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Guidance for the Model Developer on Representing Human Behavior in Egress Models

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Abstract. Structures are currently designed and typically constructed in accordance with prescriptive and performance-based methodologies to ensure a certain level of safety. The performance-based approach requires the quantification of both available safe egress time (ASET) and required safe egress time (RSET) to determine the degree of safety provided. This article focuses on the RSET side of the equation, for which an engineer would use some type of egress modelling approach to estimate evacuation performance. Often, simple engineering equations are applied to estimate the RSET value; however, over time, more sophisticated computational tools have appeared. Irrespective of the approach adopted, appropriate and accurate representation of human behavior in fire within these approaches is limited, mainly due to the lack of a comprehensive conceptual model of evacuee decision-making and behavior during fire emergencies. This article initially presents a set of behavioral statements that represent the primary elements of current understanding regarding evacuee behavior. Once presented, guidance is provided on how these behavioral statements might be incorporated by the model developer into an egress model. The intent here is to assist in the advancement of current egress models by outlining the model structures required to represent the current understanding of egress behavior.

Keywords: Egress models, Evacuee behavior, Model development human behavior in fire

1. Background

For a building to be constructed and occupied, it must first be established that it provides a sufficient level of safety during a fire incident. Structures are typically designed and constructed in accordance with two regulatory approaches to ensure

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this level of safety[1]: prescriptive and performance-based design (PBD) or some hybrid of them. Prescriptive approaches rely on the application of a predetermined set of rules that, if employed, limit the risk of the design to an acceptable level [1]. Performance-based designs rely on a quantitative assessment of the fire and evacuation performance levels achieved. This approach requires the quantification of both the time before conditions become untenable at specific locations and the time for the population to get to a place of safety. These are then compared to establish whether there is time (potentially including a given margin of safety) for the population to reach safety before untenable conditions are experienced. In recent years, PBD has become more popular given that it can be applied to more unorthodox and complex structures. This evidence-based approach requires egress models (physical, engineering, computational or otherwise) to quantify performance for both the evolving incident and the evacuating population, enabling comparison to be made.[2] This article discusses what needs to be included within computational egress models to represent our current understanding of egress performance and therefore contribute to accuracy and reliability of the PBD process.

Computer egress models have been diverse in their development but not comprehensive in their nature. In reality, any egress model is a simplification that involves a representation of current theory, data, and the knowledge and judgment that a developer or user brings. However, egress models have tended to over-simplify some areas (e.g. evacuee decision-making) while focusing on others (e.g. the representation of physical movement).

Often simple engineering models are applied. These models do not explicitly represent many of the expected evacuee behaviors or the factors that influence them, making crude assumptions regarding performance. In inexpert hands, these crude assumptions may potentially lead to an *underestimation* of the time for a population to reach safety, possibly reducing design safety levels as decisions are simplified and delays potentially ignored. Over time, more sophisticated computational tools have appeared (e.g. PathFinder, FDS_Evac, EXODUS [2]). These tools can represent the evacuating population as individual agents and often represent the nature of the space, individual attributes and the loss of routes due to the incident in a more refined manner than the engineering equations [2]. These have the *potential* for representing factors that influence agent behavior and the agent decision-making process [3]. However, although current egress models now typically include *some* representation of the physical and behavioral aspects of evacuee performance, the representation of the physical aspects is still typically more complete due to the more mature understanding of the processes involved and the availability of more supporting data, in addition to the occasionally held view that evacuee decision-making is less amenable to simulation than physical performance [3].

A comprehensive conceptual model of evacuee behavior needs to be embedded for a computational tool to more credibly represent egress behavior. A comprehensive conceptual model does not currently exist, although recent advances have been made

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[1] Other approaches are employed, such as the objective-based approach adopted in Canada, although this approach is less frequently employed.

[2] Egress model is taken to mean any method by which egress performance is understood and/or quantified.

[4]. In the meantime, what does exist is a set of micro-sociological theories or behavioral statements[3] that describe specific aspects of evacuee response during fires. These statements occasionally find their way into the design and application of evacuation models, although are by no means universally appreciated or adopted [2–4].

It is important that evacuation models represent the most current (and complete) understanding of the subject matter to reduce the number of factors excluded from the performance estimate and hopefully improve the consistency, credibility and accuracy of the results produced. Of course, it is not always possible to quantify all of the current theoretical understanding given the limited data available. However, this is insufficient reason for the decision-making process to be excluded from a model, where it can be established [5].

The purpose of this article is to briefly present our current understanding of human behavior in fire and suggest a means of incorporating this understanding within computational egress models. This article first presents a set of key behavioral statements used in the field of fire protection engineering. This article will then identify what is required of the *model developer* such that these statements can be represented within a computational model. For a fuller account of these statements and guidance on how engineers/users might enhance existing evacuation models (including computational and engineering models), please refer to a companion article [5].

This paper focuses on the following questions:

(1) What is the nature of the modelling process and the model-user's/developer's relationship to it?
(2) What is the current understanding of evacuee performance within the field?
(3) What structures would need to be present within a conceptual model for it to comprehensively represent evacuee performance?
(4) Which of these structures would be required for each behavioral statement to be represented by a conceptual model?
(5) How can these structures be constructed such they that can be implemented within an agent-based computational egress model?

2. Modelling and Simulation Process

The performance-based approach requires the quantification of both egress performance and environmental deterioration (although currently not necessarily within the same modelling environment [6]). The quantification of egress performance can be achieved by applying one of several different models based on expert opinion, egress trials, engineering calculation, and/or the application of computational models. We will focus here on the latter method: computational egress models. In each case, the approach will rely on the underlying *conceptual model* of evacuee behavior, either embedded within the computational egress model by the model developer, defined by the model user, or some combination of the two. The nature of this conceptual model may not always be obvious (e.g. in prescriptive codes,

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[3] Previously referred to as behavioral facts [3].

evacuation drills, etc.), but it will be there and will likely require additional configuration to apply the model to a particular scenario of interest. This configuration requires expertise and is a difficult task. However, this is less difficult than having to generate entirely new theoretical assumptions to account for omissions in the model being employed—effectively having to produce a new model entirely. This section discusses how the limitations in current understanding propagate through the modelling process and influence the results finally produced.

This section describes where the user and the conceptual model sit within the modelling process, and their relationship to each other. This relationship has implications on the nature of the results produced and the insight that they provide. This further demonstrates the importance of the conceptual model and the importance of understanding the assumptions on which it is based before using the results produced.

2.1. Conceptual Model Development

Figure 1 presents a simplified description of the modelling process (based on the work of Sokolowski and Petty [7]). It is instructive to briefly discuss the modelling

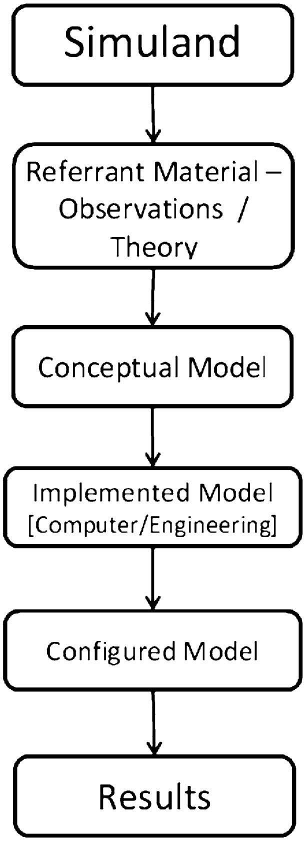

Figure 1. Modelling and simulation processes [7].

process as it affects how conceptual models are generated; affects the relationship between the implemented model, the user and the model developer; and helps demonstrate the importance of a theoretical understanding throughout.

The modelling process is assumed to initially require the identification of real-world entities that are of interest: the simuland. Information is available that describes the simuland; i.e. referrant material—the information that is actually available to describe the real-world. Referrant material is typically formed from empirical observations of the simuland, scientific theories (tested propositions used to explain or predict events or phenomena) and/or isolated behavioral statements [8]. These micro-sociological theories are often based on interpretation and typically do not have the status of repeatedly tested scientific theories, but are instead broadly accepted conventions that are assumed to provide some insight into the simuland (and often influencing engineering judgment). The acceptance (and representation within the modelling process) of these behavioral statements contributes to a more representative estimate of the simuland than would otherwise be the case. Field observations require the data collector to have a sufficient theoretical understanding to identify the need for the observations to be made, collect the observations using appropriate methods and interpret the results produced. Theory development requires the researcher to have a fundamental understanding of the subject matter in order to provide new explanations of the phenomena examined.

A conceptual model is compiled from a sub-set of the available observations, theory and (potentially) behavioral statements. The developer of the conceptual model is effectively compiling existing understanding and is therefore reliant upon the theoretical explanations of the subject matter available, and credible material that supports it, and the manner in which elements of it might interact.

The conceptual model is implemented within a modelling environment that then allows its application to scenarios of interest.[4] As part of this process, the model developer will test the model being produced; i.e., verify and validate the implemented model to assess its capability for reproducing/forecasting the actual real-world process to the required level of accuracy. In order to do this, the developer will first compare the implemented and conceptual models to verify that the implemented model performs in accordance with the original concepts, and then compare the simulated results with relevant referrant material to establish that the results produced by the implemented model match expected real-world conditions to a sufficient degree of accuracy.[5] The model developer will need to have a sufficient understanding of the conceptual model to implement it accurately and reflect how this behavioral sub-model might interact with existing sub-models such that valid output can be produced.

Once the conceptual model has been implemented (and selected for use) [9], the model user will develop scenarios of interest to investigate as part of the PBD process. In order to do this, credible scenario conditions need to be identified and

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[4] This article does not address the interaction between the embedded and existing sub-models within the computational environment, or the range of verification and validation tasks that would be required to examine these interactions.

[5] The developer may also validate the conceptual model against the referrant material to ensure the accuracy of the assumptions made.

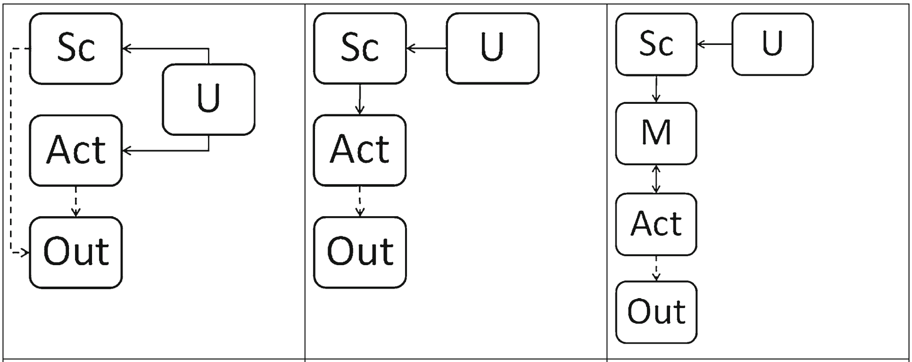
clustered to form scenarios. This is not trivial; indeed, the identification of appropriate egress scenarios is key in producing representative results. These scenarios then need to be translated into the computational tool being employed. The model needs to be configured such that the scenario is represented and results generated for examination. This requires the translation of behavioral assumptions from the real world (from examining referrant material) into modelling practice either through importing data-sets directly into the model or setting behavioral switches to represent behavioral responses. In this case, the model user will need to be able to interpret referrant material and understand the conceptual model being used within the computational tool sufficiently well to understand the impact of configuring the model; i.e. configuring the implemented conceptual model for the specific application at hand [10].

It is apparent that evacuation model developers and model users will require a detailed understanding of the referrant material when using the respective components of the evacuation model. It is contended that this understanding would be assisted by the presence of a comprehensive conceptual model—a model that would help structure this understanding and provide a representation of real-world conditions within the computational tool, and also the theories and observations that relate to the simuland. The absence of this conceptual model influences model design, model use and the interpretation of the simulated results.

2.2. Conceptual Model Configuration

Currently, there are over 60 different computational egress models that assess evacuation performance, albeit in a simplified manner [2, 11]. Computational models quantify egress performance by calculating how long it takes for occupants to evacuate a building, typically assuming that evacuees move from an initial position directly to a place of safety [3]. In order to make this calculation, the models represent two things: (1) the actions that people take and (2) the time taken to perform each action. In reality, occupants are likely to engage in a variety of activities (including those that do not move them towards a place of safety) such that their arrival at a place of safety can be significantly delayed and the routes taken are more complex than expected. It is suggested here that this tendency for models to simplify these routes is partly due to the absence of a comprehensive conceptual model.

Currently, without a comprehensive conceptual model, evacuation models are limited in how the evacuation is represented, often requiring users to provide a large amount of input data regarding evacuee behaviors to compensate for model omissions. As already highlighted, there are significant consequences from the lack of a conceptual model of evacuee behavior for users, evacuation model developers, and those who judge evacuation analysis (i.e. the authority having jurisdiction). As shown in Figure 2, models require the user to identify the scenario being faced by the evacuating population (with guidance provided by regulatory documentation) [12, 13]. However, current models often also require the user to determine the expected behavioral response of the population to some/all of the scenario conditions faced (with far less documentation available) [14]. In some



I1: No implemented model. User drives performance.

I2: Simplified implemented model (Cue -> Action). User sets scenario.

I3: Implemented model (Process represented). User sets scenario.

Figure 2. Model representation. *Sc* scenario, *Act* evacuee actions, *Out* outcome, *U* user, *M* modelled process.

instances, the user provides data to compensate for the absence of a conceptual model, in addition to data provided to configure the model for the scenario being examined. In some instances, the user dictating agent response may be desirable; for example, when a user wants to look at a specific aspect of performance and control for everything else. Where it becomes problematic, is (1) where the user assumes that dictated agent behaviors (e.g. the use of an exit), are actually a model prediction; (2) where the behavioral response is significantly reduced in scope given the user assumptions during model configuration; and, of course, (3) where the user is not qualified to determine the factors to be represented or the data to be provided. The potential relationships between the model and the user, and their implications, are now discussed in more detail [15].

In Approach I1, the conceptual model assumed is based entirely on user input; i.e. the configuration of the model requires the user to completely determine the scenario conditions and then the evacuee response (see Figure 2). This approach is focused upon pre-set behavioral responses, where the evacuee response is dictated by the conceptual model directly implemented by the user. In this approach, no behavior is simulated without user specification; the response is effectively hardwired. *Behavioral actions are an input rather than an output*. The limits of the model user and the prescribed nature of the scenarios examined may have several consequences: (1) given the control that the user has over the individual and aggregate levels of the simulation (what the agent does and what conditions emerge), the temptation to manage the scenario in order to reduce the overall evacuation time might be greater; (2) given that the conditions are dependent on user actions, the simulated conditions may not capture all of the evacuation dynamics that might reasonably be expected; and (3) the results produced are unlikely to suggest further analysis (e.g. additional scenarios) given that the conditions were largely prescribed by the user subsequently producing fewer unexpected insights. These three consequences may reduce the scope of the conditions examined and the detail in which they are represented.

In Approach I2, the conceptual model implemented within the egress tool *generates* the evacuee response directly given the conditions faced within the simulated environment. This approach approximates the outcome of evacuee performance without attempting to represent the process through which an individual passes to select a behavioral response. Behaviors are represented on a deterministic, stimulus–response basis (e.g. CUE → ACTION), rather than reflecting the complex cognitive, social and adaptive processes involved. For instance, smoke spread is defined and then rules specifying evacuee response enacted should they encounter the smoke specified [16]. This approach is incapable of representing the interaction between external factors and factors internal to the agents, cannot differentiate between the impact of external factors and internal factors upon action selection, and has no representation of the experiences of an evacuating population in terms of their situational awareness and the impact of situational awareness on performance. This approach will require the user to configure the scenario conditions to which the evacuees are exposed and may also require them to augment the conceptual model (by manipulating the implemented model) should a more credible representation of the decision-making process be required.

In Approach I3, an attempt is made to represent the evacuee decision-making process. Here, the user configures the computational tool to represent the scenario conditions; the implemented model of evacuee behavior is sensitive to these conditions, internalizing those that influence the decision-making process (potentially in conjunction with existing internal information) and eventually the action selected. This approach would be able to reflect the interaction between external and internal conditions, to establish evacuee response as the result of a decision-making process (sensitive to existing and new information) and represent emergent conditions produced as a result of interactions between evacuees and their environment.[6]

There is a more subtle limitation to the first approach (I1). Given that the model user is typically required to define the scenario *and* (some aspects of) the behavioral response to the scenario in Approach I1, it implies that the results produced only reflect the manner in which imposed behaviors/factors interact and the conditions sequently produced rather than predicting the behavioral actions that might be conducted given the scenario faced (compare I1 with I2 and I3 in Figure 2)—an entire level of output is lost to the user. The former approach requires an additional layer of assumptions and precludes an understanding of both the behaviors that might be expected and the complex dynamics that might ensue from these choices. *Approach I1 is not able to estimate agent actions. Approach I2 is able to estimate agent actions and the conditions that emerge from agent/environment interactions; Approach I3 has the potential for making this estimation more credible*. It is not suggested that Approaches I1-3 do not have their uses; only that it is important to understand the assumptions and limitations suggested by each of the approaches. The user might also require different depths of subject matter

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[6] The gap between current model development and expected behavior is most significant in locations where there is greatest dependency on the individual decision-making process; e.g. residential occupancies, as opposed to office occupancies where a formal evacuation procedure will exist and likely inform evacuation performance [17].

understanding to employ approaches I1–I3, although the same detailed knowledge would be beneficial in each case—both in understanding the assumptions made during the modelling process and in interpreting the meaning and implications of the results produced.

Where included, current egress models represent the behavioral process in a partial or pre-determined manner [2, 3, 11]; i.e. a combination of Approaches I1–I3. This simplifies the representation of the evacuee response, while conflating the impact of the user and the implemented model. Depending on the balance of the approaches adopted, critical phenomena may be missed (e.g. the potential for evacuees misunderstanding information), conditions may be inaccurate (e.g. congestion produced given inappropriate evacuee actions), and performance may be quantified inaccurately given the exclusion and oversimplification of key factors (e.g. the time of arrival at a place of safety is too short). In addition, there may be confusion between generated (emergent) results and user-imposed settings.

The implementation of a comprehensive model that more accurately represents the decision-making process and represents agent response would, ideally, address a broader array of initial conditions and allow for a more comprehensive set of responses to be represented. These are desirable objectives; however, the scale of the task for such an implementation is certainly not underestimated.

2.3. Implications of Conceptual Model Limitations

The absence of a comprehensive conceptual model influences both model developers and model users. It influences current understanding of egress behavior and the means of developing and exploring scenarios of interest. Most potential users are not familiar with (and all most models are simplifications of) the full range of the field's current understanding. As already mentioned, this influences the simulated results produced (in form and content) and the reliability of egress analysis performed as part of the PBD process. The impact of this is that these simplified models can be used by potential users as the cornerstone of a PBD where authorities having jurisdiction lack the resources to properly evaluate the model.

The lack of a comprehensive behavioral theory has hampered the development of an overarching conceptual model. No extant conceptual model is sufficiently comprehensive to reflect even our current (albeit immature) understanding of egress behavior and then go on to form the basis for an implemented behavioral model within a computational tool. This limitation is reflected in the behavioral models embedded within computational egress tools. In the next sections, a selection of existing conceptual models are presented, followed by the current understanding of evacuee performance (in the form of behavioral statements), in lieu of a comprehensive theory.

3. Representing Conceptual Understanding

This section includes a brief discussion of the conceptual models currently available and those that have been implemented (embedded) within current egress models. It goes on to discuss in more detail the behavioral statements recognized within the study of human behavior in fire (HBiF) and occasionally used within engineering practice. This is in order both to explore the nature and scope of the conceptual models currently available and the limited manner in which they have been implemented within current egress models.

3.1. Current Conceptual Models

A conceptual model is a composite of existing theories and data that has been drawn together to represent some portion of evacuee performance given the intended application. This reflects the impact of the assumptions and decisions made by the model developer regarding evacuee performance. In this instance, a conceptual model is taken to represent the key decision-making process that influences evacuee response during an evacuation given the situation faced and the information available [3]. The conceptual model represents the theoretical and empirical basis for the model development shown in Figure 2; i.e. the implemented model 'M' that forms part of Approach I3. Kuligowski [4] has identified a number of theoretical developments related to the area of evacuee behavior (for instance, [18–39]). A selection of representative examples is briefly discussed below.

The conceptual models briefly described below either originate from within HBiF or an adjacent field of study (e.g. crowd dynamics). These models are grouped into two categories: those derived independently from model implementation and those developed especially for model implementation.

There are a number of conceptual models presented in the research literature [3, 4, 8, 18]. These models tend to focus on the overall process (e.g. Canter [19]), providing limited detail regarding the application of the decision-making process in any circumstance; an aspect of the decision-making process (e.g. Whithey [40]); or refer to a specific situation (e.g. Kuligowski [4]). Therefore, they would need to be coupled with other data and theories to support the development of a more comprehensive conceptual model for implementation within a computational model.

Research into disasters, based on theories from the social sciences, has led to the development of conceptual models describing the decision-making process for public warning response, where people go through several phases (e.g. hearing, understanding, believing, and personalizing the warning) [41–43]. Additionally, researchers of evacuation from fire [20, 22, 44–46] have examined different aspects of the decision-making process. In these conceptual models, there are specific cue- and occupant-related factors that influence the outcome of each phase of the process. Breaux et al. identified three stages as part of their model of individual decision-making: recognition/interpretation, behavior, and the outcome of the action. Inputs to this process might include past experiences, situational factors, and the individual's current status, which all impact the recognition/interpretation process [46]. Building on this understanding, Canter et al. produced a theoretically-based model to represent the major sequences of actions people commonly perform/experience during an evacuation (see Figure 3) [19, 47]. As such, this represents a relatively broad description of the evacuee decision-making process. The model is based on a person receiving information, interpreting the information, preparing to act on the information and then actually performing the action. This is an example of a model that represents the key stages in the decision-making process.

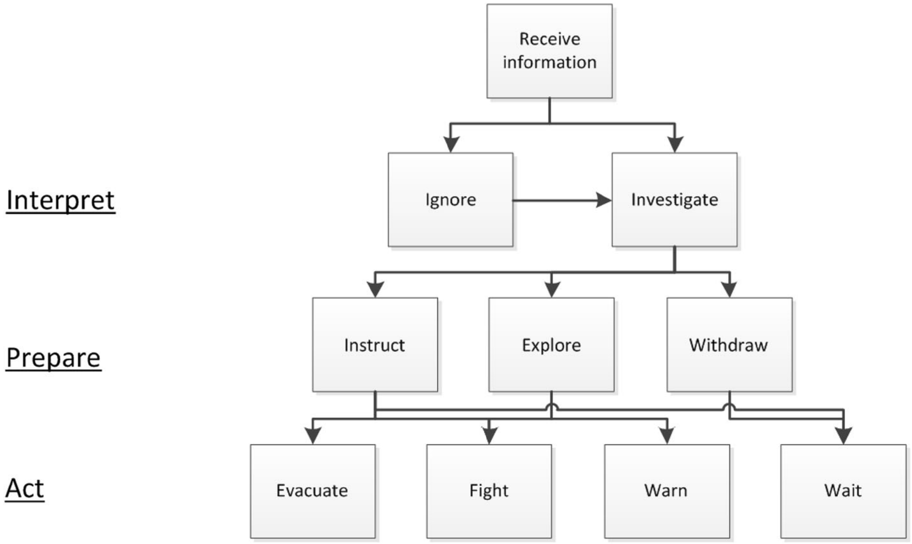

Figure 3. General model of human behavior in fire by Canter et al. [19, 22, 46, 47].

Although this is an important advance in understanding evacuee decision-making, this model would not be sufficient for implementation given the lack of detail regarding the impact of the information received on specific elements and the subsequent influence on action phases.

In contrast, Proulx developed a stress model to represent stress generation in the individual decision-making process during a fire incident [18]. In this model, the individual moves through several phases as the degree of stress increases from control to ambiguity, to fear, to worry and eventually to confusion [21]. This is an example of a model that represents the evolution of an attribute that influences the decision-making process, rather than a model of the overall process itself; i.e. it might be coupled with the earlier Canter model to provide an index by which the evacuee progresses through the various phases of the model. By coupling several of these models together, a representation of the behavioral process and the influential factors might be developed into a broader-based conceptual model. This might then be implemented within an egress model to estimate expected evacuee behavior.

A relatively limited number of computational egress models document the conceptual model that has been implemented [2]. More commonly, model developers identify each development made (and the associated functionality associated with it) and discuss them in a piece-meal manner, rather than discuss the full model implemented and the general assumptions made.[7] This may well be as much due

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[7] These conceptual models have therefore been configured such that they can be implemented within a larger model structure. This may or may not have been the case with the conceptual models described earlier [66].

to the nature of model development and article generation, as to a philosophical decision by the development teams.

Where egress models clearly acknowledge the implemented model they are typically based on a functional analogy. These models typically focus on the representation of evacuee movement rather than the evacuee decision-making process [2]. In effect, the decision-making process is represented ‘implicitly’ through the determination of the evacuee movement. Teknomo proposed the data-based Microscopic Pedestrian Simulation Model (MPSM) which is a physical force-based model similar to the social forces model [48]. In the model, the movement of agents is governed by other agents around them, the geometry and force-based algorithms to determine momentum and direction towards a specific target.

Some models [2] represent a simplified form of the decision-making process, either by fully adopting a simple existing conceptual model, or by reducing the complexity of a conceptual model and implementing it in a simplified form. Fridman proposed a theoretically-based crowd modelling algorithm whose development was inspired by Festinger’s social comparison theory (SCT). The agents within this model base their decisions on the desire to be in and act as a group through comparison of their actions/attributes with those around them adjusting them accordingly [49]. Therefore, the behavioral driver is convergence to the social environment rather than an assessment of the perceived influence of the social, physical, procedural and environmental conditions.

Less common are models that include (and document) more comprehensive representations of the decision-making process. The majority of these can be found in research dissertations—where the developer has had time (and sufficient control over the development) to produce a single, coherent decision-making model—and is typically found in crowd dynamics, rather than egress modelling. Pan developed a conceptual model [50] where an individual perceives a variety of cues and assigns them a level of importance during the perception process. This perception then leads to a decision on the response being taken. Similarly, Wijermans developed the theoretically-based CROSS conceptual model [51] of how people behave in crowds based on the influence of the agent’s physiology and the presence of leaders within a crowd. The model is formed of external influences (e.g. existence of a leader or predefined crowd conditions), internal influences recalled from memory, and possible physiological influences, that enable the agent to select a response.

The conceptual models presented above show the range of approaches adopted to reflect aspects of the decision-making process. However, none of these approaches alone are sufficient to form a comprehensive decision-making model for use within a computational egress model. In the next section, our current understanding of evacuee performance is discussed and distilled into a set of statements. Any conceptual model would then at least need the capacity to represent these behavioral statements to reflect the current understanding of evacuee behavior.

3.2. Current Behavioral Statements

A large body of behavioral research has shown that before an evacuee performs an action, they will have perceived certain cues, interpreted the situation, established the risk to them based on those cues combined with prior knowledge and experience, and then made a decision as to what to do (i.e., select an action) based on these interpretations (as previously noted by Sime et al. [18, 19, 44]). In the absence of a comprehensive theory, computational egress models are presented with piece-meal behavioral statements to use to represent evacuee behaviors [44]. These statements represent distinct behavioral influences upon actions during an evacuation. When/if these statements are embedded within computational egress models, the scenario representation and the results generated would still contain significant gaps in the simulated evacuee response, but would at least be more representative of current understanding.

Though a number of conceptual models have been developed (see preceding section), it is contended that none of these would be able to fully represent the set of behavioral statements presented below, certainly not without model modification.

These are typically derived from incidents, (repeated) observations, or aspects of existing theories in adjacent fields that have been co-opted into evacuation analysis [3, 8]. In essence, these statements have each appeared several times in the literature in some form—either as a finding from research or as an assumption in modelling analysis or some combination of the two. This list is by no means exhaustive, but represents the key behavioral conventions that are identified, understood, and employed within model development and engineering practice to some degree of frequency.

The statements are crudely grouped to simplify their presentation (see Figure 4). The groups are:

- [Phase 1] Factors that influence or represent aspects of cue processing
- [Phase 2] Factors that influence the assessment of the situation and/or the risk
- [Phase 3] Factors that influence the selection of a response
- [Phase 4] Factors that influence or represent aspects of taking protective action
- [Phase 5] Factors that influence or represent aspects of the overall process.

This should assist in placing these statements into context. For further information on these statements, refer to the companion article [5] and the following set of representative sources from which the statements were derived [39, 41, 52–69]. These statements are listed below:

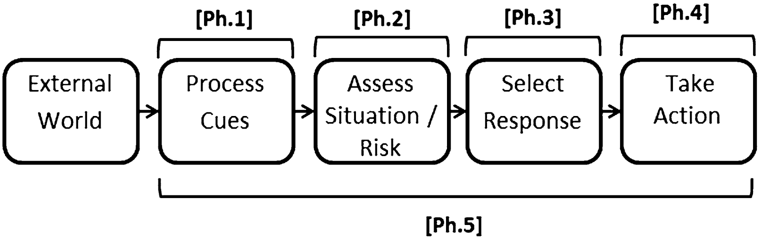

Figure 4. Grouping of behavioral statements.

3.2.1. [Phase 1] Perceiving or Receiving Cues and Information

(1) Content of the cue matters. The precision, credibility, clarity, intelligibility, comprehensiveness, intensity and specificity of the external cues will affect the assessment of the information in the individual's decision-making process.
(2) Authority of the information source affects the perceived credibility of the information and in turn the assessment of the situation and risk.
(3) The actions of the surrounding population can influence the internal processes and the actions of the individual; e.g. the use of routes/space by others increases their attractiveness.
(4) Some individuals exhibit hypervigilance that makes them particularly sensitive to certain cues.
(5) Previous experience of false alarms or frequent drills can reduce sensitivity to an alarm signal.
(6) Habituation (where a process has become routine in nature), focus and stress can narrow the perceptual field and, therefore, not all available cues will be internalized.
(7) Sensory and cognitive impairments can inhibit the perception of cues.

3.2.2. [Phase 2] Assessing the Situation and Perceiving Some Level of Risk

(8) Normalcy bias and optimism bias are commonplace. People often think that nothing serious is taking place and that nothing bad will happen to them, respectively.
(9) Training may allow the incident to be defined more quickly by the evacuee and provide hard-wired responses.

3.2.3. [Phase 3] Selecting a Response or Action

(10) People tend to satisfice rather than optimize. People are more likely to choose an option that is perceived as "good enough" rather than the best option.
(11) Presence of smoke does not always preclude the use of a route.
(12) Training and experience may increase an individual's familiarity with the use of components/devices and subsequently improve their use.
(13) Pre-event commitment to a particular activity may cause individuals to decide against taking protective action.

3.2.4. [Phase 4] Influencing Action Selection

(14) People have different abilities that influence action selection.
(15) People seek information in situations where information is lacking or incomplete.

(16) People engage in protective actions, including preparing to move to safety or helping to protect others from harm, before they move towards safety themselves.
(17) People move towards the familiar, such as other people, places, routes and things.
(18) People may re-enter a structure, especially if there is an emotional attachment to the structure, the contents and/or the inhabitants.

3.2.5. [Phase 5] Influencing the overall decision-making process

(19) People behave in a rational AND altruistic manner; panic is rare.
(20) Uncertainty, time pressure and volume of information can increase stress levels.
(21) Pre-incident experience influences how cues are processed, how the situation is defined and how protective actions are selected.
(22) Evacuation is a social process, in that groups are likely to form and/or maintain during an evacuation.
(23) Social rules and roles in place prior to a fire event form the basis of those employed during the event. A person's role before the incident, given their current location and situation, will influence their performance during the event.
(24) New norms may emerge where the existing normative structure is incapable of addressing the new fire situation.

These statements influence evacuee performance and the indicators of this performance. For instance, they may influence an evacuee's assessment of the risk posed by an incident, which leads them to continue performing their current activity. The implication of this would, in engineering terms, be that the evacuee's pre-evacuation time increased, extending the time before which the evacuee initiated movement to a place of safety. Although some of these statements may seem prosaic, they each have an impact (either direct or indirect) upon the terms used in engineering analysis: pre-evacuation times, travel times and route use. This impact is addressed in more detail elsewhere [5].

4. Development of Conceptual Model Structures

A computational egress model represents a sub-set of the agents and objects within the evacuation, and the outcome of their interaction with each other and the environment. The current state of available computational tools does not readily allow the representation of the full-set of behavioral statements described previously. There is enormous variation in the exact methods employed to do this in the models currently available and also in the factors and processes represented within these models [2, 11]. The lack of a comprehensive conceptual model (i.e. an implementation blueprint) certainly inhibits this representation. In this section, a computational egress model is assumed to have an agent-based structure—primarily because this is relatively commonplace in the field [2, 3, 11] and, potentially, allows the primary actor of interest (the evacuee) to be represented as an active agent subject to local conditions, should the developer choose to do so. The authors have derived a set of crude structures to represent the behavioral statements identified in Sect. 3.2 within a computational egress tool. The structures are also able (deliberately so) to reflect many of the elements of the major theories currently discussed in the field in an attempt to 'future-proof' the design—to allow new statements/theories to be represented as and when it is possible to do so [3, 4]. The purpose of each structure is described along with the way in which it might function within an implementation. The approach described here is but one approach that might be adopted, but it is contended that equivalent functionality would need to be represented within any comparable design of a conceptual model addressing the same subject matter.

4.1. Implementing a Conceptual Behavioral Model

A simplified behavioral model suitable for implementation within an agent-based computational egress model is now presented. This outlines the types of structures required and their relationship with each other. In reality, the method adopted to implement this behavioral model within an agent-based model will be sensitive to the host computational model and the preferences of the model developer.

This model is based on the work originally performed by Gwynne and Kuligowski [3]. The original conceptual model was produced to reflect (and expand upon) the theoretical developments made by Kuligowski regarding the WTC incident [4] and the more limited set of behavioral statements presented at the time [3]. Kuligowski's approach employs a number of sociological theories (including symbolic interactionism, social constructionism and emergent norm theory) that are deployed within a framework derived from the Protective Action Decision Model [4, 70]. Kuligowski's conceptual model is described in more detail in a companion article [5]. As part of the work presented here, this model has been updated from its original form to account for the additional behavioral statements presented and restructured to assist in the implementation process. A suggestion is also made as below as to the manner in which these structures may interact. In reality, this interaction would be complex and iterative in nature. It has been represented here as a broadly linear process to simplify the subsequent discussion. For a more detailed discussion of the model, refer to [3].

A simple example of this model is shown in Figure 5. In this model, it is assumed that the agent is exposed to cues from the external world ($ExtW$) that are either physical (C_p) or social (C_s) in nature. Given that the cues exist, they are then filtered—a process wherein cues may be perceived, attended to, understood, and deemed credible by the agent. At each step, the original set of cues ($C_s + C_p$) is reduced (from C_{perc} to C_{att} to C_{comp} to C_{cred}), such that the information that might eventually be internalized by the agent is a sub-set of that which was originally available to them. A new situational picture (i.e. understanding of the scenario faced) is formed based on the cumulative experiences amassed from similar prior events (i.e. external cues experienced in previous situations) and from the

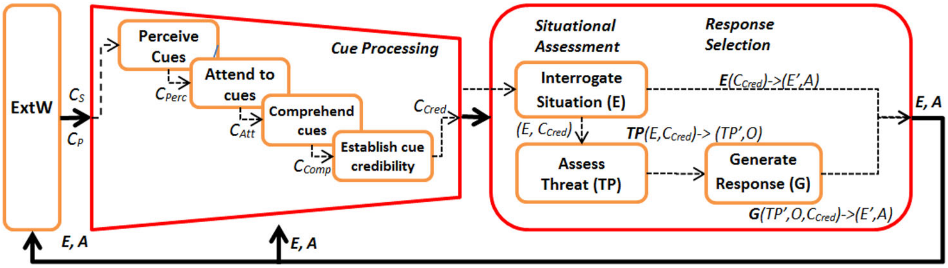

Figure 5. Simplified model for implementation [3].

external cues to which they are currently exposed (in this case the latter is represented by C_{cred}). This situational picture represents the agent's understanding of the current situation derived from the accumulation and interpretation of external cues over a period of time. This situational picture is used to interrogate an internal event map (E). The event map is a repository of experienced events (as defined by the cumulative set of experienced conditions that form situational pictures) and associated roles, threat levels, objectives and behaviors. The current situational picture is then used to select a similar event from the event map to quickly establish the normative and social environment given the information available; i.e., what the appropriate roles, social relationships, norms, and outcomes might be given the current situation faced. Put simply, the agent has an understanding of the situation and what they should do in response to it. The event map is updated as new information becomes available; i.e. the current situational picture is added producing an updated event map, E′.

For the event map to function, it requires some basic internal structures. The event map requires a spatial map (an understanding of the space around the agent allowing experienced conditions to be located and routes to be understood and recalled); a normative map (an understanding of the roles, objectives and actions associated with different situations that might be recalled); a social map (an understanding of social relationships and their role in them); role (the current role(s) being adopted allowing their position in the social network of relationships to be established); an objective (a set of short-term and long-term objectives allowing goal-based decisions to be taken and progress to be established); an action (current action being performed); a set of attributes (the agent's current status formed from static attributes—demographics, innate capabilities, etc.—and dynamic attributes set/updated as a result of the current situation—e.g. posture, psychological disposition, etc.); and threat perception (assessed risk to the well-being of agent and/or other agents/objects, should there be no change in the situation). Where the current event has an equivalent 'mirrored' event stored in the event map, then the agent can quickly update their attributes (eventually stored in later iterations of the event map) from prior experience; i.e. they recall experienced situations to determine if one is similar to the current situation faced, and then, assuming a match is identified, adopt the associated roles/actions assuming that these previously provided a relatively successful outcome.

If a match can be found in the event map, then the relevant parameter settings in the match are adopted, providing a short cut in the decision-making process employed for routine situations or emergency situations recalled from the agent's past. If no match is found in the event map, then the analysis becomes more detailed, time-consuming and intensive. The agent then needs to establish the threat posed and viable responses given the social/normative conditions indicated. At this point, the threat of the current situation is assessed (using the threat perception function). This involves examining the situational picture and determining the threat posed (to the agent or significant others/objects) and the subsequent setting of new objectives (O) given the threat established. Once new objectives have been established, a response has to be identified using the response generator in an attempt to reach the new objective. These responses might include rational and/or irrational elements depending on situation involved, the information available and the agent's attributes. This will require the agent to identify actions that can meet the new objectives given the existing situational constraints as indicated by the threat assessment (e.g. environmental deterioration, physiological condition, etc.), their abilities to perform certain actions, and the time available to complete the action. This process will be dependent upon normative, spatial and social structures, which will both constrain and inform the viable objectives and actions open to the agent. Depending on the nature of the situation and the agent's history, these structures may be derived or formed anew. If these structures are new, this process will also require the agent to project the current situation into the future, assessing the potential effectiveness of their actions given stated objectives. This process is likely to be sub-optimal; i.e. satisficing rather than optimizing [3, 4, 68].

This process may allow new relationships to emerge between actions, objectives, normative structures and social relationships that had previously not been present in their event map [3]. The exact methods employed to generate the action options will be dependent on the threat perceived; i.e., the perceived time available constraining the depth/breadth of the option search. Once this process is complete, the agent's internal attributes are then updated accordingly (E'), an action (A) is performed given the new objective and the whole process begins again in the next time frame [64]. The agent's action may influence the external environment, and their action and current situational picture may influence the future perception of new information as it arrives (feeding back into the environment and cue processing as shown in Figure 5).

It is acknowledged that this is an abbreviation of an actual decision-making process. It is also acknowledged that these structures would need to be specified in much greater detail before implementation could take place. However, it should be remembered that the primary purpose of this description is to outline the *types* of components that would need to be represented in a computational egress model (in this case an agent-based model) to enable the implementation of a conceptual model, rather than specifying them in full. Given this, these components are now taken forward into a discussion of the components required for a conceptual model to represent the full set of behavioral statements. To further simplify the description, some of the components have been combined—primarily where

Table 1
Computational Components Required to Represent Behavioral Statements

Model components	Description
EC	External cues/conditions (C_s/C_p)—external information that may be available to the agent
CP	Cue processing ($C_{Perc}/C_{Att}/C_{Comp}/C_{Cred}$)—the manner by which the agent internalizes external information
NSG	Normative/social graph—agent's understanding of roles/rules associated with the situation and their relationships with the surrounding population of agents and objects
SM	Spatial map—agent's understanding of the space around them
E	Event map—agent's representation of the current situation
TP	Threat perception– agent's assessment of the risk posed by the situation given the event map
Att	Attributes—the innate attributes of the agent including demographic information, short-term/long-term objectives, current action (A), status, etc
RG	Response generator—process by which the agent determines a response, given the threat assessment made and the current understanding of the situation

components are associated or highly interrelated and could not be employed independently. These components are described in Table 1.

Each of the behavioral statements are now listed along with the set of components required to represent them. This then provides some insight for developers (and users) into how these statements might be accounted for in egress analysis.

5. Representing Behavioral Statements Using Agent-Based Computational Tools

The behavioral statements described in Sect. 3.2 are now represented using the eight components identified in Table 1 as being core to the computational model. This description only identifies which components would need to be *included by a developer* in order for the model to represent the statement in question. This makes no reference to the sophistication or accuracy of this representation—only its potential for inclusion.

Table 2 should provide initial guidance for the model developer on the types of components required to represent each of the behavioral statements; however, the precise requirements would somewhat depend on the specifics of the computational model design. As mentioned previously, these model components have been designed to represent more than the statements themselves; i.e. they should also be able to represent the identified underlying theories that are applied within the field. However, that is not to say that additional components would not be required as new empirical and theoretical insight becomes available.

Table 2
Aspects of Computational Model to be Included by Developer in Order to Represent Behavioral Statements

Behavioral statement	EC	CP	NSG	SM	E	TP	Att	RG
[Phase 1] Process cues/information								
[1] Content of the cue matters: The precision, credibility, clarity, intelligibility comprehensiveness, intensity and specificity of the external cues will affect the assessment of the information in the individual's decision-making process	X	X				X		
[2] Authority of the information source affects the perceived credibility of the information and, in turn, the assessment of the situation and risk	X	X				X		
[3] The actions of the surrounding population can influence the internal processes and the actions of the individual; e.g. the use of routes/space by others increases their attractiveness	X	X	X			X		
[4] Some individuals exhibit hypervigilence that makes them particularly sensitive to certain cues	X	X				X		
[5] Previous experience of false alarms/frequent drills can reduce sensitivity to an alarm signal	X	X			X	X		
[6] Habituation, focus and stress can narrow the perception field and, therefore, not all available cues will be internalized	X	X			X	X	X	
[7] Sensory and cognitive impairments can inhibit the perception of cues	X	X				X	X	
[Phase 2] Assess situation/risk								
[8] Normalcy bias and optimism bias are commonplace. People often think that nothing serious is taking place, and that nothing bad will happen to them, specifically					X	X	X	
[9] Training may allow the incident to be defined more quickly by the evacuee and provide hard-wired responses					X	X		X
[Phase 3] Select response								
[10] People tend to satisfice rather than optimize. People are more likely to choose an option that is perceived as “‘good enough” rather than the best option					X	X	X	X

Table 2
continued

Behavioral statement	EC	CP	NSG	SM	E	TP	Att	RG
[11] Presence of smoke does not always preclude the use of a route	X	X		X		X		X
[12] Training/experience may increase an individual's familiarity with the use of components/devices and subsequently improve the effectiveness of their use					X			X
[13] Pre-event commitment to a particular activity may cause individuals to decide against protective action					X	X	X	X
[Phase 4] Action								
[14] People have different abilities that influence performance	X	X	X	X	X	X	X	X
[15] People seek information in situations where information is lacking or incomplete	X	X		X	X	X	X	X
[16] People engage in protective actions, including preparing to move to safety or helping to protect others from harm before they move towards safety themselves			X		X	X	X	X
[17] People move towards the familiar, such as other people, places, routes and things			X	X	X	X	X	X
[18] People may re-enter a structure, especially if there is an emotional attachment to the structure, the contents and/or the inhabitants			X	X	X	X	X	X
[Phase 5] Overall								
[19] People behave in a rational and altruistic manner; panic is rare	X	X	X	X	X	X	X	X
[20] Uncertainty, time pressure and volume of information can increase stress levels	X	X			X	X	X	
[21] Pre-incident experiences influence how cues are processed, how the situation is defined and how protective actions are selected	X	X			X	X	X	X
[22] Evacuation is a social process, in that groups are likely to form and/or maintain during an evacuation			X				X	

Table 2 continued

Behavioral statement	EC	CP	NSG	SM	E	TP	Att	RG
[23] Social rules and roles in place prior to a fire event form the basis of those employed during the event. A person's role before the incident, given their current location and situation, will influence their performance in the incident			X		X		X	
[24] New norms may emerge where the existing normative structure is incapable of addressing the new fire situation			X		X	X	X	

6. Summary/Conclusions

Understanding and representing evacuee performance is a difficult and complicated task. This task is made all the more difficult by our partial understanding of the problem at hand, further compromised by our tendency to oversimplify and focus on the physical at the expense of the psychological and the sociological.

Currently, there is no comprehensive conceptual model describing evacuee behavior. This has important consequences for egress model development in that it limits the scope and complexity of the current egress models available. In lieu of this conceptual model, this article has presented a list of behavioral statements that are employed within the field and are used as a benchmark for the design of future conceptual models. Following this, suggestions were made regarding the types of structures that would need to be present within such conceptual models in the future.

It is hoped that this discussion will promote the development of conceptual models in the field and their implementation within egress models in the future. This should at least enable model users to represent key evacuee behaviors within the modelling environment without directly imposing them upon the scenario at hand.

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