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Abstract

In evacuation models, the time between the first alarm or other initial cue until the population starts evacuating, often referred to as the pre-evacuation time or pre-movement time, is usually a user defined input. Ideally, the pre-evacuation time would be predicted by the models. This paper describes the development of the Evacuation Decision Model (EDM) from Kuligowski's qualitative model of pre-evacuation behavior [1]. EDM models the decision process a person uses based on physical, social and psychological cues as they occur over time; and predicts the evolution of the decision to take protective action from a limited number of user inputs. The paper includes a section that gives a concise description of how to implement EDM as a sub-model in an evacuation model.

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0.1 Nomenclature

$A_{I,i}$	The impact of various cues on risk assessment before agent i reaches investigating state
$A_{E,i}$	The impact of various cues on risk assessment before agent i reaches evacuating state
C_E	$= \frac{R_E}{R_I}$
$K_{P,i}(\ldots)$	Prior knowledge cue for agent i
$k_{P,i}$	Relative value of prior knowledge cue for agent i when active
$R_i(t)$	Perceived risk level for agent i
R_I	Level of preceived risk when an agent goes from normal state to investigating state
R_E	Level of perceived risk when an agent goes from investigating state to evacuating state
$\mathbf{N}_i(t)$	Vector or array of the number of agents in different states that agent i can '*see*'
$N_{E,i}(t)$	Number of agents in the evacuation state that agent i can '*see*'
$N_{I,i}(t)$	Number of agents in the investigating state that agent i can '*see*'
$N_{N,i}(t)$	Number of agents in the normal state that agent i can '*see*'
$N_{0,i}$	Number of agents in the normal state that will prevent agent i reacting to an alarm
$\mathbf{Q}(t)$	Vector or array of external cues
$Q_j(t)$	The j^{th} cue
$Q_a(t)$	The alarm cue
q_j	Relative value of the j^{th} cue when active
q_a	Relative value of the alarm cue when active, defined as $= 1$
$S_i(\ldots)$	Social influence cue for agent i
$t_{I,i}$	Time for agent i to reach investigating state with one constant continuous cue
t_a	Time when alarm sounds
t_s	Time when smoke is visible

0.2 Introduction

In evacuation models, the time between the first alarm or other initial cue until the population starts evacuating, often referred to as the pre-evacuation time or pre-movement time, is usually a user defined input. However, this time can have a significant impact on the total evacuation time. Ideally, this time would be predicted by evacuation models (e.g. FDS+evac [2], Egress Estimator [3]) using initial (pre-scenario) inputs about the population, environment and cues.

Kuligowski [1] has developed a qualitative model of pre-evacuation time using interviews and other information from survivors who were in the World Trade Center (WTC) on Sept. 11, 2001. Gwynne [4] defined all the actions that need to be implemented in order to fully incorporate Kuligowski's qualitative model into an agent-based evacuation model. The Evacuation Decision Model (EDM) presented in this paper addresses another aspect of the problem, how agents make the decision to evacuate. It is a simple first order quantitative model of the decision process an individual uses to interpret cues from the environment to determine if protective action, in this case evacuation, is warranted. It is inteneded to be a sub-model in an evacuation model like those previously mentioned.

There are a number of features from a model implementation perspective that are desirable to include. For example, minimize the number of parameters, especially parameters that are tracked for each agent. User inputs should be clearly defined so even if not practically measurable, the user can understand the concept. Finally, it is desirable that EDM can serve as a framework in which future sub-models of pre-evacuation behavior can be easily added.

What follows is a description of both EDM and what a model developer requires to implement the model, followed by some concluding remarks. This paper provides an initial description of EDM in order to elicit comments from interested researchers.

0.3 Model Development

In this section, a brief step-by-step development will be given to serve as motivation for the final form of the model. This is to make it easier for others to understand and modify or extend the model. Subsections 0.3.1 to 0.3.6 lay out the steps of developing the model starting with the assumptions made based on Kuligowski's work [1]. Section 0.3.7 describes how EDM could be implemented in an egress model.

Before starting a description of the model there needs to be a brief discussion of terminology. Through out the rest of this paper the theory will be described in terms of how an agent and not a person responds. There are two reasons for this. First this model is a numerical implementation of Kuligowski's sociological model of the behaviors of people observed and documented in evacuations. It is not meant to be an actual description of the thought process of people. Secondly, the model functions at the individual level so it is easiest to explain it in terms of an agent-based evacuation model. So to keep the distinction between actual people and their actions separate from agents intended to simulate people's actions in an evacuation model the paper will refer to agents and not people except where the discussion is about observations or insights about people.

0.3.1 Assumptions

Kuligowski's qualitative model [1] is built on a detailed analysis of 245 interviews from survivors of WTC 1 and 2 for pre-evacuation cues and the impact of those cues on an individual's actions and risk assessment. Her analysis is organized into a decision loop that each individual repeats until either the decision to evacuate is made or the emergency event ends. EDM simplifies the findings of Kuligowski and includes them in the model through the basic assumptions the model uses, which will now be described. The ultimate subject of this research is to create tools to help building designers, authorities having jurisdiction and other stakeholders in new and existing buildings to estimate the hazards and risks of the buildings. The model focuses on predicting the time it takes to decide that protective action is necessary. It does not predict what investigative or protective behaviors an agent may take, such as searching for others, trying to fight a fire or warning others. The model is not meant to reproduce a particular person or a particular set of people on a particular day in a particular scenario. That level of detail is beyond this model and outside the scope of the research. To that end:
Assumption 1. *The purpose of this model is to predict the point in time when the decision to take protective action is made.*

In the WTC attack, the cues that people received varied and were often more extreme than those received in the past. These cues resulted in a many different interpretations by survivors and many different actions performed because of those interpretations. The framework that Kuligowski used, the Protective Action Decision Model (PADM) [5], models the internal questions that a person involved in an incident would ask and answer. For example, the first question a person asks in PADM is 'is there a real threat that I need to pay attention to?' For the purposes of predicting the time it takes to start protective actions, it is important to understand the agent's level of risk perception. This translates into:
Assumption 2. *Risk perception is the key factor to simulate when predicting the timing of the evacuation decision.*

Kuligowski's model simulates three major types of behavior based on risk perception. First, those who do not perceive any risk, continue normal activities. Second, those who perceive some risk, seek additional information, referred to as milling/sensemaking. Third, those who perceive a sufficient level of risk, take protective actions. Kulgowski notes after WTC 1 was hit 15 % of survivors of WTC 1 and 2 interviewed continued previous activities. Clearly, it is not reasonable to assume that all agents stop normal activities at the first cue.

It is also important to understand that different models have differing levels of capability. For EDM to be as flexible as possible, the choices about what behaviors the agents demonstrate in each state is left to the model developer.

Assumptions 3 and 4 describe how EDM is included in an egress model. For an agent-based model each agent has three different states of behavior and EDM determines which state each agent is in. The types of behaviors agents preform in each state are determined by the egress model, and the full range of actions and interactions are included in Gwynne [4].

Assumption 3. *Each agent's level of risk perception determines the agent's state, which determines the agent's actions.*

Assumption 4. *Agents have three states*

1. *Normal - where agents continue previous actions*
2. *Investigating - where agents seek additional information*
3. *Evacuating*

Kulgowski found that different physical and social cues elicited different levels of response. For example, some high intensity physical cues that people received included the building moving and hearing a loud boom, while lower intensity physical cues included muffled sounds and lights flickering. "Cues and information were categorized as high or low intensity based upon the danger they appeared to pose to occupants, the level of difference from normal conditions, and the meaning occupants assigned to the cues."([1] page 114) Kuligowski also found that a person's reaction to a cue was in part dependent on the level of risk the person was currently experiencing. EDM includes these finding as follows.

Assumption 5. *An agent's change in risk perception is proportional to the intensity of the cues the agent receives as well as the agent's current level of perceived risk.*

In an analysis of WTC survivor interviews, Kuligowski found that a number of the interviewees were, as she termed it, hyper-vigilant on the day the WTC was attacked. In some cases, this was due to being present in the WTC when the 1993 bombing occurred and subsequently evacuated the building. Likewise, a person who had experienced a number of false alarms could become complacent, possibly as a result of the 'cry wolf' syndrome. The impact of prior knowledge on agents is captured in Assumption 6.

Assumption 6. *Agents perspective and memories of previous experiences can increases or decrease the rate of change of an agent's risk perception when processing external cues.*

Some of the high intensity social cues listed by Kuligowski are people yelling and screaming, fearful facial expressions and people running around. One example of a low intensity cue is people not reacting i.e., acting as if nothing is happening. The impact of the observed behavior of other agents is captured in Assumption 7.

Assumption 7. *The observed state of other agents can increase or reduce the risk perception of an agent.*

Assumption 7 does not include agents exchanging verbal information. EDM currently does not include the exchange of verbal information behavior.

Assumptions 1 and 2 govern the overall philosophy of EDM, while assumptions 3 and 4 describe the interface between EDM and an evacuation model that includes it. The impact of the rest of the assumptions will be pointed out at the appropriate points in the documents.

0.3.2 Basic Model

There are two parts to the model. The first is the loop structure and the second is evaluating information to determine the agents level of risk perception.

Loop Structure

Kuligowski [1] has a detailed two level decision loop that describes what people did in the WTC. The loop builds on the Protective Action Decision Model (PADM) of Lindell and Perry [5].

The basic loop is given the information just collected, reassess the level of risk perception. The first level is if current information is not sufficient to cause the person to seek information, which is the normal state from Assumption 4, what does the person do. The second level focuses on decisions made once a person starts to seek information, which is the investigating state. If the person's risk level is not sufficiently high enough to start evacuation, determine the appropriate action and repeat. In order to have as much flexibility as possible EDM determines which state the agent is in and the evacuation model implementing EDM determines what actions the agent preforms, as discussed in Section 0.3.1 assumptions 3 and 4.

Therefore, EDM is really a loop where at each step the cues active at that step are evaluated to change the level of risk perception. We can think of this as a difference equations $R_{k+1} = R_k + f(t_k)\Delta t$, where R_k is the risk level at step k and $f(t_k)$ is the impact of active cues. In the limit as Δt goes to zero, the decision loop becomes a differential equation. this differential equation is the subject of the rest of the paper.

Level of Risk Perception

From Assumption 2, EDM focuses on the level of risk perception for each agent i, given as $R_i(t)$. Level of risk perception is, of course, an abstract concept meant to capture a part of the thought process people go through during an emergency event. When measuring level of risk perception social scientists often use a Likert scale. An example of a Likert scale would be:

On a scale of 1 to 7 during the event what was your level of risk perception with 1 representing no risk and 7 representing about to die.

The values for $R_i(t)$ can be thought of as a Likert scale. Because of Assumption 4 two values, R_I and R_E, will be introduced as levels of risk perception at which point the state of an agent changes to investigating and evacuating respectively. Since a numerical value for risk perception is an artifact of the model, it will be desirable in the development that the actual values used for R_I and R_E do not have an impact on the results. More information will be given on $R_i(t)$, R_I, and R_E as the development continues.

In order to calculate the level of risk perception of agent i, $R_i(t)$, start with Assumption 5, which gives

$$\dot{R}_i(t) = A_i R_i(t) \tag{1}$$

where A_i is the impact of a constant continuous cue on agent i. An example of a constant continuous cue is an alarm. It sounds and continues to sound for the time period and does not change the information content. An enunciator that changes message during the event to indicate a second alarm activating would not be constant. An explosion might be an intense cue but would not be continuous. With these assumptions Eq (1) can be solved analytically to obtain:

$$R_i(t) = R_i(0)\, e^{A_i t} \tag{2}$$

Becasue the risk perception scale is an arbitrary scale it can be assumed to have an initial value of 1, i.e. $R_i(0) = 1$. Assumption 5 leads to Eq (2), which states that the risk perception to a simple cue such as an alarm is an exponential growth model. If we define $R_I > 1$ as the level of risk perception which causes any and all agents to go from the normal state to the investigating state and $t_{I,i}$ is the point in time where the i^{th} agent reaches the investigating state with only a single continuous cue, such as an alarm, we have

$$R_i(t_{I,i}) = e^{A_{I,i} t_{I,i}} = R_I \tag{3}$$

Solving for $A_{I,i}$ gives

$$A_{I,i} = \frac{\ln R_I}{t_{I,i}} \tag{4}$$

Note that from this definition the value of R_I does not have an impact on the time agent i evacuates. The only requirement is that $R_I > 1$ as risk perception is assumed to grow.

0.3.3 Expanding the Model

At this point, the model looks to be just a tautology, i.e. it just returns the pre-evacuation time the user supplies. However, this analytic solution has two additional assumptions that are not a part of EDM. The first is that there is only one cue, and second, the cue doesn't change with time. How EDM eliminates these assumptions is discussed below.

More than One Cue

Assume for the i^{th} agent that $t_{a,i}$ is the time it takes to transition to the investigating state for a single alarm and $t_{s,i}$ is the time it takes if agent i sees smoke. Using Eq (4) gives:

$$A_{a,i} = \frac{\ln R_I}{t_{a,i}} \tag{5}$$

$$A_{s,i} = \frac{\ln R_I}{t_{s,i}} \tag{6}$$

We assume that cues have an additive effect, which gives

$$\dot{R}_i(t) = (A_{a,i} + A_{s,i})\, R_i(t) \tag{7}$$

Simplify by factoring $\ln R_I / t_{a,i}$ from both terms gives

$$\dot{R}_i(t) = \frac{\ln R_I}{t_{a,i}} \left(\frac{t_{a,i}}{t_{a,i}} + \frac{t_{a,i}}{t_{s,i}} \right) R_i(t) = \frac{\ln R_I}{t_{a,i}} \left(1 + q_s\right) R_i(t) \tag{8}$$

where

$$q_s = \frac{t_{a,i}}{t_{s,i}} \tag{9}$$

The ratio of time of the smoke cue compared to the impact of an alarm, q_a. For example, if agent i starts investigating in half the time seeing smoke as opposed to hearing an alarm, the relative impact of the cue would be $q_s = 2$.

In EDM, it is assumed that each cue has the same relative impact on each agent. This assumption is made because it is highly likely that there is a strong correlation in the relative impact of different cues on the general population. While people in a population don't all have the same experiences they do share a significant number, so it is likely that any person in a population will be more concerned about smoke in a building than a fire alarm, which everyone has heard many times in drills. Making this assumption results in the change in risk perception for agent i to be

$$\dot{R}_i(t) = A_{a,i} \left(\sum_j q_j \right) R_i(t) \tag{10}$$

where q_j is the relative impact of the j^{th} cue for all agents, with the cue for a simple alarm, such as a single tone or tone pattern without a verbal announcement, defined as $q_a = 1$. In our example of an agent seeing smoke and hearing an alarm, Eq (8), if $q_s = 2$ then agent i would transition to the investigating state in $\frac{1}{3}$ the time when both seeing smoke and hearing an alarm than the agent would take if there was only an alarm. Cues like the alarm sounding or seeing smoke are termed external cues. Whether agent i is aware of a particular cue is determined by the evacuation model that includes EDM.

Non-constant Cues

Suppose that instead of two continuous cues both starting at the same time, the agent first sees smoke and after some period of time hears the alarm sound. The analytic solution is then not appropriate but can be solved numerically using Euler's method, for example with $q_a = 0$ for $t < t_a$ and $q_a = 1$ for $t \geq t_a$. Cues then should be thought of not as constants but as functions, $Q_j(t)$ where, in its simplest form,

$$Q_j\left(t\right) = \begin{cases} q_j & t \geq t_j \\ \\ 0 & t < t_j \end{cases} \tag{11}$$

To eliminate confusion, $t_{I,i}$, is defined as the time the i^{th} agent takes to start to investigate if the only cue is a single alarm. The variable t_a is globally defined as the time the alarm sounds and t_s is the time smoke is visible.

Note that before any cue activates, the change in risk perception would be 0 and so the risk perception of the agent would stay the same as for $t = 0$, specifically $R_i(t) = 1$ for $t < \min(t_j)$ for all j cues. Therefore, t in EDM is referenced to the activation of the first cue and not from the start of the simulation. Finally EDM will require, $R_i(t) \geq 1$. As will be discussed, it is possible to have cues that decrease the risk perception of an agent. It can be rationalized that there are cues that would make an agent even less likely to start investigating an incident, i.e. $R_i(t) < 1$. However, without an empirical or theoretical basis, EDM will not include that possibility. Therefore, in equation form, if $\dot{R}_i(t) < 0$ when $R_i(t) = 1$ then $\dot{R}_i(t) = 0$.

0.3.4 Interpreted cues

As stated before the cues discussed so far are termed external cues, meaning that the cue's value is determined independent of the agent. Interpreted cues are defined as cues whose value is set specifically for an agent. There are currently two interpreted cues in EDM. The first is the prior knowledge cue, which indicates a scenario-dependent tendency for agent i's response to cues to be based on prior experiences of the agent. The second is the social influence cue. This is a measure of how the observed actions of other agents indirectly impacts an agent's perception of risk. The two will be discussed in order. The interpreted cues' values are on the same relative scale as the external cues and are assumed to be additive with external cues.

Knowledge Cues

Knowledge cues are information an agent receives or remembers in response to some interaction or trigger, and the impact of the knowledge cue continues after the trigger. The one knowledge cue included in EDM is the prior knowledge cue, $K_{P,i}(t)$ from assumption 6. The prior knowledge cue attempts to account for scenario-specific information that would impact a specific agent such as Sept 11^{th} survivors that had been in the WTC for the 1993 bombing. It may be represented as

$$K_{P,i}\left(\mathbf{Q}(t), R_i(t)\right) = \begin{cases} 0 & \mathbf{Q}(t) = 0 \text{ and } R_i(t) = 1 \\ \\ k_{P,i} & \text{else} \end{cases} \tag{12}$$

where $\mathbf{Q}(t) = (Q_1(t), \ldots, Q_m(t))$ is the array or vector of all the possible external cues. The cue value $k_{P,i}$ can take all real values both positive and negative but is normally 0. For $k_{P,i} > 0$ agent i is hyper-vigilant while $k_{P,i} < 0$ means agent i is more complacent than normal about emergency-type cues.

Social Influence Cue

Assumption 7 is included in EDM through social influences. For example, suppose a person is sitting in an empty auditorium and an alarm sounds. The expected behavior, after a certain amount of time, is that the person would start investigating the situation. Now suppose the same person is in the same auditorium that is now filled with people who do not react to the alarm. The expected behavior, because of social influence, would be for the original person to remain in his or her seat. Kuligowski found this type of behavior recalled in WTC interviews.

To implement this cue, the egress model using EDM must have agents aware in some way of other nearby agents or '*see*' them. Also agents have to be able to determine the state of any other agent '*seen.*' The numbers of observed agents in each state are passed to EDM through the vector $\mathbf{N}_i(t) = \{N_{E,i}(t), N_{I,i}(t), N_{N,i}(t)\}$ where $N_{E,i}(t)$ is the number of agents in the evacuating state observed by agent i at time t, $N_{I,i}(t)$ is the number of agents observed in the investigating state, and $N_{N,i}(t)$ is the number of agents observed in the normal state. Define $N_i(t)$ as

$$N_i(t) = N_{E,i}(t) + N_{I,i}(t) + N_{N,i}(t) \tag{13}$$

Agent i observes some agents in either the evacuating or investigating state whenever $N_{N,i}(t) < N_i(t)$.

There are four properties that any social influence sub-model, $s_i(\mathbf{N}_i(t))$ has to satisfy. First is if agent i doesn't see any other agents, i.e. $N_i(t) = 0$, the social influence is 0. Second, if all observed agents are in the normal state and the number of agents that agent i equals a user specified value, $N_{i,0}$, than the alarm, $q_a = 1$, plus the social influence has no effect on agent i. In other words, if $N_i(t) = N_{N,i}(t) = N_{0,i}$ than

$$q_a + s_i(\mathbf{N}_i(t)) = 0 \Rightarrow s_i(\mathbf{N}_i(t)) = -1 \tag{14}$$

Third, if all the observed agents are in the normal state and the total is greater than $N_{0,i}$ than $s_i(\mathbf{N}_i(t)) < -1$ and if the total is less than $N_{0,i}$ than $s_i(\mathbf{N}_i(t)) > -1$. Finally, if agent i sees agents in the evacuating state or the investigating state the agent is more likely to start investigating than if that agent does not see any. A simple functional form that meets all the requirements is

$$S_i\left(\mathbf{N}_i(t)\right) = 2\frac{N_{E,i}(t) + N_{I,i}(t) - N_{N,i}(t)}{N_{E,i}(t) + N_{I,i}(t) + N_{N,i}(t) + N_{0,i}} \tag{15}$$

To demonstrate the impact of $N_{0,i}$ suppose that $N_{N,i}(t) = N_{0,i}$, $N_{E,i}(t) = N_{I,i}(t) = 0$ and the only cue is $Q_a(t) = 1$. The change in risk perception is

$$\dot{R}_i(t) = \frac{\ln R_I}{t_I} \quad Q_a(t) + 2\frac{N_{E,i}(t) + N_{I,i}(t) - N_{N,i}(t)}{N_{E,i}(t) + N_{I,i}(t) + N_{N,i}(t) + N_{0,i}} \quad = \frac{\ln R_I}{t_I} \quad 1 + \frac{-2N_{0,i}}{N_{0,i} + N_{0,i}} \quad = 0 \tag{16}$$

In this case if $N_{N,i}(t) < N_{0,i}$ then $\dot{R}_i(t) > 0$ and if $N_{N,i}(t) > N_{0,i}$ then $\dot{R}_i(t) < 0$ unless, as discussed earlier, $R_i(t) = 1$ then $\dot{R}_i(t) = 0$.

From this definition, the very first cue for an agent can be some other agent changing state. Such a change may also trigger any prior knowledge that the agent has. Therefore the definition for the prior knowledge cue changes to

$$K_{P,i}(\mathbf{Q}(t), \mathbf{N}_i(t), R_i(t)) = \begin{cases} 0 & \mathbf{Q}(t) = 0, R_i(t) = 1 \text{ and } N_{N,i}(t) = N_i(t) \\ k_{P,i} & \text{else} \end{cases} \tag{17}$$

Putting everything together, the equation for the change in risk perception for agent i is

$$\dot{R}_i\left(t\right) = \frac{\ln R_I}{t_{I,i}} \left(\sum_j Q_j\left(t\right) + K_{P,i}\left(\mathbf{Q}(t), \mathbf{N}_i(t), R_i(t)\right) + S_i(\mathbf{N}_i(t)) \right) R_i(t) \tag{18}$$

Eq (18) is written with external cues, prior knowledge cues, and social influence cues as functions to emphasize the aspect of EDM as a framework. As was stated in the Introduction, one of the intents of developing the model is for it to be flexible and able to serve as a framework for future research. The simple functions defined in this paper for each of the cues could be replaced with more sophisticated models that change with time or other conditions. Other cues could be added. The basic model would still be valid.

0.3.5 Investigating State

Thus far, model development has been for an agent in the normal state. Once the agent transitions to the investigating state, the agents behavior will change. In the normal state, the behavior is characterized as continuing behavior the agent would normally be doing. In the investigating state, the agent preforms information-collecting behaviors. Details are covered in Kuligowski [1] and the implications for an agent-based evacuation model are discussed in Gwynne [4]. Often, the investigating behavior is for an agent to go to some common area to meet with other agents to exchange information. This is called milling. Whatever behaviors a particular egress model implements, EDM takes cues collected by the agent during the investigating mode to update the agent's risk perception.

To start, simplify (18) by defining $A_{I,i}(t)$ as

$$A_{I,i}(t) = \sum_{j} Q_j\left(t\right) + K_{P,i}\left(\mathbf{Q}(t), \mathbf{N}_i(t), R_i(t)\right) + S_i(\mathbf{N}_i(t)) \tag{19}$$

Again consider the case of agent i with only one alarm. In this case $A_{I,i}(t) = A_{I,i} = 1$. Eq (2) gives the analytical solution. Define R_E to be the level of risk perception at which an agent transitions from an investigating state to an evacuating state. The one requirement is that $R_E > R_I$. It will be useful to define $R_E = C_E R_I$, which means $C_E > 1$. Finally define t_E as the time the agent enters the evacuating state, so $\Delta t_E = t_E - t_I$. To find Δt_E solve

$$R_E = C_E R_I = e^{\frac{\ln R_I}{t_{I,i}} t_{E,i}} = e^{\frac{\ln R_I}{t_{I,i}}(t_{I,i}+\Delta t_{E,i})} \tag{20}$$

Take the log of both sides and simplify to get

$$\ln C_E + \ln R_I = \ln R_I \frac{t_{I,i} + \Delta t_{E,i}}{t_{I,i}} \Rightarrow \frac{\ln C_E}{\ln R_I} + 1 = 1 + \frac{\Delta t_{E,i}}{t_{I,i}} \Rightarrow \frac{\ln C_E}{\ln R_I} t_{I,i} = \Delta t_{E.i} \tag{21}$$

Because $C_E > 1$, $\ln C_E > 0$ and since the other factors are also positive, $\Delta t_{E,i} > 0$. A nice feature is that $\Delta t_{E,i}$ is proportional to $t_{I,i}$, which reduces the number of user defined variables. However, notice that $\Delta t_{E,i}$ is explicitly dependent not only on C_E but also R_I. As was discussed in section 0.3.2, it is desirable for the results to be independent of the values of R_I and/or R_E.

Modifying the Change in Risk Perception

Now consider a different approach to calculating the change in risk perception of an agent in the investigating state. In this example, because of the simplifying assumptions, the transition from normal to investigating occurs at, $t_{I,i}$. Normally transition does not have to happen at $t_{I,i}$. Assume that once an agent has transitioned into the investigating state the calculation of risk perception changes to

$$R_i(t_I + \Delta t) = e^{\frac{\ln R_I}{t_{I,i}} A_{I,i} t_{I,i} + A_{E,i}\Delta t} = e^{\frac{\ln R_I}{t_{I,i}} A_{I,i} t_{I,i}} e^{A_{E,i}\Delta t} = R_I e^{A_{E,i}\Delta t} \tag{22}$$

Now solve for $A_{E,i}$ when $\Delta t = \Delta t_{E,i}$ to get

$$C_E R_I = R_I e^{A_{E,i}\Delta t_{E,i}} \Rightarrow C_E = e^{A_{E,i}\Delta t_{E,i}} \Rightarrow \frac{\ln C_E}{\Delta t_{E,i}} = A_{E.i} \tag{23}$$

This is a similar result to Eq (4) and the development of the equation for all cues follows a similar path. The result is the equation for change in risk perception for agents in the investigating state, $R_I \leq R_i(t) < R_E$, is

$$\dot{R}_i(t) = \frac{\ln C_E}{\Delta t_{E,i}} \left(\underset{j}{} Q_j(t) + K_{P,i}(\mathbf{Q}(t), \mathbf{N}_i(t), R_i(t)) + S_i(\mathbf{Q}(t), \mathbf{N}_i(t), R_i(t)) \right) R_i(t) \tag{24}$$

It is important to remember that transitioning from one state to the next is dependent on the value of $R_i(t)$ not on the time.

Modifying the Social Influences

Finally, S_i changes from Eq (15) for an agent in the investigating state. The function now uses the current level of risk perception as follows

$$S_i(\mathbf{Q}(t), \mathbf{N}_i(t), R_i(t)) = \begin{cases} 2\frac{N_{E,i}(t)+N_{I,i}(t)-N_{N,i}(t)}{N_{E,i}(t)+N_{I,i}(t)+N_{N,i}(t)+N_{0,i}} & R_i(t) < R_I \\ \\ 2\frac{N_{E,i}(t)-N_{N,i}(t)}{N_{E,i}(t)+N_{I,i}(t)+N_{N,i}(t)+N_{0,i}} & R_i(t) \geq R_I \end{cases} \tag{25}$$

The assumption is when an agent is in the investigating state, observing other agents in the investigating state adds to the confusion, it does not help resolve the confusion. As more agents in the investigating state, $N_I(t)$, are observed, $N_I(t)$ dilutes the impact of agents in the evacuating or normal state but does not directly have any impact on the rate of change of perception of risk, $\dot{R}_i(t)$. For example, consider two agents, i and k, that are both in the investigating state and have the same $N_0 = 5$. Agent i can '*see*' only 6 agents all in the evacuating state, $N_{E,i}(t) = 6$ and $N_{I,i}(t) = N_{N,i}(t) = 0$. The social influence is

$$S_i(\mathbf{N}_i(t)) = \frac{2 \cdot 6}{6 + 5} = 1.09$$

Agent k can also '*see*' 6 agents in evacuating state but also 5 agents in investigating state, $N_{E,k}(t) = 6$, $N_{I,k}(t) = 5$ and $N_{N,k}(t) = 0$. The social influence for agent k is

$$S_i(\mathbf{N}_k(t)) = \frac{2 \cdot 6}{6 + 5 + 5} = 0.75$$

The 5 agents in the investigating state that agent k '*sees*' dilutes the social influence of observing 6 agents in evacuating state as compared to agent i.

0.3.6 Evacuating State

In the evacuating state the agent begins evacuation behaviors. These can include some preparation behaviors such as collecting personal items but culminates with evacuating the building. The important point regarding EDM is that the agent has made the decision to evacuate and so the model is complete.

0.3.7 The Complete EDM

For an egress model to include EDM, the model has to make the assumptions in Section 0.3.1. For the model, the cue vector $\mathbf{Q}(t)$ has to be defined where $Q_a(t) = 1$. $\mathbf{Q}(t)$ may be dependent in part on calculations of other parts of the evacuation model or other models. An example would be using a fire model to determine when an alarm sounds and when smoke is visible. It is also possible for $\mathbf{Q}(t)$ to vary with position of an agent. For example, smoke being visible in one room and not in another. The values and timings of $\mathbf{Q}(t)$ are determined independent of EDM and passed to it. The same is true of the vector $\mathbf{N}_i(t)$. It is determined by the egress model and passed to EDM. Also the values of R_I and C_E have to be set by the model developer. The only requirement is both values are > 1.

For each agent the user has to provide four values:

- $t_{I,i}$ - the time agent i takes to transition to the investigating state with only a single alarm. (i.e. without the presence of other cues)
- $\Delta t_{E,i}$ - the time it takes for agent i to transition to the evacuating state from the point in time that agent i first enters the investigating state.
- $k_{P,i}$ - the relative value of the prior knowledge cue as compared to a single alarm
- $N_{0,i}$ - the number of agents in the normal state that keeps agent i from responding to a single alarm.

Each agent i has a risk perception level $R_i(t)$, with initial condition $R_i(0) = 1$. When agent i experiences the first cue, then an ODE solver is used and the derivative or change in risk perception is calculated, if $R_i(t) < R_I$ with

$$\dot{R}_i(t) = \frac{\ln R_I}{t_{I,i}} \left({}_{j} \; Q_j(t) + K_{P,i}(\mathbf{Q}(t), \mathbf{N}_i(t), R_i(t)) + S_i(\mathbf{N}_i(t)) \right) R_i(t) \tag{26}$$

and if $\dot{R}_i(t) < 0$ while $R_i(t) = 1$ then $\dot{R}_i(t) = 0$. If $R_I \leq R_i(t) < R_E = C_E R_I$ then

$$\dot{R}_i(t) = \frac{\ln C_E}{\Delta t_{E,i}} \left({}_{j} \; Q_j(t) + K_{P,i}(\mathbf{Q}(t), \mathbf{N}_i(t), R_i(t)) + S_i(\mathbf{N}_i(t)) \right) R_i(t) \tag{27}$$

For both Eqs (26) and (27)

$$Q_j(t) = \begin{cases} q_j & \text{If } j^{\text{th}} \text{ cue is active} \\ 0 & \text{else} \end{cases} \tag{28}$$

$$K_{P,i}(\mathbf{Q}(t), \mathbf{N}_i(t), R_i(t)) = \begin{cases} 0 & \mathbf{Q}(t) = 0, R_i(t) = 1 \text{ and } N_{N,i}(t) = N_i(t) \\ k_{P,i} & \text{else} \end{cases} \tag{29}$$

$$S_i(\mathbf{N}_i(t)) = \begin{cases} 2\frac{N_{E,i}(t)+N_{I,i}(t)-N_{N,i}(t)}{N_{E,i}(t)+N_{I,i}(t)+N_{N,i}(t)+N_{0,i}} & R_i(t) < R_I \\ 2\frac{N_{E,i}(t)-N_{N,i}(t)}{N_{E,i}(t)+N_{I,i}(t)+N_{N,i}(t)+N_{0,i}} & R_i(t) \geq R_I \end{cases} \tag{30}$$

Once $R_i(t) \geq R_E$, agent i has made the decision to evacuate and the normal evacuation behavior of the egress model using EDM takes over.

0.4 Conclusions

This paper describes the development of the Evacuation Decision Model (EDM). The model builds on a few simple assumptions from Kuligowski's qualitative model of pre-evacuation behavior [1]. The number of parameters is kept small. The cue vector $\mathbf{Q}(t)$ is the size of the number of external cues the modeler wishes to include. The number of visible agents in each mode, $\mathbf{N}_i(t)$, is also passed to EDM from the egress model. There are 5 parameters by which each agent, in this agent-based implementation, is described. Only four, $t_{I,i}$, $\Delta t_{E,i}$, $k_{P,i}$, and $N_{0,i}$, are user inputs as described above. The final parameter is the calculated value, $R_i(t)$, the level of risk perception. The structure and rationale of the model should make it usable as a framework to include the impact of other actions and information that affects an agent's behavior during the pre-evacuation period.

Given EDM, the key question is where do modeler supplied values come from, for example the q_j's in the cue functions, as well as what guidance can be given to users for the user supplied values. Currently, there is not a lot of guidance to give. However, the availability of a model makes it possible to address these problems in a systematic way as a parameter estimation problem. Given some data on pre-evacuation behavior it should be possible to use EDM to estimate the values of the parameters that give the best results. While it is not a simple problem it should be tractable. Especially since EDM is a model of individual behavior a single set of pre-evacuation data could be split into several sub groups. Some of the groups could be used to estimate parameters and others as test groups.

EDM is just one step in the process of improving occupant safety in buildings. To continue to develop and test it, the model needs to be incorporated into at least one evacuation model. Pre-evacuation data needs to be collected and the model tested against that data. It is a long process but one where real progress is being made. Hopefully, EDM will be a useful part of that progress.

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