ABSTRACT
Evacuation is one of the most urgent measures of disaster response. It requires spatiotemporal decision making by many individual agents under circumstances that include an unknown impact of the disaster on the environment, which impedes the evacuation planning, and potentially destroyed, blocked or lacking communication infrastructure, which impedes central management. This paper suggests and investigates a novel paradigm for evacuation planning: decentralized planning based on sharing local knowledge. The paradigm is not only independent from infrastructure, and adapts to dynamic disasters, but also is as successful as centralized management in many scenarios.

Categories and Subject Descriptors
H.4 [Information Systems Applications]: Miscellaneous; I.2.11 [Computing Methodologies]: Distributed Artificial Intelligence—Intelligent agents; I.6.4 [Computing Methodologies]: Simulation and Modeling—Model validation and analysis

General Terms
Experimentation, Performance, Theory

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agent-based simulation, collaborative decision making, decentralized disaster management, spatial information

1. INTRODUCTION
In case a disaster strikes, such as an earthquake, fire or other sudden threats to safety, one of the foremost needs is to get people out of the disaster zone. Accordingly, evacuation is a significant measure of response in disaster management, and a broad field of research. Research topics so far included:

- Human behavioral aspects, including simulation of this behavior [9, 26], typically in correspondence to the design of the environment (buildings, malls, subway stations, airplanes).
- Optimal evacuation planning, including modeling of spatial information systems [17, 19].
- Communication to people, for example, guiding by maps and signs [12] or by mobile services.

In all these cases the evacuation planner has global knowledge and plans ahead of a potential evacuation, preparing for the risk, by measures such as changing the design of the environment, changing the place or appearance of maps or signs, or designing a location-aware service for mobile phones to support wayfinding. In contrast, this paper concentrates on the disaster response phase, and a disaster that strikes by surprise. In this scenario there is no or little preparation for evacuation planning, and it is also likely that communication infrastructure is blocked [33], congested, destroyed, or non-existing, such that individuals rely mostly on themselves in their evacuation planning.

This paper will suggest and investigate the adoption of cooperative technology to improve the chances for a quick evacuation. Since people do not have the time for extensive communication in the event of evacuations, we suggest that their mobile devices act as sensors, communicate in a peer-to-peer manner via short-range radio, and guide their owners. Thus, we suggest a completely decentralized evacuation management service.

Such approach to thinking of evacuation management is challenging if not counter-intuitive: Individuals (or their devices) not knowing the full environment are not guaranteed to find the shortest routes to closest exits, they do not know the impact of the disaster on potential evacuation routes, and they cannot consider flow capacities without knowing where everybody else is. If they follow affordances in the environment or apply any other wayfinding heuristic they may run into dead ends or circles. But there are also strong reasons for considering decentralized evacuation management:
its robustness to infrastructure failure, its direct, real-time access to in-situ information, and its scalability due to local problem solving. The most promising reason, however, is its ubiquity. While a centralized service is either designed only for a particular environment (e.g., as a part of an intelligent building’s infrastructure) or designed as a global service that must lack information of higher level of detail for indoor environments, the decentralized solution will work everywhere in an ad-hoc manner.

The challenge of decentralized evacuation management is the limited knowledge of the individual decision-making agents, or evacuees. Accordingly the main aims of this paper are:

- Decentralization: Generating desirable global behavior based on local rules and limited information about the global scenario.
- Cooperation: Designing a spatiotemporal framework in which agents can share their knowledge.

We will prove the hypothesis that cooperation improves the evacuation performance in decentralized evacuation services, independent from the prior knowledge of the agents. For this purpose several levels of knowledge (you may call it preparation) are considered and compared, starting from the most generous case that the agents know the environment. But we will also investigate more realistic assumptions, such as that the agents only remember the way they came into the environment to find their way out. Cooperation in all these scenarios is sharing of knowledge. This way, the term wisdom of crowds gets a new meaning.

The paper closes an important gap in current disaster management procedures, providing evacuation information for individual people in situations where central management or infrastructure has failed or was non-existing. It opens up several pathways to improve the decentralized intelligence by heuristics managing the individual and group behavior. The presented research is a proof of concept, in many respects preliminary. But it presents convincing evidence why the fundamental idea should be pursued further.

2. EVACUATION MANAGEMENT

Evacuation management, i.e., guiding large numbers of people facing a threat out of a zone of danger, is part of any disaster management plan. Evacuation management has passive components, such as signs and you-are-here maps in the environment, and active components, such as evacuation orders distributed from a central command center, trained personnel send out to channel evacuation flows, and locally or centrally controlled smart environments, such as automatic gates, dynamic signage, or mobile devices [11, 14, 28].

Both components are known to be prone to breakdown. Passive components cannot adapt to changes in the environment that are caused by the actual threat or emergency, and they fail psychological considerations when communicating to panicking people [12]. Active components rely on intact and non-congested communication and transportation infrastructure at the time of evacuation, and they do not cope well with ad-hoc needs for detailed spatial information.

In this paper we will investigate cooperating mobile services that form ad hoc networks, and hence, are independent from any existing communication or service infrastructure. In the context of this paper, these mobile services will be simulated by agents. These agents can form beliefs by using a-priori knowledge of their environment and additionally by sensing their environments. They have desires, namely to find out of a zone of danger, and they have intentions, i.e., plans how to find out of those zones. Since these agents can also communicate with their neighbors, cooperation emerges (e.g., [32]).

Agent-based simulation is a broadly accepted method both for evacuation modeling as well as for studying mobile ad hoc networks. Simulation of evacuation behavior focuses on forecasting evacuation times, typically to improve the design of environments (e.g., [6]) or for routing purposes (e.g., [7, 19]). Others have studied cognizing agents in their wayfinding behavior [8], or in behavior of crowds that accumulates from interactions between individuals (e.g., [1, 9, 10]). So far, interactions of crowds were based at a biological (perceptual and cognitive) level. In this paper we will study evacuation planning and behavior of agents that interact by sharing spatial knowledge. In other related work evacuation behavior has been simulated where agents take different roles such as trained personnel and evacuees, but also share spatial knowledge [21].

Simulation of mobile ad hoc networks typically focuses on efficient communication behavior, motivated by scarce energy resources on hand-held mobile platforms [3, 13]. In this paper, however, energy resources are less an issue, and instead we will focus on information gains by sharing spatial knowledge between the agents. Decentralized evacuation management assumes that individuals are equipped with mobile devices that can communicate with each other in a peer-to-peer fashion over short distances even in cases where global information from centralized infrastructures is not available. It also assumes that these mobile devices serve as sensor platforms [35], for example, tracking themselves, or sensing relevant environmental parameters. The mobile devices create a local situation picture and provide relevant, real-time evacuation information to evacuees.

Mobile devices usually rely on a central infrastructure for positioning. In outdoor environments, this is typically the Global Positioning System (GPS); in indoor environments fingerprinting methods are commonly used based on wireless network infrastructure [4], mobile phone networks [18], or even inbuilt power lines [20]. As argued before, these positioning methods are prone to fail in disasters. Today, smart phones come equipped with other sensors, such as compass and accelerometers, that can be exploited for localization without relying on a global infrastructure [5]. These sensors capture their movement relative to the point of origin, i.e., where recording started, and will deliver a coarse map of an environment’s paths. Noise and inaccuracies in data collection result in increased effort in integrating these paths [30]. Still, it is possible to generate coherent global maps of an environment in such settings as (multi-)robot exploration has shown [2, 15]. While the goal of producing a global map is beyond the task in this paper, the collaboration strategies of merging individual maps into a common reference frame are useful to consider in a refinement of this work towards application development. In recent work on collaborative simultaneous localization and mapping agents are able to label places in addition to tracking their trajectories [24]. These (crowd-sourced) labels can help to integrate individual maps as well.

Until a disaster occurs mobile devices can always track
themselves globally. Current research on static geosensor networks focuses on efficient collection or distribution of information (e.g., [25, 34]). In mobile geosensor networks not only information flows, but also the nodes move. Thus, more recent research focused on (local) recognition of movement patterns [16], or (local) control of intentional movement behavior [22]. In decentralized self-organizing travel decision making [32] it has already been proven that trip plans can be made effectively from local transportation network knowledge. Other previous work focuses on cooperating autonomous agents for physical tasks (e.g., [22, 23]). Physical cooperation is out of the scope of this paper.

3. EVACUATION BASED ON LOCAL KNOWLEDGE

Assume a mobile service Get-Me-Out-Of-Here, GOH. GOH runs on mobile platforms, is location-aware by some positioning sensors and methods, is cooperative, i.e., can communicate ad-hoc with neighboring mobile platforms, and aims to find the shortest and safest way out of an environment in the event of an alarm demanding evacuation.

We have identified three scenarios for GOH, ordered from least to most challenging for solving the evacuation problem:

1. When entering a new environment GOH is greeted with a complete map of this environment;
2. GOH tracks its movements continuously, and hence has formed some knowledge of the environment by the time the alarm goes off;
3. GOH is started at the time of the alarm, i.e., has no further knowledge of the environment at that time.

In a classical categorization of spatial knowledge [27] the agents in Scenario 1 will start their evacuation planning with survey (or global) knowledge, the agents in Scenario 2 will plan based on route (or local) knowledge. The agents in Scenario 3 have no knowledge, although human beings in this situation may have landmark knowledge (of the exits) by path integration. All types of knowledge are time stamped; the impact of the disaster on the environment may have outdated it by the time of the emergency.

In Scenario 1 the agents will plan a shortest route to the nearest exit (not necessarily the one they came through entering the environment). If they do this based only on the maps they received and do not communicate with each other they show exactly the behavior of a centralized evacuation management: all signs and evacuation plans in the environment reflect this level of knowledge. Unfortunately for the agents this knowledge can be outdated by the disaster. Thus, we will compare GOH in Scenario 1 for agents that do not communicate with agents sharing their (potentially updated) knowledge of the environment, and expect that sharing proves to be more effective than centralized evacuation management. In Scenario 2 agents will first attempt to find their way out along the way they came in and start exploring alternatives once this fails. In Scenario 3 agents can only explore their environment to find their way out. When the agents get stuck by a blocked segment, they revise their plans either by finding an alternative route from their knowledge of the environment, or they choose a heuristic to explore the unknown environment.

In all three scenarios, when the agents “meet” other agents, i.e., when they find themselves within broadcast range of other agents, they share their knowledge. The mutual update of knowledge lets them also revise their plans. The experiment has to provide evidence that in all three scenarios cooperation improves the evacuation performance. Evacuation performance is measured both as the number of agents evacuating successfully within a reasonable time frame and the average time successful evacuation takes.

4. EXPERIMENT DESIGN

The experiment is set up as an multi-agent simulation. Individual, autonomous agents enter and move freely in an environment until an alarm demands evacuation. From that moment on they cooperate by sharing their location histories when they are in radio range. All three scenarios listed in Section 3 have been realized, for varying numbers of agents and varying environments. The experiment has been implemented in repast, an open source agent-based modeling and simulation platform (http://repast.sourceforge.net).

In this experiment all agents share a global spatial reference system and perfect positioning capabilities within this reference system. That is, questions of mapping between a local coordinate system and a global spatial reference system (or between different local coordinate systems when it comes to sharing maps) are left out here because they are addressed elsewhere (see Section 2). Also questions of positioning accuracy and reliability are left out here. They depend on the type of environment, available positioning techniques, and the special circumstances in the event of a disaster. However, in the spirit of the scenario—decentralized decision making independent from infrastructure—we can argue that at least on-board sensors and technology can be used for positioning (inertial systems, compass, map matching).

Agents are tracking themselves, but can also share their collected knowledge via short range communication. The communication radius is set by default to one network edge in the environments described below, however, this parameter can be varied. With a default of one edge, and a global spatial reference frame, the sharing of knowledge always leads to connected graphs, which is not necessarily the case with larger communication ranges. Communication is realized as instantaneous: once two agents find each other to be in communication range they exchange their knowledge. However, no message forwarding is implemented, i.e., agents do not pass on received knowledge immediately to other agents in communication range. The agents start sharing their knowledge only after an alarm demanded evacuation.

In reality, a GOH service may be confronted with a variety of environments. Hence, three qualitatively different environments were developed for the simulation. A dense network (Fig. 1) represents an environment with relatively unconstraint movement possibilities: agents can move in many directions at each location. A sparse network (Fig. 2) reflects better the movement constraints in a street network: nodes have a degree in the range of street networks. A further reduction of node degree, and a more regular and hierarchical network structure, reflects typical properties of an indoor environment, which was tested as well using the plan of a floor of a larger university building.

In our simulation, the environments are first populated by agents. At each time step, some agents enter at the exits, such that their trajectories at the time of the disaster are
of different lengths. An agent entering the environment is assigned randomly a destination, and walks to this destination along a shortest path (assuming that they show a goal-directed behavior and follow some affordance, for example signs). It is important to note that this shortest path is implanted from the outside; except for Scenario 1, where agents get a complete map upon entry in the environment, they do not possess the knowledge to calculate shortest paths themselves. When agents have reached their destination they get assigned a new destination. In Scenario 2 the agents store their trajectories and the exits they passed.

The number of agents vary in the experiments; each setting is run with 5, 10, 20, 40, or 80 agents present in the network, respectively. Few agents in the environment have less chances to meet, and advantages from sharing their knowledge should be low. A densely populated environment should enable sharing agents to quickly converge to global knowledge of the environment. In each simulation the agents enter the environment over a period of twenty time intervals.

At the twenty-first time instance the disaster happens. A disaster causes an alarm requesting evacuation. The nature of the disaster is of no relevance, but it is modeled as being local. The disaster blocks its location (a node) and all neighboring nodes. The location of disasters is chosen randomly with every simulation run. In a dynamic version of our experiments, the disaster also grows over time (like a spill, plume, or fire): for every two time steps, another node is added to the connected blocked part of the network. Disasters at multiple locations, or of global impact (like an earthquake), are not studied, but certainly the simulation tool would allow to do this.

Route planning happens by a standard shortest path algorithm (A*), and if this fails due to lack of knowledge the agents switch to wayfinding heuristics. The currently implemented heuristics are random exploration and backtracking.

Each setting is run 50 times with each number of agents, i.e., there are 50 runs with 5 agents, 50 runs with 10 agents, etc. For each run, success rate and average number of steps is measured. The success rate is defined as the ratio between the number of agents reaching an exit after the alarm went off and the number of agents having entered the environment beforehand. Agents have 30 time steps to reach an exit after an alarm (50 time steps in case of Scenario 3). If they do not reach an exit during that time, they are assumed to have fallen victim to the disaster. Agents that do not successfully evacuate do not count towards the average number of steps, i.e., their step count is discarded when calculating how many time steps evacuation took on average.

5. SIMULATION RESULTS

In the following, we will report first on the three scenarios introduced above, comparing the effect communication has on evacuation performance in the case of global (Section 5.1), local (Section 5.2), and ad-hoc knowledge acquisition (Section 5.3). After briefly discussing these effects in Section 5.4, we will finally illustrate the effects of dynamic disasters and increasing the communication range (Section 5.5).

5.1 Global Knowledge

In this scenario, agents get a complete map of the environment (dense, sparse, or floor plan graph) as soon as they enter the environment through one of the exits. In principle each agent has all knowledge required to reach any of the exits. They will only fail to evacuate if they get trapped by the disaster, i.e., if this disaster blocks all paths to any of the exits. Accordingly, in all settings almost all agents manage to escape (Fig. 3); for none of the graphs a statistically significant difference exits between the success rates of sharing and not sharing knowledge. Agents are also rather quick to evacuate, again with no significant differences between sharing and not sharing. However, clearly agents need more steps in the sparse graph than in the other two graphs.

5.2 Local Knowledge

In this scenario, agents only know about those parts of an environment that they previously traveled through; they gain only local knowledge. When disaster strikes, they initially try to escape along the way they ventured into the environment. Oftentimes, this works (Fig. 4). For all settings, success rates are above 80%. However, looking at these results in more detail reveals significant differences.
**5.3 Ad-hoc Knowledge Acquisition**

When acquiring knowledge in an ad-hoc fashion, agents initially know nothing about the environment. They only start recording spatial knowledge once a disaster strikes. Thus, when trying to evacuate, they largely depend on an exploration of the environment in order to get out. This is a hard task, as Figure 6 illustrates.

Without communication, only those agents that happen to be located close to an exit when the disaster occurs manage to get out (and possibly a few other lucky ones). Success rates are well below 50% for the dense and sparse graphs (between 23% and 30%), and just close to 50% for the floor plan (43% to 50%). When sharing knowledge, however, success rates go up drastically once a sufficient number of agents are present in the environment. When communicating, success rates go up to 95% in the dense graph, and to 91% in the sparse and floor plan graphs. This occurs with 80 agents in the network, i.e., once many opportunities for communication arise. A different picture emerges for the number of steps, though. With a medium number of agents in the network (10, 20, or 40), the number of steps tend to go up compared to not sharing knowledge. As discussed below, this is likely an artifact of how the average number of steps is calculated.

ANOVAs reveal that there is no significant difference between success rates when not communicating; this holds for all three graphs. However, there is a clear effect when communicating with more agents increasing the success rates ($p = 0.00$, $F = 237.53$ for dense graph; $p = 0.00$, $F = 287.27$ for sparse graph; $p = 0.00$, $F = 210.00$ for floor plan). For the number of steps, statistically significant differences usually exist both in the sharing and the non-sharing settings, but no clear picture emerges regarding a relation between number of agents and number of steps.

In the dense graph, 80 agents in the network reach the same success rate that is achieved in the local non-sharing setting (T-test, $p = 0.68$); they do need significantly more steps, though. The same holds for the sparse graph ($p = 0.18$) and the floor plan ($p = 0.41$).
5.4 Comparison of Scenarios

The results achieved for the three scenarios global knowledge, local knowledge, and ad-hoc knowledge acquisition clearly show that collaboration is beneficial in evacuating an area after a disaster struck:

1. In case of global knowledge, while it does not improve evacuation performance of the agents, it also does not hurt them.

2. When only having local knowledge, communication allows agents to reach the same performance as if they had global knowledge in terms of success rates. Given enough agents in the network, i.e., enough communication incidences, they also are as quick as with global knowledge.

3. For ad-hoc knowledge acquisition communication even becomes crucial. Without communication, agents are most likely not to escape. With communication, however, most agents indeed manage to escape. Given many agents in the network, they even become as successful as in the local knowledge case, with more than 90% of the agents evacuating.

There are some peculiarities to observe in the data. First, in the floor plan, agents are more likely to escape than in the other graphs. There are five instead of only two exits in this graph, probably due to building regulations. Thus, it becomes more likely to find an exit by chance. Second, in the sparse graph, agents tend to require more steps to evacuate than in the other two graphs. Again, while the floor plan has similar average node degree, there are more exits offering more options for evacuation, which results in fewer steps. And in the dense graph, due to the higher connectedness, there are more options to locally navigate around the disaster, thus resulting in smaller detours. Third, when looking at the number of steps in the ad-hoc knowledge acquisition scenario, medium numbers of agents seem to take more steps when communicating than without communication. This is an effect of how the average number of steps is being calculated. Those agents that do not evacuate, i.e., do not manage to leave through an exit after 50 steps, are excluded from calculating this number. That is, only successful agents contribute to the average number of steps. Because there are significantly more agents evacuating in the sharing setting, there are more agents contributing to this number. In the non-sharing case, only those lucky enough to be close to an exit manage to escape; they will likely use a comparably small number of steps for this. The sharing setting allows much more agents to escape by making parts of the network known to them without exploration; other parts still need to be explored, though, which leads to a high number of steps required for evacuation.

5.5 Extensions

In order to further validate our initial hypothesis regarding the utility of collaboration in evacuation, and also to strengthen the additional findings reported here about some drastic increases in performance through collaboration, we performed further experiments. We first checked the effect an expanding (dynamic) disaster may have on successful evacuation. We then tested the influence of the communication range by increasing it from 1 hop (edge) to 2 hop (edges) radius.

A dynamic disaster was modeled by blocking, during the evacuation phase, every two time steps an additional node on the fringe of the current disaster. Consequently, the longer evacuation takes, the more of the network is blocked and the more outdated initial knowledge becomes. In general, the same patterns as before emerge, but lower success rates are observed. Different to the static case is a clear trend that communication becomes relevant also for the global knowledge scenario.

Increasing the communication range was tested on the dense graph, where it should have the largest impact. Again, the same patterns emerge. Compared to a 1-hop commu-
6. THE POWER OF COLLABORATION

Overall, the results of the various agent simulation experiments clearly show that communication is not only beneficial in evacuation scenarios, but also that it is feasible in principle to base this evacuation on locally acquired user-contributed knowledge.

By exchanging knowledge about the environment with fellow evacuees encountered along the way, agents that only have local knowledge manage to get the same level of performance as if they had complete knowledge about the environment. Increasing the communication range beyond direct encounters even allows for achieving these results in the ad-hoc knowledge acquisition scenarios, where agents only start recording knowledge once a disaster struck.

As the experiments with expanding disasters indicate, a globally provided, static view on the environment is quickly in danger of being outdated and of less use than knowledge acquired in-situ and shared among those affected by the disaster. The more time elapses, i.e., the longer agents take to evacuate, the greater is the danger of a planned path being blocked by the disaster and the more outdated their knowledge has become. This knowledge is brought up-to-date again through communication with other agents.

Increasing the communication range clearly improves evacuation success rates. A reasonable approach, thus, seems to be to allow for a communication range that spans the whole environment. However, as argued before, this bears the danger of people having bits and pieces of knowledge of an environment that are disconnected. It requires sophisticated reasoning mechanisms, and thus precious time, to really benefit from such an increased, but patchy knowledge acquisition. Also, peer-to-peer communication is often short-range only (e.g., Bluetooth).

7. CONCLUSIONS AND FUTURE WORK

This paper explores whether communication, i.e., the sharing of knowledge about the layout and state of an environment, is beneficial in evacuation scenarios. Several different settings are tested in an agent simulation, looking at global knowledge, local knowledge, and ad-hoc knowledge acquisition scenarios and comparing in each the sharing with not sharing of knowledge between agents. Results demonstrate a clear benefit of communication. Through communication, agents in the local knowledge scenario are able to achieve the same evacuation performance as if they had global knowledge. In the ad-hoc scenario, communication is a crucial mechanism to be able to escape at all.

The conclusion of this paper is that collaboration in evacuation is highly beneficial and that in principle it is possible to devise successful evacuation management based on decentralized mechanisms of user-contributed content alone without the need of a centralized evacuation management authority.

The experiments in this paper ignore flow capacities of paths and congestion effects. Since agents sharing their knowledge will have identical knowledge afterwards, and hence, make identical plans (if they have similar movement constraints) cooperation will lead to flocking behavior of people. Future work can consider smarter group behavior, splitting groups and balancing loads accordingly.

The strategies applied in the evacuation so far are relatively simple, and additional heuristic behavior could be implemented and tested as well. Agents could follow the affordance of long lines of sight in preference to the random behavior implemented, or they could prefer directions away from the emergency, to name only two alternatives. Recording additional information to their trajectories, more elaborate decision making could be implemented. While these heuristics may change the overall evacuation times, we do not expect changes to the support for the hypothesis. Even with these heuristics sharing knowledge will still improve the evacuation times.

This paper focuses completely on agent interaction, and neglects the human-computer interaction. In evacuation scenarios, however, the human user of mobile services will not give up control and autonomy. Affordances in the environment may outweigh the affordance provided by information of their mobile device. For this reason it needs services of quiet cooperation with autonomous users [31], respecting the user’s actions and integrating them into search strategies.

8. REFERENCES


