the environment.

Hypothesis 2: The efficiency of the team of firefighter agents is proportional to $\frac{N}{K}$. However, if $N \ll K$, then the efficiency becomes non-existent, and the firefighters are all likely to be killed.

Hypothesis 3: If $L \times L \gg N$ and $K \gg N$, then the system will not achieve coherence. On the other hand, if $N \approxeq L \times L$ and $N \gg K$, then the system will achieve coherence quickly.

Hypothesis 4: The effectiveness of the system is proportional to V. That is, the farther a firefighter can see in the environment, the better the chances are that he will see a previously undetected fire, and thus yielding a higher overall effectiveness for the system.

Hypothesis 5: The chances of one or more firefighter agents becoming a "super-agent" is directly proportional to K. A "super-agent" is a firefighter agent an energy level that is higher than the maximum allowed fire strength, thus allowing that firefighter to extinguish any fire in the environment in one shot. If there are more initial fires in the environment, there are more chances for one or more agents to put out enough fires to earn "super-agent" status.

2 Presentation

The experiments were designed to test each of the above hypotheses by adjusting key parameters as shown in Table 1. Thirty-two simulations were run for each possible combination of the values shown in order to maintain statistic validity.

Table 1: Experiments

Parameter	**Variable**	**Range of Values**
Grid size	L	100
Number of firefighter agents	N	0, 10, 50, 100, 500
Number of fires started	K	1, 5, 10, 500
Firefighters' visibility range	V	1, 15, 50

Hypothesis 1: Hypothesis 1 required testing the effectiveness of the system for various values of N and K. Table 2 and Figure 2 show the results of these tests.

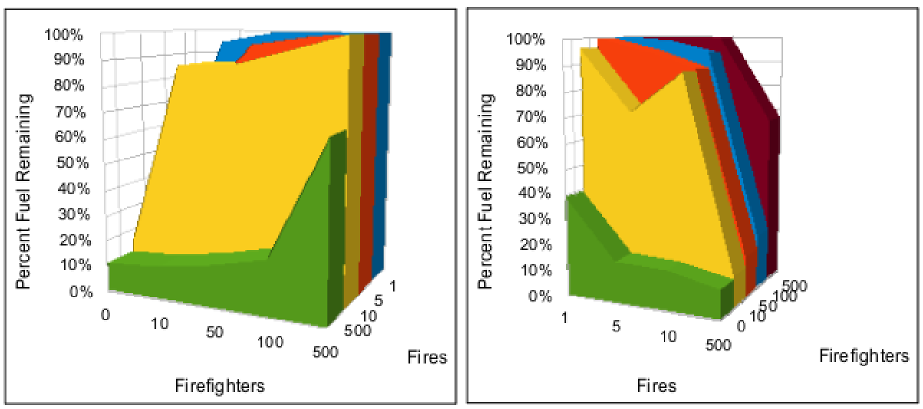

Figure 2: System Effectiveness

Hypothesis 2: Hypothesis 2 required testing the efficiency of the system for various values of N and K. Table 3 and Figure 3 show the results of these tests.

Hypothesis 3: Hypothesis 3 required testing both the efficiency and effectiveness of the system for extreme values of N and K, such that $N \gg K$, or $N \ll K$. Tables 2 and 3 as well as Figures 4 and 5 show the results of these tests.

Hypothesis 4: Hypothesis 4 required testing the effectiveness of the system for various values of V. Table 4 and Figure 6 show the results of these tests.

Table 2: System Effectiveness

Fires	Firefighters	Percent Fuel Remaining
1	0	39.66%
1	10	95.98%
1	50	99.80%
1	100	99.94%
1	500	99.99%
5	0	15.88%
5	10	72.34%
5	50	95.17%
5	100	98.61%
5	500	99.97%
10	0	15.35%
10	10	87.84%
10	50	88.46%
10	100	93.97%
10	500	99.93%
500	0	11.17%
500	10	12.21%
500	50	16.19%
500	100	21.52%
500	500	66.90%

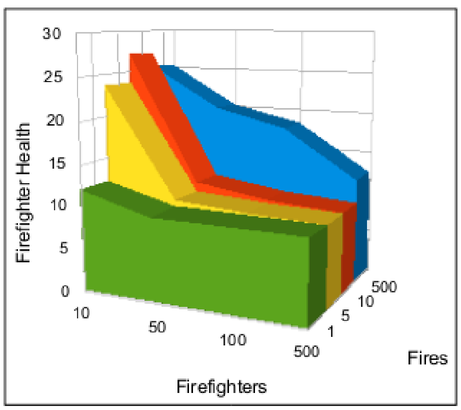

Figure 3: System Efficiency

Table 3: System Efficiency

Fires	Firefighters	Firefighter Health
1	10	12.16
1	50	9.82
1	100	9.73
1	500	9.7
5	10	23.77
5	50	10.66
5	100	9.94
5	500	9.71
10	10	27.22
10	50	11.68
10	100	10.36
10	500	9.72
500	10	25.41
500	50	20.34
500	100	18.35
500	500	12.54

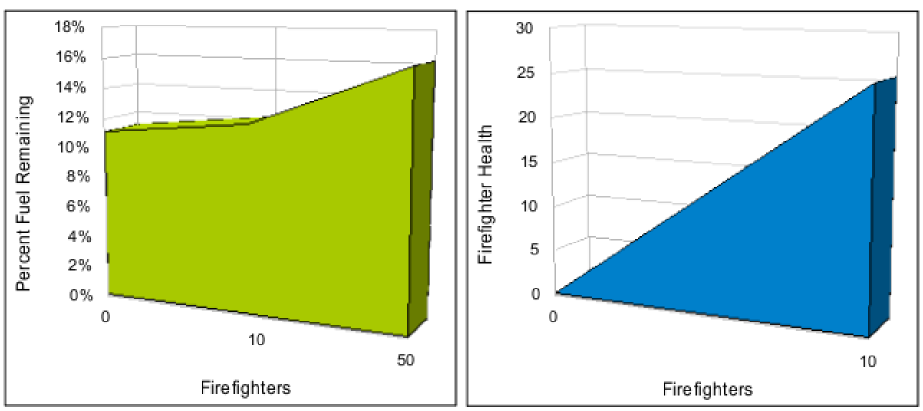

Figure 4: System Convergence when $K \gg N$ ($K = 500$)

Table 4: Visibility

Visibility	Percent Fuel Remaining
1	70.65%
15	81.01%
50	82.50%

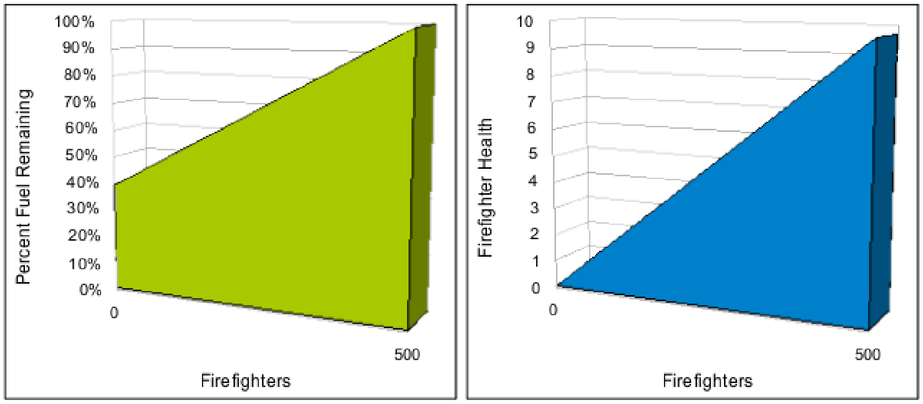

Figure 5: System Convergence when $N \gg K$ $(K = 1)$

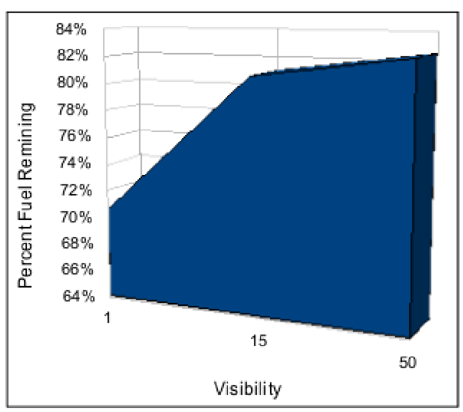

Figure 6: Visibility

Hypothesis 5: Hypothesis 5 required checking for the regular emergence of "super-agents." While there were instances of "super-agents" in the raw data, the were very isolated.

3 Observations

Hypothesis 1: According to the experimental data, this hypothesis is shown to be true. The effectiveness of the team of firefighters is proportional to $\frac{N}{K}$. That is, if there are more firefighters than there are fires, the system is more effective. The converse is also true, if there are more fires than there are firefighters, then the system is less effective. It also holds that if $N \ll K$, the effectiveness becomes nearly non-existent, and the fire burns approximately the same amount of fuel as if there were no firefighters to begin with.

Hypothesis 2: According to the experimental data, this hypothesis does not hold. Instead, the opposite is true. The efficiency is actually inversely proportional to $\frac{N}{K}$. That is, if there are more firefighters than there are fires, the system is *less* efficient. The converse is also true, if there are more fires than there are firefighters, the system is *more* efficient. Also, if $N \ll K$, the system still retains a certain amount of efficiency.

Hypothesis 3: According to the experimental data, the system achieves coherence, regardless of the relationship between $L \times L$, N, and K. That is, in no instance did all of the firefighters die during a simulation. Therefore, coherence was always achieved at some level.

On the other hand, when $N \approxeq L \times L$ and $N \gg K$, the system did achieve coherence very quickly.

Hypothesis 4: According to the experimental data, the effectiveness of the system is proportional to V. That is, the farther the firefighters can see in the environment, the more effective the system is.

Hypothesis 5: There are instances when one or more "super-agent" emerges during a simulation. However, it does not happen frequently enough to conclusively determine whether it is proportional to K.

4 Justifications

Hypothesis 1: Recall that the effectiveness of the system is measured by the percentage of total fuel remaining in the environment. So, when there are more firefighters, the firefighters are more likely to find a fire more quickly. In doing so, the other firefighters are then notified of the location of that fire, and the more firefighters there are, the more likely there are firefighters that do not have a task that can respond to the new fire notification. More firefighters that are fighting a given fire results in the fire being extinguished more quickly, resulting in a higher amount of fuel remaining at the space that the fire was. Multiplied over the space of the environment, this yields a higher overall effectiveness.

Likewise, when there are more fires, the effectiveness of the system is lower. Even though the firefighters are more likely to find a fire if there are more of them throughout the environment, they are not able to keep up with the fire, and it ends up burning more of the fuel in the environment.

Hypothesis 2: Recall that the efficiency of the system is determined by the total amount of firefighter health after a simulation. Due to the design of the firefighter agents, when they find themselves in a situation that reduces their health, they are very good at choosing the action that minimizes how much their health is reduced. Because of this, the firefighters are able to be very aggressive when they find a fire. Therefore, when there are more fires, there are more opportunities to earn the bonus from extinguishing a fire. This leads to a higher overall efficiency when there are more fires.

This is different than what was hypothesized. It was thought that when there were more fires, the firefighters would be more likely to be injured or killed, thus reducing the overall efficiency. However, the ability of the firefighters to minimize the amount of damage they receive from being in a bad situation was not taken well enough into account.

Hypothesis 3: The fact that coherence is always achieved can also be accounted to the design of the firefighter agents. The decisions that are made to minimize the amount of damage taken lead to agents being very good at surviving even the worst scenarios.

As expected, when there are many more firefighters than there are fires, the system converges very quickly. This is due to the fact that the firefighters cover much of the environment, and are likely to locate the fire(s) very quickly. Also, when a fire is located, there is a larger number of firefighters that are not very far away. Thus, they are able to respond very quickly, resulting in a very rapid convergence.

Hypothesis 4: Again, recall that the effectiveness of the system is determined by the total amount of fuel remaining in the environment after the simulation. The farther a firefighter is able to see, the more likely he is to locate a previously undetected fire, and move towards it. When the firefighters were not given any visibility range, they would wander aimlessly, even if there was a fire two spaces away. They simply could not see it, so it was allowed to burn, resulting in a lower effectiveness. When the fire can be more easily detected, the overall effectiveness of the system is higher.

Hypothesis 5: Recall that the definition of a "super-agent" is a firefighter agent that achieves a health level that is higher than the maximum allowed fire strength, thus allowing the firefighter to easily extinguish any fire in one step. While "super-agents" did emerge on occasion, the lack of consistency is believed to be due to the iterative nature of the simulations as well as the reward system only rewarding the firefighter that actually extinguishes the fire. That is, there can be multiple firefighters in the same location fighting the same fire, but only the firefighter that extinguishes the fire earns the bonus health point. This leads to a fairly even distribution of the bonus health points which actually reduces the chances of the emergence of a "super-agent."

5 Implications

Hypothesis 1: As shown, hypothesis 1 proved to be true. This means that when designing a system, in order to make it as effective as possible, the designer should be sure to make the ratio of firefighters to initial fires as high as possible.

Hypothesis 2: The results of this hypothesis indicate two errors in the design and implementation of the firefighter agents.

The first is that the firefighters were made to be too competitive. This was not in the intention of the design. It originally did not appear that there was anything to compete over. The problem is that only the firefighter that extinguishes a fire gets the energy reward. This means that all of the other firefighters that were helping fight the fire do not receive any reward for helping.

Part of the reason for this competition is because of the nature of Repast. Since Repast iterates through the steps of each agent, the agents are not actually spraying the fire at the same time (which is what the simulation intends). If there were a way to run a multi-threaded version of the simulation, this problem would be minimized.

The best way to solve this problem, is to reward all agents who actively participated in extinguishing the fire, and were present at the time the fire was extinguished. Although this solution still does not allow for the agents to all be spraying at the same time, it provides a logical method of rewarding the firefighters as though they were all working together in real time.

If the reward problem is not solved, this presents an interesting dilemma for the design of future simulations. A higher ratio of firefighters to fires means fewer firefighters are going to be able to receive energy bonuses, and the average firefighter energy will be low, meaning the efficiency of the system will suffer. However, as previously noted, using a higher ratio means the firefighters are more effective.

This is a delicate balance that needs to be chosen appropriately for the type of simulation being run. If the firefighters need to maximize their energy, a low ratio should be chosen, while a high ratio should be chosen if the fire needs to be put out quickly with little damage done to the environment.

Hypothesis 3: The firefighter design works very well. The firefighters seem to have a very good balance between teamwork and self interest in order to keep everyone alive while extinguishing the fire in a timely manner. The next step for making the firefighters more intelligent would be to add a way for them to learn and plan. If the firefighters were able to recognize areas of low flammability, or low fuel levels, they could plan on retreating back to that place if they get overwhelmed with fire. They could also communicate with each other so that they can share their "safe zones" so that they can team up and conquer the fire in an organized manner.

These additions would require a more robust communication protocol than the blackboard system currently implemented. Some sort of negotiation protocol would be needed for the agents to choose the best location to set up their "safe zones." They would also require some modifications to the way the agents store the maps in their memory. Currently, the agents construct a map of spaces they have visited in case they get lost in a maze of fire while trying to move toward a call for help. This internal map can be modified to store flammability and fuel level information so that the firefighter can recognize larger areas of safe spaces to suggest as a "safe zone."

Hypothesis 4: Obviously, a higher visibility leads to a more effective system. The only problem is keeping that visibility within a reasonable range. If this system is being used to try and model a real fire fighting situation, it would be important to use realistic visibility levels.

In future versions, it would be interesting to make the visibility levels of the firefighters a variable value based on a firefighters location in the environment. Fires that burn for longer periods of time, or fires that have lower flammability would tend to create more smoke in the area surrounding them and would cause lower visibility.

Hypothesis 5: Assuming "super-agents" are desirable, the system can be altered to allow for easier emergence of one or more "super-agents." The reasons there are only occasional "super-agents" are almost the same for the reason that the efficiency goes down when more firefighters are added to the system.

This provides more reason to alter the system as outlined in the implications for hypothesis 2. The simulation would ideally be run in a multi-threaded environment so that the agents can all spray fires simultaneously. The system should also assign rewards to agents who are actively trying to extinguish the fire at the time that the fire goes out.

References

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[2] “Two-dimensional fire spread decomposition in cellular DEVS models”, Ntaimo, L. and Khargharia B., Proceedings of Spring Simulation Multi-Conference, Huntsville, AL, April, 2006