Evacuation Centrality: Agile Evacuation Routing in Unpredictable Hazardous Conditions

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Abstract. In this paper, we study the agility of evacuation routes in relation to dynamically changing unpredictable hazardous conditions. Infrastructure safety conditions may unpredictably change through time. Due to unpredictability, evacuees' safety can get jeopardized at any point of the evacuation route. Thus, it is not sufficient only to find the shortest evacuation route considering present safety conditions, but we should also consider other relevant characteristics that make the evacuation route sufficiently safe through time. With this aim, we propose a new node importance metric called evacuation centrality, inspired by betweenness centrality. The node evacuation centrality is a parameter that represents the importance of the node for evacuation considering the availability of alternative safe and efficient routes from that node towards safe exits. Relatedly, we propose the concept of agility of an evacuation route, which represents the ability of a route to efficiently and safely reroute from the route's constituent nodes in case of contingencies. Given a building network with a set of evacuees' positions and safe exits, we mathematically formulate the problem of finding agile evacuation routes. In addition, we propose a solution method for that problem. The functioning of the proposed method is demonstrated by means of a case study.

1 Introduction

Emergencies or disasters occur unexpectedly and disrupt human activities and cause physical and/or environmental damage. They can strike anyone, anytime, and anywhere. Emergencies may be natural or manmade, small scale, as e.g., in a building due to an explosion or fire, or large scale, as e.g., in a city or a region because of a radiological accident, bombardment or dangerous weather system.

Emergency evacuation is the immediate and urgent movement of people away from the threat or actual occurrence of a hazard. In this situation, evacuees should be able to evacuate safely, rapidly, seamlessly, and in a coordinated way through an evacuation space while avoiding hazardous conditions.

Traditional evacuation approaches are based on the following procedure. In the case of an imminent or ongoing danger, evacuation is organized by a trained personnel that coordinates the evacuation process on critical evacuation points. In larger watercrafts, these are dedicated areas where evacuees must assemble in case of emergency (assembly stations). Each evacuee should reach his/her assembly station or exit by following the escape route shown on a plan which is usually positioned on a limited number of positions in the building, and the signs in the corridors and stairs that are attached on the floor or walls. If the primary escape route is blocked, there is usually a second escape route, which is marked on an evacuation plan. Moreover, if visibility is limited due to smoke, evacuees should follow the emergency lights situated close to floor level.

The routes in evacuation plans are predefined and static. In the case there is a blockage of these routes, evacuees are provided with no alternatives. Moreover, since the evacuation plans are randomly present in the evacuation infrastructure, evacuees might not get the necessary evacuation information. This may have hazardous consequences and may result in panic.

The concepts of rapidness and seamlessness, which are necessary in evacuation, are closely related to the concept of agility. Oxford dictionary (2016) describes the term agile as "the ability to move quickly and easily" and "the ability to think and understand quickly". It is a well known concept in many areas, such as, e.g., manufacturing, software development, and business organization, see, e.g., [2, 12, 13]. In terms of outcomes, agility is a means of a system to swiftly and easily handle continuous and unanticipated change by adapting its initial stable configuration and to effectively manage unpredictable external and internal changes, e.g., [12, 13]. Based on this conceptualization and paradigms of agile manufacturing and agile business systems, in this work we propose the concept of agility in evacuation routes and route recommendation systems.

Agility of an evacuation route assures to an evacuee a high reactivity to safety changes possibly occurring along the route. It expresses the ability to reroute from intermediate nodes to alternative routes towards safe exits. Agile route recommendation systems, hence, should be capable to run in real time in the cycle sense-analyze-decide-act. To achieve it, we need complete, accurate and up-to-the-minute situational awareness along the route. While in the open spaces, GPS and e.g., 3G and 4G communication can be used, in inner spaces, this requirement can be facilitated by the interaction of ambient intelligence and smartphone technologies. Hence, an agile evacuation route recommendation system should respond quickly in inner and open spaces to sudden changes in evacuation safety conditions caused by a hazard, crowdedness or any other type of requirement or disruption. To the best of our knowledge, the literature on such route recommendation systems is very scarce (Section 2).

We model evacuation agility of a route in terms of the characteristics of its intemediate nodes. For this scope, we examine relevant node centrality measures and propose new node importance metrics called evacuation centrality in Section 3. The evacuation centrality is a measure that represents the importance of a node for evacuation considering the availability of alternative temporally efficient safe routes from that node towards safe exits.

Given a building network with a set of evacuees' positions and safe exits, in Section 4 we mathematically formulate the problem of

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finding agile evacuation routes, where by agile we mean the ability to efficiently and safely reroute from the route's constituent nodes in case of unpredictable safety drops. We conclude the paper in Section 6.

2 Related work

Building evacuation has been studied over the last decades from different perspectives such as, e.g., evacuees' behaviors, traffic coordination strategies, and evacuation route optimization, see, e.g. [1, 3, 8, 9, 10, 11]. For example, Pursals and Garzon in [11] considered the building evacuation problem and developed a model for selecting the proper routes for movement of people in a building during an emergency situation. Abdelghany et al. in [1] present a simulation - optimization modeling framework for the evacuation of large - scale pedestrian facilities with multiple exit gates. The framework integrates a genetic algorithm (GA) and a microscopic pedestrian simulation - assignment model. The GA searches for the optimal evacuation plan, while the simulation model guides the search through evaluating the quality of the generated evacuation plans. Evacuees are assumed to receive evacuation instructions in terms of the optimal exit gates and evacuation start times. The framework is applied to develop an optimal evacuation plan for a hypothetical crowded exhibition hall. A mixed-integer programming solver is used to derive routing plans for sample networks.

Conventional emergency evacuation plans often assign evacuees to fixed routes or destinations based mainly on geographic proximity. Such approaches can be inefficient if the roads are congested, blocked, or otherwise dangerous because of the emergency. Han and Yuan proposed in [3] the concept of *most desirable destination* for evacuees. This concept recognizes that municipalities responsible for large-scale evacuation have routinely assigned evacuees to routes and destinations based on limited experience and intuition rather than methodical optimization processes. Even with the implementation of dynamic traffic assignment, models that are based on fixed origin-destination tables are inefficient when a destination becomes difficult (or impossible) to access due to congestion or blockage. In [3], options that allow evacuees flexibility in selecting their exit routes and destinations are explored.

Destination assignment and route assignment to enable optimal evacuation operations are interrelated. To optimize the routing problem, one has to know the destinations; to optimize the destination assignment, one has to know the minimal travel time, and hence route assignment to all destinations.

To address the inherent complexity of the problem, Han et al. in [3] devised a framework for simultaneously optimizing evacuation-traffic destination and route assignment. Based on this framework, we can determine the optimal evacuation-destination and route assignment using a one-step optimization procedure.

In [7], we propose a pedestrian route recommender system for smart spaces in steady state conditions that recommends the safest routes to pedestrians and simultaneously optimizes conflicting objectives of finding the social optimum and minimizing individual path travel times while considering people flow and fairness, similarly to [5, 6]. Moreover, the system considers the influence of stress on human reactions to the recommended routes and iteratively ponders user response to the suggested routes influenced by stress-related irrational behaviors until system acceptable routes are found. However, in the case of a sudden safety drop on a part of the route, it might not be able to guarantee a safe evacuation of the safety jeopardized areas since in the route recommendation, it does not consider the unpredictability of safety conditions. In this case, it might thus result in evacuees' fatalities. Moreover, in [8], we consider the influence of affiliate ties among evacuees and their interaction with self-concerned individuals and model self-concerned and social group behavior via individual and team reasoning. The recommended evacuation routes take in consideration the affiliate ties to guarantee evacuee's compliance with the routes.

The aforementioned papers assume steady evacuation state and do not treat the safety dynamics in transitory evacuation safety conditions. Therefore, in this paper, we concentrate on evacuation routing in highly unpredictable dynamically changeable hazardous evacuation safety conditions. In this case, it is important to find the shortest safe routes for all evacuees considering other relevant characteristics that make the evacuation route sufficiently safe through time.

3 Centrality measures for evacuation routing

Generally, centrality measures indicate the most important nodes of a network. Some of the measures relevant for the computation of routes are node degree, eigenvector, and betweenness centrality. In the following, we describe the relevance of these measures to evacuation routing and identify their flaws in this respect.

3.1 Degree centrality

The degree centrality $C_d(i)$ of node $i \in N$ of a graph $G = (N, E)$, where N is a set of nodes and E is a set of edges, is the number of arcs incident to the node. In directed graphs, we can either use the in-degree, the out-degree, or their combination as the degree centrality value. When we combine in-degrees and out-degrees, we are basically ignoring arc directions.

In general, nodes with a higher degree centrality tend to be used by more paths. However, connections of a node with the neighboring nodes that are a part of the shortest paths to safe exits are more important than others. Since the degree centrality does not guarantee the connectedness of a node to safe exits, it cannot be used in the computation of efficient safe evacuation routes.

3.2 Eigenvector centrality

A step forward the evacuation route's efficiency guarantee is the eigenvector centrality of a node, which depends both on the number and the *importance* of its adjacent nodes. In general, adjacency of a node to nodes that are themselves adjacent to more *important* nodes will give a node more *importance*.

While node degree centrality counts walks of (geodesic) unitary length from a node, the eigenvalue centrality takes into consideration walks of length infinity. It is the expected number of visits to a node $i \in N$ of an infinite random walk over graph $G = (N, A)$. It can only be calculated for connected undirected graphs and strongly connected digraphs. More formally, if we let $\mathbf{Ad} = (a_{i,j})$ be the adjacency matrix of graph $G = (N, A)$, eigenvector centrality $C_e(i)$ of node $i \in N$ is given by:

$$C_e(i) = \frac{1}{\lambda} \sum_{j \in N \setminus \{i\}} a_{i,j} C_e(j), \qquad (1)$$

where $\lambda \neq 0$ is a constant. In matrix form, we have $\lambda \mathbf{C_e} = \mathbf{Ad} \cdot \mathbf{C_e}$. Hence the centrality vector $\mathbf{C_e}$ is the eigenvector of the adjacency matrix $\mathbf{Ad}$ associated with the eigenvalue λ. If we choose λ as the largest eigenvalue in absolute value of matrix $\mathbf{Ad}$, then as a result of Perron-Frobenius theorem, if matrix $\mathbf{Ad}$ is irreducible (i.e., the graph is (strongly) connected), then the eigenvector solution $\mathbf{C_e}$ is both unique and positive.

The nodes with a high eigenvector centrality values, then, will be traversed by more paths. Moreover, nodes with a high eigenvector centrality are network hubs and their presence is crucial in maintaining the paths among all network nodes. However, a high centrality value of a node does not guarantee the existence of fast and safe paths from that node towards safe exits. Additionally, a high eigenvector centrality value of a node might be a root to panic and a related herding problem [7] in the case of high people flows traversing the node. Therefore, eigenvector centrality does not characterize sufficiently the importance of the nodes for evacuation. Since we want to find safe and fast evacuation paths towards a limited set of safe exit nodes, as such, it can not be directly used as a parameter for evacuation route optimization.

3.3 Betweenness centrality

Betweenness centrality is a concept that is closer to the efficiency of evacuation routes and is a departure point in our proposition of the evacuation centrality metrics. It is defined as the fraction of shortest geodesic paths between nodes different than $i \in N$ that i is a part of:

$$\sum_{o \in N} \sum_{d \in N} \frac{\sigma_{od}(i)}{\sigma_{od}}, \forall i \neq o \neq d \in N, \tag{2}$$

where $\sigma_{od}(i)$ is the number of shortest geodesic paths (the paths with the minimum number of arcs) between origin node o and destination node d and $i \in N$ is an intermediate node of the path. Moreover, σ_{od} is the total number of shortest geodesic paths between o and d.

Betweenness centrality is, therefore, an indicator of the frequency a node serves as the "bridge" on the shortest geodesic paths connecting any two other nodes of the graph. That is, we find the shortest geodesic path (or paths) between every pair of nodes, and calculate the fraction of these paths that node i lies on. If we imagine crowd flowing between nodes in the network and always taking the shortest possible geodesic path, then betweenness centrality measures the fraction of that crowd that will flow through i on its way to wherever it is going.

Even though this measure might be relevant to the use cases with constant arcs' costs, the issues with the usage of betweenness centrality in evacuation are related with the definition of distance and the origin-destination pairs. In particular, we are concerned with the lowest evacuation time and not the shortest geodesic distance. Moreover, we are not interested in all origin destination pairs, but only in a limited subset of evacuees' origins $O \subset N$ and safe exits $D \subset N$. In the following, we deal with these two issues.

3.4 Proposed evacuation centrality measure

When an unpredicted hazard occurs on a part of the evacuation route, the same gets unsafe and impassable. If, in the computation of an evacuation route, we do not consider this fact and the related possibility to reroute to other safe evacuation routes on its intermediate nodes, then, in case of contingency, rerouting towards safe areas might be impossible causing imminent fatalities. Similar may occur in the case of a too high flow of evacuees that might overload an evacuation route and cause panic. Therefore, for constituent nodes of each evacuation route, we need to find a sufficient number of the safest, dissimilar, and simple paths towards safe exits whose travel time is preferably within some given maximum evacuation time.

Thus, we modify the betweenness centrality measure in the following way. If we substitute the geodesic distance with a path travel time $c^p \geq 0$, most probably there will be only one fastest path for every pair of nodes. This is why, here, we present a modification of betweenness centrality that considers k_{od} distinct temporally efficient paths for each (o, d) pair, with $o \in O$ and $d \in D$. Here, by k_{od} temorally efficient paths, we mean the number of distinct paths of travel time at most, e.g., $\gamma \cdot c_{\min}^{od}$, where $\gamma \geq 1$ is a maximum evacuation route travel time tolerance factor and $c_{\min}^{od}$ the travel time of the path with the minimum travel time for (o, d) pair. In more detail, we define the evacuation centrality as follows.

Definition 3.1. Evacuation centrality $C_\epsilon(i)$ of node i is a parameter that represents the importance of node i for evacuation. The value of the evacuation centrality of the node is the number of the safest sufficiently dissimilar (simple) temporally efficient paths from that node towards safe exits constrained by the paths' total cost (travel time) c_{max}, i.e., $c^p \leq c_{max}$.

In Definition 3.1, c_{max} is the maximum building's evacuation time.

4 Agile evacuation routes: problem formulation

If real-time infrastructure information is available to evacuees and they can negotiate their routes, it becomes possible to provide a selection of optimized routes. Therefore, we assume that the evacuees are monitored by strategically positioned sensors as, e.g., cameras, and are communicated with via smart space displays, acoustic signs, smart-phones, etc. Monitoring permits us both to recognize the evacuees' behavior as to perceive their momentary position and flow together with their safety conditions. Furthermore, we assume that the evacuee flow demand is defined by the presence of infrastructure occupants at their momentary positions whose evacuation destinations are defined as the safe exits at which evacuees are considered to be safe.

Our aim is, thus, to safely evacuate all the evacuation requests and if not possible, then, as many people as possible within the allotted time period. To this aim, we should find agile evacuation routes toward safe exits that consider evacuation centrality of the routes' constituent nodes and other relevant characteristics that make the evacuation route sufficiently safe through time.

4.1 Evacuation network model

We represent a smart space evacuation network (building and/or urban district) by a directed graph $G = (N, A)$, where N is a set of n nodes representing rooms, offices, halls, and, in general, a relatively small portion of space within a building or other structure separated by walls or partitions from other parts. In the case of larger spaces that can host a larger number of people, for simplicity, the same are divided into sections represented by nodes completely connected by arcs $a \in A$, where A is the set of m arcs $a = (i, j)$. Here, nodes $i, j \in N$ and $i \neq j$ represent physical or conceptual portals, doors, and gateways connecting nodes i and j. Each arc $(i, j) \in A$ has an associated cost c_{ij}, which in our case is its travel time t_{ij}. Moreover, each arc has also an associated safety $S_{ij} \in [0, 1]$. Considering a critical safety value S^{cr}, where $0 < S^{cr} < 1$, an arc is considered safe if $S_{ij} > S^{cr}$.

We opt for a directed graph representation of the evacuation infrastructure since in the case of bi-directional corridors, roads, and passages, we can easily reduce the undirected graph to the digraph by connecting two adjacent nodes with an arc in each direction, while in the case of unidirectional roads, representing the direction by an (undirected) edge is not possible.

Let $O \subseteq N$ and $D \subseteq N$ be the set of all evacuees' origins and safe exit destinations, respectively. We assume that there are n_O evacuees' origin nodes $o \in O$ disjoint from n_D safe exit destination nodes $d \in D$, where $n_O + n_D \leq n$.

For the definition of origin-destination demand, we introduce fictitious sink node $\hat{d} \in N$ that is adjacent to all the destination nodes (safe exits) by fictitious (dummy) arcs. In this way, we assume that graph G includes (together with actual nodes) also fictitious node $\hat{d}$ and its incoming dummy arcs. Then, let $w \in W$ be a generic evacuation request from node $o \in O$ to fictitious sink node $\hat{d}$, i.e., $w = (o, \hat{d})$, where W is the set of all such evacuation requests.

Moreover, let R be a vector of cardinality n_O representing evacuation requests from origins O towards fictitious safe exit $\hat{d}$, where $R_{o\hat{d}} = R_w$ entry indicates the demand of evacuees in unit time period who request to leave origin node $o \in O$ to go to any of the safe exits $d \in D$ and, hence, to fictitious destination $\hat{d}$.

Then a simple path p is a finite sequence of adjacent distinct nodes connected by a sequence of arcs, each connecting two adjacent (different) nodes. Its total travel time c^p is composed of the travel times of the connecting arcs $c_{ij}(x_{ij})$, where x_{ij} is people flow on arc $(i, j) \in p$. Moreover, we define x^p as a flow along path $p \in P_w$, where P_w is a set of simple safe paths for evacuation request w from origin $o \in O$ to dummy node $\hat{d}$ of travel time $c^p \leq \gamma c^p_{\min}$. Furthermore, let safety S^p of path p be the lowest safety value of the constituent arcs of the path, i.e., $S^p = \min_{a \in p} S_a$. We search for the safest paths, i.e., the paths whose safety $S^p \in [0, 1]$ is relatively high and preferably higher than some critical safety S^p_{cr}, where $0 < S^p_{cr} < 1$. Path p is considered safe if all its constituent arcs are safe, i.e., if $S_a > S^{cr}$ for all $a \in p$.

4.2 Finding node's evacuation centrality measure

To determine evacuation centrality of each node, we need to determine the maximum number of dissimilar simple paths from origin node o to safe exits (destination nodes) $i \in D$ subject to the condition that the cost c^p of each path be not greater than a specified value, i.e., $c^p \leq \gamma c^p_{\min}$. Mathematical formulation of this (maximum network flow) problem is as follows:

(Z)

$$m = \max K \tag{3}$$

subject to

$$\sum_{p \in P} \Big(\sum_{j:(i,j) \in A} \phi_{(i,j),p} x_p - \sum_{h:(h,i) \in A} \phi_{(h,i),p} x_p \Big) = \begin{cases} K, & \text{if } i = o \\ 0, & \text{if } i \in N \backslash \{o, \hat{d}\} \\ -K, & \text{if } i = \hat{d} \end{cases} \tag{4}$$

$$\Phi \mathbf{x^P} \leq \mathbf{1} \tag{5}$$

$$x_p \geq 0, \forall p \in P_w, \tag{6}$$

where Φ is the $[|A| * |P_W|]$ arc-path incidence matrix and P_w is a set of simple safe paths from origin $o \in O$ to dummy node $\hat{d}$ of cost $c^p \leq \gamma c^p_{\min}$. In particular, $\gamma c^p_{\min} \leq c_{max}$, i.e., the upper bound on the length of path p is limited by the maximum building's evacuation time c_{max}. Note that this formulation produces an unbounded linear program if there are negative cycles and under this condition the problem is in general NP-hard. However, in the case of evacuation network, all the arcs' costs (travel times) are greater or equal to zero, so we avoid this problem.

Finding the maximum number of arc-disjoint simple shortest paths might result in a very limited number of solutions since the number of arc-disjoint paths depends on the topology of the graph. It will be limited from above by the number of outgoing arcs from origin o and the number of incoming arcs to $\hat{d}$. This is why we opt for finding a number of sufficiently dissimilar paths for each evacuation origin-destination (O-D) pair. To this aim, a penalized objective function, which takes into consideration the violation of Constraint (5) becomes:

$$z(\lambda^{\mathbf{A}}) = \max K - \lambda^{\mathbf{A}^T} \mathbf{y^A} \tag{7}$$

subject to

$$\sum_{p \in P} \Big(\sum_{j:(i,j) \in A} \phi_{(i,j),p} x_p - \sum_{h:(h,i) \in A} \phi_{(h,i),p} x_p \Big) = \begin{cases} K, & \text{if } i = o \\ 0, & \text{if } i \in N \backslash \{o, \hat{d}\} \\ -K, & \text{if } i = \hat{d} \end{cases} \tag{8}$$

$$\mathbf{y^A} \geq \Phi \mathbf{x^P} - \mathbf{1} \tag{9}$$

$$\mathbf{y^A} \geq \mathbf{0}, \tag{10}$$

$$x_p \in \{0, 1\}, \forall p \in P_w, \tag{11}$$

where $\mathbf{y^A}$ is a vector composed of non-negative variables related to a multiple usage of each arc $a \in A$ by paths $p \in P_w$. $\lambda^{\mathbf{A}}$ is a non-negative penalty vector of cardinality $|A|$ for using each arc $a \in A$ more than once. In this way, we penalize a multiple usage of arcs by multiple paths.

Since we are not interested in the structure (i.e., the constituent arcs) of dissimilar paths, but in the maximum number K of the same, we can approximate the computation by assuming that path variables are continuous and, by doing so, we substitute Constraint (11) with the following:

$$0 \leq x_p \leq 1, \forall p \in P_w. \tag{12}$$

Finally, for the best approximation, we resolve a dual of the former problem, i.e.,

$$C_\epsilon = \min \mathbf{z}(\lambda^{\mathbf{A}}) \tag{13}$$

subject to

$$\lambda^{\mathbf{A}} \geq \mathbf{0}. \tag{14}$$

Note that the value of C_ϵ is an upper bound on the number of dissimilar paths and, therefore, also on the number of arc disjoint paths.

The model will return a maximum number of dissimilar paths (of length at most $c_{\max}$. It is easy to demonstrate that $z(\lambda^{\mathbf{A}}) \geq m$ for any $\lambda^{\mathbf{A}} \geq \mathbf{0}$.

4.3 Finding agile evacuation routes

Once we find the evacuation centrality measure value for each node of the evacuation network, we can proceed with finding agile evacuation paths for each evacuation origin node $o \in O$ i.e., each node with present evacuees. The formula for the computation of agility Λ_p of a path p is the following one:

$$\Lambda_p = \sqrt[|p|]{\prod_{a \in p} C_\epsilon(a)}, \tag{15}$$

where $|p|$ is the number of nodes in the path. We opt for the formulation of agility by using geometric mean since it balances the average and minimum values of the evacuation centralities of the path's constituent nodes. Moreover, let Λ^{cr} be a critical agility value, such that a route is considered sufficiently agile if $\Lambda_p \geq \Lambda^{cr}$.

After computing agility of each available path, we recommend to evacuees only the paths that are sufficiently agile.

Moreover, we propose to find routes over arcs that are sufficiently short in terms of travel time and, therefore, introduce an upper bound on an admissible arc's cost (e.g., travel time) c^{arc}_{max} such that:

$$c_a(x_a) \leq c^{arc}_{max}\ , \forall a \in A. \tag{16}$$

The value of c^{arc}_{max} is related both to the structure of the evacuation network as to the evacuees' maximum allowed travel time on each arc. In this light, if we introduce (16) into the path's optimization constraints, if all arcs are very large, then putting a too low value on c^{arc}_{max} and relaxing (16) will result in a too high cost in terms of relaxation penalties, while if c^{arc}_{max} is too high, then all arcs will be acceptable from this point of view.

Since (16) introduces further complexity to the problem since it might give non-integer solutions, we opt for a modelling approach that multiplies the costs of the arcs that do not comply with (16) with a very high number M such that in the case there is no alternative arc for the computation of a shortest path, these origin-destination pairs include the arcs with such high arcs' values. On the contrary, if there are arcs available that comply with Constraint (16), they will be taken into consideration first for finding evacuation paths.

4.4 Proposed agile evacuation route recommendation system

The objective of the proposed agile evacuation route recommendation system is to find agile evacuation routes for all pedestrians.

We assume the presence of a set of node agents N who communicate and compute pedestrian routes in a distributed manner similar to [6]. Pedestrians request their route from the smart space node agent closest to the origin of their evacuation (origin agent o). Based on the total evacuation demand expressed in terms of person flow per time unit, each origin agent o tries to achieve a sufficient number of shortest paths towards a dummy destination node $\hat{d}$. This demand is made by the persons starting the evacuation on o and the paths are computed through, e.g., modified Yen's loopless k-shortest path routing algorithm [4].

After the traffic assignment is made for O-D pairs, the latter decide on the pedestrians' assignment to the paths based on relevant social welfare parameters that guarantee equality through an iterative auction. The negotiation through auctions is local between each origin agent and the persons starting their travel at that origin, similar to [6].

Guidance g^k_a is considered a decision variable for each arc $a \in A$ and each path $k \in \bar{P}_w,\ w \in W$ instead of flow rate x_a as in traditional models. It enables pedestrians to follow a proposed path by following visual, tactile, acoustic or audio-haptic signals. Vector $\mathbf{g}^k_A = [g^k_1, \ldots, g^k_{|E|}]$ specifies an egress decision at each passageway for routes $k \in \bar{P}_w, \forall w \in W$. These decisions, when filtered for each member of route $k \in \bar{P}_w$ for each O-D pair $w \in W$ depending on his/her affiliate ties, provide an individual's route plan.

A possible rereouting recommended by the system is performed in regular time intervals by the algorithm's execution considering the evacuees' momentary positions. The evacuees are given only a necessary information of the next part of the route to pass, without saturating them with the unnecessary route information that may change through time.

5 Case Study

We demonstrate the functionality of the proposed approach by means of a simple case study example in Figure 1, which is a modified version of the example appearing in [7].

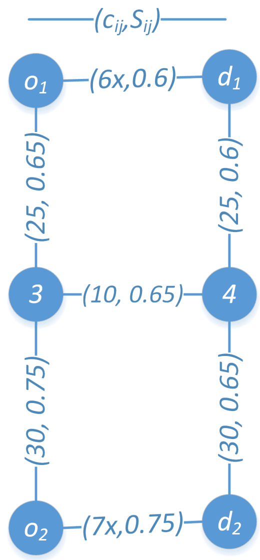

Figure 1: A simple case-study example of an evacuation network

Given is an evacuation scenario of a building network with 6 nodes and 7 arcs, as seen in Figure 1. The network contains two evacuation origin nodes, o_1 and o_2, two transit nodes, 3 and 4, and two evacuation destination nodes (safe exits) d_1 and d_2. Moreover, given are arcs' travel times c_{ij}, $[min]$, and arcs' safeties S_{ij} for all arcs (i, j) as seen in Figure 1. Note that all the arcs of the network have fixed travel times except for the arcs (o_1, d_1) and (o_2, d_2) whose travel times depend on the flows of people on these arcs.

Let us assume that the critical safety both for arcs and paths is $S_{cr} = 0.55$ such that our case-study evacuation scenario contains all safe arcs. Moreover, given is the tolerance factor for the maximum allowed evacuation route cost (travel time), $\gamma = 1.2$. The objective is to find agile evacuation paths towards safe exits for all evacuation demands.

In the following, we analyze the case study network and find the value of evacuation centrality measure C_ϵ for each node. Evacuees from all origins can use all safe exits for their evacuation based on their personal preferences and overall safety constraints. If there does not exist any path p from a node to any of safe exits with $S^p > S_{cr}$, this approach will propose the least unsafe paths.

Evacuees are located at the evacuation origin nodes o_1 and o_2 and have available two safe exits for evacuation (evacuation destination nodes). Starting at node o_1, there are two O-D pairs available, (o_1, d_1) and (o_1, d_2). For the evacuees at node o_2, there are two possible evacuation O-D pairs, (o_2, d_1), and (o_2, d_2). For each of the pairs (o_1, d_1) and (o_2, d_2), there are three simple paths available. For the pairs (o_1, d_2) and (o_2, d_1), there are four simple paths available for each pair.

In any case, the travel time of temporally efficient paths cannot surpass the tolerance factor $\gamma \cdot c^{od}_{min}$ in respect to the fastest path. Therefore, temporally efficient paths for O-D pair (o_1, d_1) are $p^1_{o_1 d_1} = (o_1, d_1)$ with travel time $c_{p^1} = 6x_{o_1 d_1}$ and $p^2_{o_1 d_1} = \big((o_1, 3), (3, 4), (4, d_1)\big)$ with travel time $c_{p^2} = 60$. Path $p^3_{o_1 d_1} = \big((o_1, 3), (3, o_2), (o_2, d_2), (d_2, 4), (4, d_1)\big)$ with travel time $c_{p^3} = 7x_{o_2 d_2} + 110$ is not temporally efficient. As a consequence, the travel time for O-D pair (o_1, d_1) will be no more than 60 min.

Depending on flow $x_{o_2 d_2}$ on arc (o_2, d_2), the shortest paths for O-D pair (o_2, d_2) will be $p^1_{o_2 d_2} = (o_2, d_2)$ with travel time $c_{p^1} = 7x_{o_2 d_2}$ and $p^2_{o_2 d_2} = \big((o_2, 3), (3, 4), (4, d_2)\big)$ with travel time $c_{p^2} = 70$. Path $p^3_{o_2 d_2} = \big((o_2, 3), (3, o_1), (o_1, d_1), (d_1, 4), (4, d_2)\big)$ with travel time $c_{p^3} = 6x_{o_1 d_1} + 110$ is not temporally efficient so that the travel time for O-D pair (o_2, d_2) will be no more than 70 min.

For O-D pair $o_1 - d_2$, temporally efficient paths are $p^1_{o_1 d_2} = \big((o_1, d_1), (d_1, 4), (4, d_2)\big)$ with travel time $c_{p^1} = 6x_{o_1 d_1} + 55$, $p^2_{o_1 d_2} = \big((o_1, 3), (3, o_2), (o_2, d_2)\big)$ with travel time $c_{p^2} = 7x_{o_2 d_2} + 55$, and $p^3_{o_1 d_2} = \big((o_1, 3), (3, 4), (4, d_2)\big)$ with travel time $c_{p^3} = 65$. Path $p^4_{o_1 d_2} = \big((o_1, d_1), (d_1, 4), (4, 3), (3, o_2), (o_2, d_2)\big)$ with travel time $c_{p^4} = 6x_{o_1 d_1} + 7x_{o_2 d_2} + 65$ is not temporally efficient due to its too high travel time in any case of the flows on arcs (o_1, d_1) and (o_2, d_2). Thus, O-D pair (o_1, d_2) has three temporally efficient paths available whose traversal time will be no more than 65 min.

Similarly, O-D pair $o_2 - d_1$, depends on flows on arcs (o_1, d_1) and (o_2, d_2). Temporally efficient paths will be $p^1_{o_2 d_1} = \big((o_2, 3), (3, o_1), (o_1, d_1)\big)$ with travel time $c_{p^1} = 6x_{o_1 d_1} + 55$, $p^2_{o_2 d_1} = \big((o_2, d_2), (d_2, 4), (4, d_1)\big)$ with travel time $c_{p^2} = 7x_{o_2 d_2} + 55$, and $p^3_{o_2 d_1} = \big((o_2, 3), (3, 4), (4, d_1)\big)$ with travel time $c_{p^3} = 65$. The travel time on these paths will be no more than 65 min. On the other hand, path $p^4_{o_2 d_1} = \big((o_2, d_2), (d_2, 4), (4, 3), (3, o_1), (o_1, d_1)\big)$ with travel time $c_{p^4} = 6x_{o_1 d_1} + 7x_{o_2 d_2} + 65$ will not be used since it is not temporally efficient. Similarly, we analyze the rest of the nodes of the network and based on these numbers, in Table 1, we give the values of evacuation centrality measure of each node.

Table 1: Evacuation centrality measure values for the network in Figure 1

Node	o_1	o_2	3	4	d_1	d_2
Evacuation Centrality	5	5	4	3	4	4

Here, the computation of the evacuation centralities for safe exit nodes d_1 and d_2 is found counting only the number of the safest temporally efficient simple paths towards the other safe exit.

Based on the evacuation centrality measure values of the nodes of the network, we find agile evacuation paths by applying Formula (15) for o_1 and o_2 since momentarily these are the nodes with present evacuees.

We find the two paths with the highest value: $p^1_{o_1 d_1} = (o_1, d_1)$ and path $p^2_{o_1 d_2} = \big((o_1, 3), (3, o_2), (o_2, d_2)\big)$, both with path agility value $\Lambda_{p^1} = \Lambda_{p^2} = 4,472$. Other three paths have the path agility value $\Lambda_p = 3,936$.

The critical agility of the evacuation paths is assumed to be $\Lambda^{cr} = 2$, so all the paths are sufficiently agile for evacuation. For origin o_2, the two paths with the highest evacuation values are $p^1_{o_2 d_2} = (o_2, d_2)$ and $p^1_{o_2 d_1} = \big((o_2, 3), (3, o_1), (o_1, d_1)\big)$, both with the value $\Lambda_{p^1} = \Lambda_{p^2} = 4,472$. These paths are first recommended to evacuees.

6 Conclusions

In this work we studied the agility of evacuation routes in relation to dynamically changing unpredictable hazardous conditions in smart spaces. We analyzed node's degree, eigenvalue, and betweenness centrality measure and proposed the term of evacuation centrality related with the node's importance for evacuation. Moreover, we introduced and defined the term of agility in evacuation routes and mathematically formulated agile evacuation route problem and discussed its capability to adjust to possible contingencies through time.

In future work, we intend to analyze in depth the efficiency of our approach related with unpredictable safety drops through simulations on building networks of varying complexity. Related is the issue of scalability. We plan to evaluate real-time responsiveness of our approach to varying number of evacuees and a varying size of the evacuation network.

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