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Original Article

Perception-based analytical technique of evacuation behavior under radiological emergency: An illustration of the Kori area

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ABSTRACT

A simulation-based approach is proposed to study the protective actions taken by residents during nuclear emergencies using cognitive findings. Human perception-based behaviors are not heavily incorporated in the evacuation study for nuclear emergencies despite their known importance. This study proposes a generic framework of perception-based behavior simulation, in accordance with the ecological concept of affordance theory and a formal representation of affordance-based finite state automata. Based on the generic framework, a simulation model is developed to allow an evacuee to perceive available actions and execute one of them according to Newton's laws of motion. The case of a shadow evacuation under nuclear emergency is utilized to demonstrate the applicability of the proposed framework. The illustrated planning algorithm enables residents to compute not only prior knowledge of the environmental map, but also the perception of dynamic surroundings, using widely observed heuristics. The simulation results show that the temporal and spatial dynamics of the evacuation behaviors can be analyzed based on individual perception of circumstances, while utilizing the findings in cognitive science under unavoidable data restriction of nuclear emergencies. The perception-based analysis of the proposed framework is expected to enhance nuclear safety technology by complementing macroscopic analyses for advanced protective measures.

1. Introduction

After the Fukushima disaster, many lessons on improving nuclear safety were learned [1]. No direct victim was reported in the nuclear meltdown and only one worker died of lung cancer caused by radiation [2]. Meanwhile, a total of 573 indirect victims were reported among whom 90% were aged over 65 y, as determined by evacuation procedures and stress-induced factors. Therefore, protective measures have been strongly recommended to consider individual and situational circumstances in terms of an individual's vulnerability to the evacuation [3], which was chosen in the national 5-year program for nuclear safety in South Korea (the target area of this study) in 2020 [4]. However, many studies have failed to address the human aspects, which involve psychological and cognitive issues [5].

This research proposes a simulation-based approach to accounting for microscopic perceptions and behaviors under nuclear emergencies. To explore protective responses of residents, two steps are presented. First, a simulation model is developed using a generic framework [6] for agent-based simulations in evacuation study, which is based on the ecological concept of affordance. The framework is constructed for general evacuations with user-defined parts for uncertain behaviors and basic elements for believable findings. Thereafter, the applicability of the simulation model is verified using an illustration of a nuclear emergency. A nuclear power plant (NPP) in Kori, South Korea, is targeted because that NPP has the third highest population density within its urgent protective action planning zone (UPZ) in the world [7]. A shadow evacuation problem under nuclear emergencies, which involves the individual perception of socially transmitted cues, is implemented with user-defined inputs based on the survey for the targeted NPP.

The remainder of this study is organized as follows: section 2 outlines the research background of the evacuation simulations under nuclear emergencies; Section 3 presents the system architecture of agent-based simulation models using affordance-based finite state automata (AFSA); section 4 illustrates a nuclear emergency scenario in the Kori area (South Korea) of the targeted NPP;

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and finally, section 5 concludes this paper with a discussion on possible extensions for future research.

2. Research background

2.1. Evacuation under nuclear emergency

Evacuation studies under nuclear emergencies have previously focused on evacuation time estimation (ETE) by the nuclear plant operators and governments [8–10]. Evacuation times consist of two major parts: (i) when people start the evacuation and (ii) how long it takes to reach the safe place. Generally, for example, travel times are collected based on the traffic at the time, while vehicles are generated based on the questionnaire given to the residents. Recent studies on ETE have been varied in terms of the second part such as path selections [11] and the range of evacuations [12]. Meanwhile, the estimation of the first part has not been highlighted in nuclear disasters. In reality, the first part includes everything prior to the evacuation, such as the recognition of hazards (e.g., unawareness of the hazard owing to dysfunctional telecommunication networks) and the decision making (e.g., no intention to evacuate because the individual distrusts the government). The empirical studies showed that the vulnerability to evacuation must be reconsidered in terms of the situational responses prior to the evacuation [13].

One of the biggest obstacles in studying an individual's vulnerability for nuclear emergencies is the shortage of evidential data: the research area of disasters simply does not have enough data. To overcome this shortcoming, some researchers have focused on the human aspect of protective responses rather than the type of hazard [14]. In case of nuclear emergencies, the public may decide whether or not to evacuate based on their recognition of the danger from socially transmitted cues rather than on their knowledge of radiation. Another popular solution involves the use of experimental data with computational simulations. Evacuations in a virtual world can be simulated to generate various dynamics based on available evidence and plausible assumptions. Recently, plans for nuclear emergencies have been revised using an agent-based simulation to incorporate the responses and decisions for evacuation grounded on the lessons learnt from Fukushima [9]. However, not many simulations in this disaster study support the micro-level analysis (e.g., situational recognition, individual vulnerability) as well as their own extensions (i.e., the reuse of developed models).

2.2. Affordance theory

The decision-making process and behavior of human beings have been studied in economics and psychology for over 50 years [15]. However, modeling human behavior digitally remains a challenge owing to indeterminism and uncertainty [16]. In cognitive science, affordance is a key concept in describing the decision-making process and behavior of animals. Gibson [17] first defined the term as follows: "The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill." A representation of this concept [18] was established for use in understanding prospective controls (PCs), using the juxtaposition function of effectivities and affordances within space-time as follows:

Let $Wpq = j(Xp, Zq)$ be a function composed of two different objects X and Z, and p and q be properties of X and Z, respectively. Then, p means an affordance of X and q means an effectivity of Z, if and only if there exists a third property r such that:

(i) $Wpq = j(Xp, Zq)$ possesses r;
(ii) $Wpq = j(Xp, Zq)$ possesses neither p nor q;
(iii) Neither Z nor X possesses r.

Here, the basic example of PC is revisited [18]. A bird (Z) is flying at a certain velocity toward a tree branch (X). Z possesses the disposition (q) to be fractured when the change in the velocity at contact approximates 7.6 m s^{-1} [19]. Then, X possesses the disposition (p) to offer fracture. This system (W_{pq}), given by $j(X_p, Z_q)$, exhibits the relational property of fracturing. If Z perceives the incoming property, Z may decelerate to avoid the danger. Thus, successful PC requires the perception of affordances over wide-ranging circumstances.

2.3. Affordance-based finite state automata (AFSA)

Agent-based modelling (ABM) is a popular approach in many research areas such as physics, economics, and politics, for representing complex systems at both the micro-level and macro-level [20]. Unlike classic models, autonomous entities, the so-called agents, in agent-based models interact with their surroundings and may change both themselves and the surroundings similar to most living beings. With this capability, systems are discretized at the level of individual behaviors that might generate system-level emergences in the real world (e.g., segregation in demography [21]). Notwithstanding the clear advantage, its applications for practical use are relatively limited because of the abundance of just-in-case models for specific situations [22]. To overcome this, a few formal representations were proposed to standardize agent-based models of social systems [23,24]. In evacuation studies, formalism and its agent-based extension have been developed for human-involved systems based on the ecological concept of affordance [6].

Kim et al. [25,26] proposed a novel approach, the affordance-based finite state automata (AFSA) to apply the affordances to human-involved systems. The formal representation works by converting non-deterministic human actions into a computable form for computational simulations. According to Kim et al. [27] and Rothrock et al. [28], the 6-tuple finite state automata (FSA), $\boldsymbol{M}^{\mathbf{comb}}$, describes the transitions among system-level states with a 12-tuple FSA, $\boldsymbol{M}^{\mathbf{atom}}$, that contains both human and environment, as shown in Eqs. (1) and (2). The internal state of affordances (p) and effectivities (q) changes over time (t_{int}). Based on the perception, a set of possible actions (PA) under preconditions (C) are generated by the generation function (π), and one of them is targeted to manifest. If all perceptions are true at the specific space-time, the target action (ta) is available, while its corresponding external transition (δ_{ext}) is generated by juxtaposition (j). Thus, the internal transition of AFSA may invoke the state transition of itself similar to finite state machines and atomic DEVSs (discrete event system specifications). AFSA has been used to build agent-based simulations for fire evacuations [29], human-robot control [30], manufacturing [31], and driving systems [32]. However, none of them represent the prospective control of a human agent under outdoor evacuations (e.g., nuclear incidents) and the accurate capability of human actions (e.g., locomotion) for examinations of various protective measures. To provide a fully-fledged affordance-based agent for megaregional events, a mobile agent is represented in terms of Newton's laws of motion and then extended to handle evacuation problems under a nuclear emergency.

$$M^{comb} = < \Sigma,\ S,\ s_0,\ M^{atom},\ \delta_{ext},\ F > \tag{1}$$

$$M^{atom} = < \{X,\ Z,\ W\},\ \{P,\ Q,\ PA\},\ Pr,\ j,\ \pi,\ ta,\ \delta_{int},\ t_{int} > \tag{2}$$

3. Agent-based modeling of affordance-based human behavior

3.1. Formal representation of a mobile human using AFSA

In this section, the agent-based modeling involving AFSA is explained using the bottom-up approach. First, the AFSA of a mobile human is specified as a default component for evacuation simulations. The only entity of interest in this research is a human evacuee with a desire for safety. At the microscopic level, the only key action that the human can carry out is motion and the protective action requires a series of mental processes [33] including risk notice, attention, and decision-making, which do not require any physical interaction with its surroundings. In this sense, the elemental action of the evacuees is aimed at properly representing the agent–environment interactions according to Turvey's definition (Section 2), which breaks down motion in terms of forces for the proposed AFSA. If a world (W) obeys the laws of physics, a human evacuee (Z) can move with its surroundings (X) including the ground and gravity of the planet. Technically, what a human can do is to be pushed with the leg-swing motion (q). The reason why this movement (r) is possible in the system is that there is an equal and opposite reaction (p) to the action in line with the laws of physics, i.e., the action of moving is possessed by the system, but the ability of the leg swing is the property of the human. In reality, evacuees may drive or ride a bike to move. However, for convenience, all types of human actions for movements are represented by a move-directed force.

Based on Kim et al. [25] and Joo et al. [6], the external part of the AFSA model for a mobile agent in an n-dimensional space (with one-dimensional time) is given such that,

As defined above, all physical transitions of a mobile human are mapped onto the AFSA. It can be seen as a machine moving with the controller's input. Similarly, the role of AFSA in the developed ABM is the body or avatar in the virtual world. With time, it might approach the final state if the target action is appropriately selected. In the viewpoint of evacuations, the AFSA model can successfully escape from an emergency using proper combinations of perception, judgement, and action.

3.2. Simulation model with AFSA of a mobile human

This subsection briefly introduces the architecture of the generic simulator using AFSA as proposed by Kim et al. [29]. Following the tradition of AFSA [6,30,32], an agent-based approach is used to simulate the developed descriptive model in this study, which describes the targeted system with finite states and discrete events. The agent and its interaction with surroundings are the core components of agent-based models. Here, the agent represents a human evacuee that consists of the body and its pilot (brain). The central processor needs to select from one of many possible actions (i.e., whether to go and where to go) in a certain circumstance. However, these issues are open questions that should be approached with many assumptions and evidence in hand. Thus, the aim of this study was to create an agent that could make decisions according to the user-defined rules and input distributions based on the generic simulator.

Fig. 1 depicts the diagram of the system architecture. There are four major components: (1) the AFSA model, (2) agent (in simulation model), (3) event generator, and (4) action planner. As mentioned, AFSA describes an entire state map on the physical world for an agent. An agent represents an autonomous and

Σ	$= \{\vec{f} \mid \vec{f} \in \mathbb{R}^n\}$, where $\vec{f}$ is the net force on the entity during the user-defined unit time (t_{unit}) and n is the user-defined dimension for the physical space,
S	$= \{(\vec{x}, \vec{v}, \vec{a}) \mid \vec{x}, \vec{v}, \vec{a} \in \mathbb{R}^n\}$, which denotes movement at position ($\vec{x}$) on the site with velocity ($\vec{v}$) and acceleration ($\vec{a}$),
s_0	is an element of S (given by user-defined rules),
$\delta_{ext}((\vec{x}, \vec{v}, \vec{a}) \vec{f})$	$= (\overrightarrow{x_{new}}, \overrightarrow{v_{new}}, \overrightarrow{a_{new}})$, and according to Newton's laws of motion: $\overrightarrow{v_{new}} = \vec{v} + \vec{a} \cdot t_e$, $\overrightarrow{x_{new}} = \vec{x} + 0.5(\overrightarrow{v_{new}} + \vec{v})t_e$, where t_e is the elapsed time since the last event, and $\overrightarrow{a_{new}} = \frac{\overrightarrow{f}}{mass}$ for the mass of this entity (mass),
F	is the subset of S (may be exits of the space).

The internal part is given such that,

X	is the ground (all the other entities in W),
Z	is a mobile animal,
W	is an animal-moving-ground system,
P	{the support abilities in space-time that generate $\vec{f} \in \Sigma$},
Q	= {the capabilities of Z to be pushed with $\vec{f} \in \Sigma$ },
C	= {true: if the evacuee perceives no other item in the user-defined safe radius of the evacuee and the evacuee is on the floor, false: otherwise}, the juxtaposition conditions are confined to the set of true and false, which is given by W,
$Pr(X_p)$	= P in a user-defined perceivable boundary (Z believes X supports in all perceivable space-time of W, whereas the slippery or unfixed floor of X may remove some in others),
$Pr(Z_q)$	$= \{q_{\theta r} \in Q \mid r \in [0, r_{max,\theta})\}$ with user-defined maximum force ($r_{max,\theta}$) of Z to the direction θ,
$\pi(p, q_{\theta r}, true)$	$= \vec{f} \in \Sigma$ to the direction ($\theta = \vec{f} / \lvert\vec{f}\rvert$) with the magnitude of the force ($r = \lvert\vec{f}\rvert$),
$\pi(p, q_{\theta r}, false)$	= 0,
PA	$= \bigcup_{q_{\theta r} \in Q} \pi(p, q_{\theta r}, true)$,
ta	is an element of PA,
$\delta_{int}((p,q), t_{int})$	= (p',q'), where p' and q' are the affordances and effectivities existing at the time; thus, the juxtaposition of both generates an input for external transitions,
t_{int}	$= t_{unit}$, which is the sampling frequency of the evacuees.

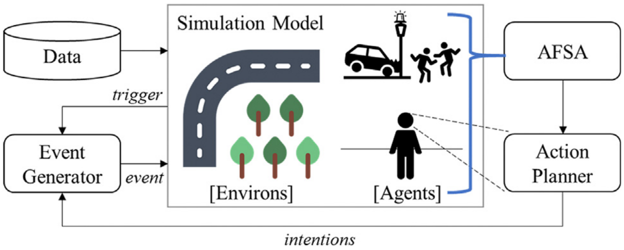

Fig. 1. Architecture of the affordance-based behavior simulator [1].

intelligent entity in the system. Each agent can sense, think, and make a proactive action in the system with its action planner, whereas the environmental entities have neither sense nor thought. The event generator creates situations for environmental entities and agents following governing rules, such as classical physics. Thus, the event generator enables all entities to make a reaction force of the same magnitude but opposite direction against the incoming force.

The action planner requires the sequence of steps to reach the goal state from the current state. The original generic planning algorithm [6] was developed for affordance-based simulations of fire evacuation problems. Human agents in this model set a plan according to the generalized version of the algorithm as follows:

i) Update the current location and perceivable boundary (PB).
ii) Check the situational information in PB. If the human agent reaches the intended state, then remove the plans and goals related to the intention. Go to step v) if all states in the plan are affordable. Otherwise, go to step iii).
iii) Based on the current belief, set a goal. It is assumed that an evacuee, who has noticed a certain risk, shares the recognition with other agents who are physically or socially accessible.
iv) Based on the current belief and goal, plan for the final state with a user-defined planning function (for each application domain). If multiple solutions exist, then randomly select one of them.
v) Execute the action in the plan as long as the action is actually affordable at the temporal and spatial instance. Go to step i) if the simulation clock is advanced.

Fig. 2. Satellite map of the targeted village nearest to the Kori NPP in South Korea.

4. Illustrative example: an evacuation problem in a nuclear emergency

4.1. Application scenario

The proposed model illustrates crowd evacuation behaviors under a nuclear emergency in the Kori nuclear power plant (NPP) where the first commercial reactor in South Korea exists. The area surrounding NPP has the third highest population density within a 30-km radius (i.e., its UPZ) [7]. The invisibility of radiological materials is expected to incite fear and create congestion in the population, regardless of whether an accident actually exists. Indeed, the two disasters of maximum classification on the international nuclear event scale (i.e., the Chernobyl and Fukushima cases) had a significant difference in the number of direct deaths and promulgation of relevant information [34]. Therefore, perception-driven evacuation was explored in terms of socially transmitted warnings.

4.2. Implemented model

In the scenario, people living the nearest village from the Kori NPP begin protective actions by themselves when they noticed the danger. The road map of the area is shown in Fig. 2. Then, modeling and simulation are implemented, as illustrated in Fig. 3, using Anylogic™, which has an agent-based module platform that allows the message-based transitions in FSA. The targeted shadow evacuation problem in nuclear emergencies is described as follows:

(i) A few residents feel strange sensation together and suspect that a severe abnormality occurs in the NPP. Although the plant operators and emergency response organizations (EROs) are under investigation and the official announcement has not been released. The residents start evacuation and their recognition propagates among the public.
(ii) Residents show the desire for safety if and only if it is worthwhile in their thoughts.
(iii) Residents follow the generic planning algorithm (listed in Section 3).

First, the global variables contain spatial and temporal information of each site (i.e., streets and roads) that is shown as follows:

- *roadNetworks*: a matrix in which a binary entity stands for the connectivity between two sites. For example, the entity of ith row and jth column represents whether the starting exit of ith site is connected to the starting (ending) exit of the jth site for $i > j$ $(i < j)$. The number of streets is 99, as shown in Fig. 3,
- *roadLengths*: an array in which an entity represents the length of each site, coordinates of two exits in the site are 0 (starting) and the length (ending) in the illustration,
- *roadWidths*: an array in which an entity represents the width of each site, all widths are set to 5 m in the illustration,

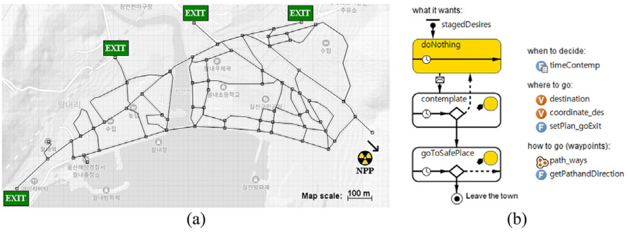

Fig. 3. Anylogic™ snapshots of the implemented simulation model: (a) a road map and (b) arc-arrow transition map.

- t_{unit}: a simulation step that represents 0.5 s (a unit time).

In addition to the ASFA model, a human agent has the following attributes:

- *goal*: a binary variable of {0: nil, 1: contemplate, 2: go to exit},
- *site*: the identifier of the site where the agent is placed,
- *perceivableBoundary*: 10-m radius within which agents perceive the situation [35],
- *mass*: mass of the agent, uniformly distribution from [60, 100] kg in Ref. [35],
- *acc*$_{\max}$: 2.6 ($=1.3 \cdot t_{\text{unit}}^{-1}$ in Ref. [35]) $\text{m} \cdot \text{s}^{-1}$, which is the maximum acceleration equal to the $r_{\max,\theta} \cdot \textit{mass}^{-1}$ for the maximum force ($r_{\max,\theta}$) of the agent,
- *sociallyLinkedAgents*: a collection of unidirectional links to accessible agents via electronic devices. This is an input parameter for the experiment (discussed in Section 4.3).

In each step, every agent conducts the generic planning algorithm described in Section 3. All detailed items of the algorithm are specified for the nuclear emergency problem as listed below:

- Perceivable items: physical states of other agents and socially transmitted warnings,
- Establishment of goals: the goal of "contemplate" is activated as soon as the agent perceives any warning. Under this goal, human agents are assumed to conduct pre-decision processes information as reported in Ref. [33]. After the process, the goal is set "go to exit" or "nil" according to the user-defined rules such that:
  - An agent is activated as soon as the agent perceives a warning from accessible agents,
  - After a contemplation time, *T*, the agent determines its response according to a probabilistic function of the collected information, *Prob*,
  - In this study, *T* and *Prob* are specified by questionnaire data surveyed for the Kori NPP [36]. That is, the 42.8% of agents start evacuation after the time uniformly distributed according to Table 1,
- Action plan (path selections); two well-known methods were employed as the individual planning function for the nuclear emergency problem:
  - Long-term items: the waypoints (*F*) for the shortest path to a random exit, driven by Dijkstra's algorithm [37] with the environmental variables of *roadNetworks* and *roadLengths*,
  - Short-term items: the magnitude and direction of the force (*ta*) that are controlled under the situational affordances according to the behavioral heuristics defined in Ref. [35].

The developed simulation has the most typical execution algorithm of ABM [38]. After the initialization of the model, (i) state variables are updated with the first step of the planning algorithm and then reluctant forces will be generated if any contact exists, (ii) agents perform the left part of the algorithm in a random order, and (iii) a tick count will be advanced until the predefined time to stop.

Table 1
Distribution of time estimates required to make a decision after recognizing an evacuation alert related to Kori NPP (no government command for an evacuation) [36].

Time estimates (min)	Number of respondents	Ratio of the response (%)
10–20	239	23.0
20–30	309	29.8
30–40	236	20.8
40–50	47	4.5
50–60	85	8.2
60+	140	13.5

4.3. Experiments

4.3.1. Experimental settings

To verify the applicability of the proposed simulation model, the impact of the online interactions was tested. Based on the number of advisors for important decisions, the initial population is linked according to the number of online links (n_β). A fixed number of links are considered such that $n_\beta = \{0,1,2,3,4\}$, where the scenario $n_\beta = 0$ indicates no online interaction. At the initialization, 887 agents (N_{init}) with the inactivated goal of "nil" are uniformly distributed to random positions in all streets. The initial number of agents was estimated based on the percentage of land area (10%) and the official population of 8865 in the civic unit which the target village belongs to. Next, nine random agents (1% of the entire population) were activated with the goal of "go to exit." The stop time of the simulation was set to 3 h.

All simulation outputs in this section were averaged from 30 replications. Both modeling and simulation were developed using the 64-bit windows version of Anylogic™ on the same computing system with a processor of i7-7700 and a maximum available memory of 4 GB. The implemented model is considered to be lightweight as the processing time of the simulation is less than 1 min for a single replication. The simulation outputs were then statistically analyzed using Minitab®.

4.3.2. Simulation results

To investigate the propagation of information in the specified physical and social networks, the number of activations and that of the corresponding leaves were collected. Table 2 lists the ratio of the never activated and leaved population at the end of the simulation. The input number of online links was found to be a significant factor for both outputs. The p-value is 0.000 for the both outputs. That is, the existence of online links markedly activates the evacuation, while the increment in the number of leaves nonlinearly decreases with increase in the number of links. Identical to empirical evacuations [39], the evacuation times in the simulations exhibit nonlinear dynamics with the p-values below 0.005. The interactions between agents, which are nearly incorporated in the conventional approaches, are checked to generate the nonlinear responses corresponding to the user-defined inputs of road and social networks.

The temporal pattern of the ratio of leaves among the whole population is presented in Fig. 4. The pattern of the leaves resembles the sigmoid-shape distribution of preparation times in typical evacuations [39]. Notably, the temporal patterns in evacuation studies remains a highly contested subject [40]. More complex patterns are also reported as a result of multiple factors in the event [41]. Thus, in this section, the capability of the model is assessed to produce the typical output of the evacuation study with user-defined networks and time distributions of the contemplation stage.

When the abnormality of the NPP becomes critical, the contacts are observed as the perception of socially transmitted warnings as

Table 2
Ratio of the never activated and leaved agents among the initial population.

	$n_\beta = 0$	$n_\beta = 1$	$n_\beta = 2$	$n_\beta = 3$	$n_\beta = 4$
Avg. Never activated (%)	35.45	3.762	1.082	0.4059	0.1278
Std. Never activated (%)	10.41	1.130	0.4942	0.2574	0.1014
Avg. Leaves (%)	50.74	70.71	75.03	76.98	77.16
Std. Leaves (%)	8.198	2.688	2.508	1.668	3.607

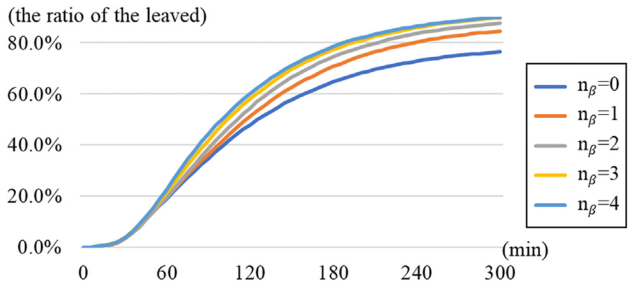

Fig. 4. Temporal pattern of the leaved population among the whole population in every 5 min.

residents conform only to the cues they can see on the streets. The vulnerability of the residents is then directly connected to the contacts. This phenomenon is popularly known as the bandwagon effect [42] in which some people are uncertain about how to respond to an approaching threat and assume their neighbors are responding properly to the unknown. Concerning the vulnerability on the road networks as the dependent variable, spatial patterns of the vulnerability is illustrated in Fig. 5. The perception-based vulnerability of each road is calculated at the end of the simulation (T_F) according to Eq. (3):

$$V_{r\_id}^{T_F} = \frac{\sum\limits_{cnt=1}^{N_{r\_id}} t_{cnt}}{N_{r\_id} \cdot T_F}, \tag{3}$$

where $N_{\mathrm{r\_id}}$ is the initial number of agents on the road of which the identifier is *r_id*; t_{cnt} is the time at which the *cnt*-th agent on the road starts the evacuation with the upper limit of T_{F}. The vulnerability of road networks is expressed in terms of number of links, position of roads, simulation runs for each road; roads with the biggest vulnerability are shown in Table 3. As expected, the scenario of absent online interaction (visual perception only) results in the highest level of vulnerability in every observation, which decreases with the number of social links. Meanwhile, each road has a different vulnerability depending on the roads and simulation runs, in that it has a bounded value between 0 and 1. For example, the scariest road with the biggest vulnerability is not fixed by the number of online links. This indicates that perception should be revised with situational circumstances (i.e., individual networks and the position of the initializer) in evacuation studies.

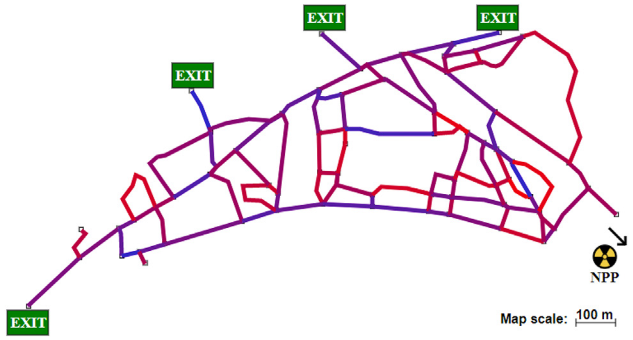

Fig. 5. Spatial pattern of the visualized vulnerability on the road networks ($n_\beta = 2$), where the line color of each road is adjusted to its level of vulnerability between blue color (the zero vulnerability) and red color (the full vulnerability). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Perception-based vulnerability of the road networks by the number of online links.

	$n_\beta = 0$	$n_\beta = 1$	$n_\beta = 2$	$n_\beta = 3$	$n_\beta = 4$
Overall average	0.6999	0.6155	0.5815	0.5701	0.5573
Overall standard deviation	0.04445	0.02329	0.02171	0.01872	0.01678
Deviation between roads	0.2564	0.1873	0.1678	0.1580	0.1449
Deviation for each road	0.1521	0.1307	0.1283	0.1234	0.1198
Avg. Of the scariest road	1.0000	0.8651	0.7671	0.7406	0.7098
Index of the scariest road	75, 80	42	9	31	9

Despite the simplified application scenario, this study verifies that the proposed model is capable of analyzing the temporal and spatial dynamics of the perception-based evacuation behavior. The analysis of perception has not been incorporated in existing simulations; however, this analysis is important as it can highlight areas and residents of high vulnerability that would in turn optimize the police staffing problem depending on the availability of telecommunications between the residents. Findings in cognitive science have been utilized to correlate individual protective actions and the macro-level dynamics within the limited data of nuclear emergencies. The formal representation of the developed simulation model enables the cooperation with the existing approaches for the examination of various protective measures.

5. Discussion and conclusion

A simulation-based approach was proposed to investigate protective responses under nuclear emergencies for residents using cognitive findings. Human perception-based behaviors are not heavily incorporated in the evacuation study for nuclear emergencies, despite their known advantages. The study introduces a generic framework of perception-based behavior simulation, based on the ecological concept of affordance theory and AFSA. The proposed simulation model is developed such that an evacuee can perceive available actions and execute one of them according to Newton's laws of motion. The case of a shadow evacuation under a nuclear emergency is used to demonstrate the applicability of the proposed framework. The illustrated planning algorithm enables residents to compute not only the prior knowledge of the environmental map, but also the perception of dynamic surroundings using widely observed heuristics. The simulation results confirm that the temporal and spatial dynamics of the evacuation behaviors can be analyzed based on the individual perception of circumstances.

Notably, the presented model offers an agent-based and perception-based approach. In an emergency, most people will not be allowed to spend much time to gather sufficient information and decide on the optimal course of action. Actual people make decisions with limited information and consideration in almost every situation [43] but many previous studies have presumed the full rationality of human beings [44]. Since the proposed model represents individual actions in terms of affordances given by the surrounding environment, the implemented agents can be analyzed at the microscopic level of their perception. To illustrate this, the vulnerability of physical and social networks was checked for a nuclear emergency in Kori NPP of South Korea. The findings demonstrate the simulation capability of the proposed approach to analyze human responses in nuclear emergencies on the individual level of wide space-times. Thus, the findings of the study are expected to enhance nuclear safety technology by supporting existing macroscopic analyses.

The proposed framework is designed to be extendible for examinations of various emergency scenarios. Basically, FSA formalism is a traditional approach to representing systems and previous studies using the extended FSA have reported its computability and scalability [6,28]. Moreover, the demonstrated simulation model has the default setting for evacuees with generalized algorithms and functions. For instance, the Newton's laws of motions form the most fundamental elements in the real world and this is also incorporated in the proposed simulation model. The individual planning algorithm generates evacuation plans based on both prior knowledge of the road networks and situational perception with the widely observed heuristics [35]. This enabled the simulation to exhibit the heuristic control of human behaviors as reported by cognitive scientists [45]. The generalized agents are expected to offer more realistic human movements for experimenting on complex human-involved systems in nuclear emergencies and nuclear industries.

There are still many challenges that hinder the practical application of the developed model. The proposed model lacks many aspects of actual nuclear emergencies. For example, people may consider a different response in unusual situations, according to cue types (e.g., ERO activities and visual abnormality) as well as physical and social factors, such as disability, age, and language fluency, which were not considered in this research. The recent technologies of information and communications (e.g., virtual reality systems, human-in-the-loop experiments [46]) are expected to provide a suitable task environment with no risk for human experiments. With the structural advantage of the proposed model (i.e., the split structure of a pilot and an avatar), experiments with these technologies could support the validation of adopted hypotheses and their agent-based approaches. The valid simulations are expected to improve not only disaster managements for public relations, but also improve on the education of the residents.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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