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A Structured Evacuation Simulator Framework for Federation Strategy during Flood Disasters#

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ABSTRACT

This paper proposes a structured evacuation simulator framework that incorporates various factors influencing evacuation behavior during flood disasters. The framework aims to advance the development of cyber-physical systems for disaster damage by simulating multiple factors, emphasizing their interaction, and incorporating information factors. The proposed framework consists of four main components: the main loop, module sets, variable blocks, and interactions with the external environment. The main loop controls the state of the evacuees and represents their state transitions. The psychological and environmental variables representing the evacuees' state and situation are stored in the variable blocks, and the module sets describe the rules for updating these variables. The proposed framework adopts a federation strategy to realize interaction with other simulators and systems. By integrating the knowledge from previous evacuation simulation research and adapting to a society with advanced information technology, this study contributes to the development of comprehensive and dynamic evacuation simulators for flood disasters. The proposed structured evacuation simulator framework offers flexibility and extensibility in modeling evacuation behavior, facilitating the analysis and planning of evacuation strategies in the context of cyber-physical systems for disaster damage reduction.

Keywords: flood disaster, structured evacuation simulation, federation system

NONMENCLATURE

Abbreviations	
ADAPEN	Advances in Applied Energy
Symbols	
n	2024

1. INTRODUCTION

The global climate system's complex changes and greenhouse gas-induced global warming have led to a steady increase in disasters and human casualties worldwide [1]. By 2050, urban populations are projected to surpass 6 billion, with 68% concentrated in disaster-prone areas. Flood disasters, in particular, have the highest number of human casualties, affecting approximately 3.39 million people in 2018, and these figures are expected to rise further.

This research aims to develop a cyber-physical system for disaster damage. While numerous simulations of disaster phenomena and human behavior have been researched and developed, disaster damage results from the complex interaction of various factors. These factors include the disaster phenomenon itself, victims and damaged urban infrastructure, evacuation behavior, countermeasures to protect victims, disaster information, and information services for victims. However, conventional simulators often represent only a single factor or a subset of these factors.

Simulations focusing on specific factors can provide useful analysis for particular objectives. However, from an urban cyber-physical system perspective, such simulations assume certain conditions for factors beyond the objective, which can hinder the development of comprehensive disaster damage cyber-physical systems. In today's information society, disaster management heavily relies on information systems, and more damage information can prevent further harm. Nevertheless,

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disaster damage simulations rarely incorporate information factors. Therefore, simulating multiple factors, emphasizing their interaction, and incorporating information factors is expected to advance the development of cyber-physical systems for disaster damage.

This paper focuses on social simulations that model evacuees' behaviors. Evacuation simulators reproduce evacuation behavior in various situations, such as during a disaster event. Behavior modeling approaches include empirical and agent-based methods [2]. Several models have been developed, including evacuation models that dynamically select destinations [3], consider collisions between evacuees in indoor settings [4], account for the influence of nearby evacuees on evacuation behavior [5], and simulate crowd evacuation [6]. Reference [7] used an evacuation simulation in disaster phenomena, considering smoke diffusion behavior during a fire and providing directions to evacuees, discussing its potential for formulating efficient evacuation plans.

However, treating such simulations as components of a cyber-physical system faces various barriers, particularly regarding how evacuation simulations handle the influence of other factors on human behavior. Smart city technology's impact on human behavior cannot be ignored, as it collects diverse urban data, such as traffic flow, human flow, and weather, using IoT sensors and predicts the supply and demand of city residents in real-time using AI. This research aims to develop an evacuation simulator that flexibly reproduces the impact of flood disasters occurring under the influence of climate change and smart city technology on human behavior. By incorporating the wisdom of previous evacuation simulation research and adapting to a new society with advanced information technology, this study contributes to the development of cyber-physical systems.

2. RELATED WORKS

Evacuation simulations during disasters have been extensively researched for a long time, with various developments. Among them, many papers have used actual flood cases as model cases. Reference [8] focused on dam safety risk assessment, developed a life safety model based on agents to quantify risk and support decision-making on structural maintenance methods, and used real-world examples to demonstrate various scenarios for estimating potential loss of life and evacuation time resulting from extreme flood events. Reference [9] developed an evacuation model integrated with a numerical simulation of tsunamis and used the case study of the Arahama settlement in Miyagino Ward, Sendai City, to estimate evacuation rates and compared and verified them with actual evacuation rates during the tsunami disaster. Reference [10] focused on the potential of individual, corporate, and government actions before, during, and immediately after a disaster to dramatically impact its consequences and recovery time, and conducted an integrated flood risk assessment that is mindful of societal behavior and behavioral adaptation dynamics.

Such evacuation simulations have been primarily developed with the expectation of their application in flood risk management, evacuation planning, and urban planning. Reference [11] developed a dynamic agent-based model for effective flood incident management and obtained new insights that can be used for policy analysis and other practical applications. They coupled a multi-agent simulation with a fluid dynamics model to estimate individual vulnerability to flooding under varying storm surge conditions, defense breach scenarios, flood warning times, and evacuation strategies, and analyzed people's risk from flooding. Reference [12] proposed a hybrid approach that integrates simulation tools and machine learning algorithms for effective evacuation management in subway stations, aiming at simulating evacuation events and proactive evacuation management. From the analysis results, they identified the number of congested areas, proposed evacuation guidance strategies, and suggested improvements for evacuation events. Reference [13] presented a multi-scenario risk assessment approach to simulate and evaluate the impact of future urban growth scenarios with flooding under climate change, addressing urbanization and climate change as challenges. Using Shanghai as an example, they quantified the role of urban planning policies in future urban development and compared urban development under multiple policy scenarios.

Considering the above applications, recent research on evacuation simulations can be classified into three main categories. The first is how to improve the accuracy of evacuation simulations, and various techniques have been introduced into evacuation simulations for this purpose. For example, Reference [14] focused on the time-dependent characteristics of networks and demonstrated how to adapt an existing multi-agent traffic simulation framework for large-scale pedestrian evacuation simulations. Reference [15] proposed an agent-based model for evacuation simulation based on the analysis of videotapes of actual events. This model analyzes the possibilities of pedestrian choices in various scenarios. Reference [16] implemented econometric models and statistical models that represent travel behavior and decision-making behavior in the evacuation process as an agent-based travel demand model system for hurricane evacuation simulation.

The second category is to incorporate the characteristics of evacuees, the agents in evacuation simulations, to perform simulations tailored to specific applications. Reference [17] focused on how effectively the built environment responds to the evacuation needs of people with disabilities and proposed a simulation that more appropriately represents the diversity and prevalence of disabilities and their interactions with the built environment. Reference [18] developed a computer program to simulate and analyze the progress of evacuation in large public buildings in the event of a fire, and analyzed crowd pedestrian flow phenomena such as detours from visual illustrations of scenarios. This study represents the overall and dynamic process of occupant evacuation under fire spread and the interrelationship between occupant safety and fire hazards. Reference [19] developed an evacuation simulation that incorporates the unique behaviors of first-time visitors with incomplete knowledge of the area and families who do not necessarily adhere to generally assumed pedestrian behaviors, showing that they significantly impact evacuation time. Reference [20] constructs a simulation model of multiple agents in a virtual community and investigates the impact of behaviors such as neighbors, personal contacts, and volunteer monitors on overall warning communication. They analyze the effects of varying parameters such as the proportion of people warning their neighbors and the delay time before warning their neighbors.

The third category is the advancement of the computational environment for evacuation simulations. The intention is to utilize parallel computing, cloud computing, and big data analysis to simulate a vast number of agents and complex scenarios, enabling detailed analysis of evacuation behavior and efficient creation of evacuation plans. Reference [21] proposed a broad simulation of a multi-cloud architecture by deploying evacuation services to multiple cloud providers. Reference [22] proposed a method to formulate crowd behavior using cellular automata and multi-agent models and simulated large-scale crowd scenarios on clusters. Reference [23] adopted GPUs and proposed an efficient scheme to minimize computational overhead through ultra-parallel modeling and simulation of evacuation scenarios. Reference [24] proposed a

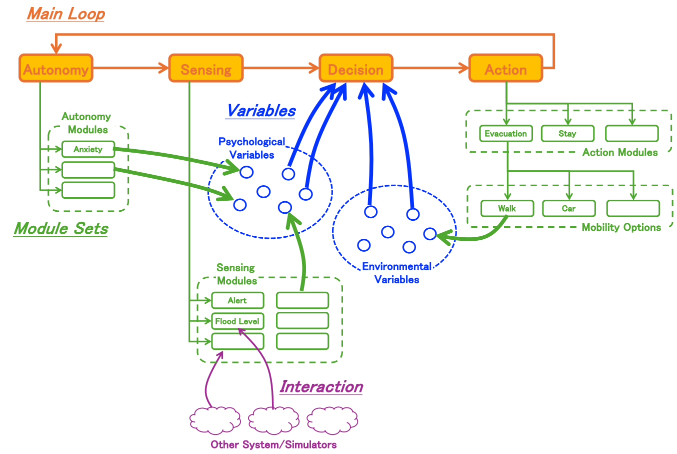

Fig. 1 Structured evacuation simulator framework

parallelization strategy for large-scale microscopic tsunami evacuation simulations and demonstrated its application in real urban environments.

As discussed above, there is a long history of research on evacuation simulators, with various research and development efforts from multiple perspectives, such as accuracy and computational performance. Building upon this, we aim to challenge the development of evacuation simulators by focusing on their structure itself. This is because, although these previous studies have high accuracy and performance, they are limited to researching a single model. The scope of considerations for evacuation simulators is wide-ranging, including model accuracy, parameter settings, evacuee characteristics, and computational performance. Furthermore, it is necessary to consider the influence of factors other than evacuees, such as flood situations and information access. What is required in the concept of cyber-physical systems is a mechanism that can flexibly select simulator models with excellent functions and elements that should be adapted according to the situation. Our idea is a framework for evacuation simulators that can flexibly expand and replace the elements that influence the evacuation simulator. In this paper, we propose a structured evacuation simulator for this purpose.

3. STRUCTURED EVACUATION SIMULATOR FRAMEWORK

3.1 Overview

We describe our structured evacuation simulator framework. Our perspective is on how to incorporate elements that influence evacuation behavior into the simulator and how to reproduce them in the simulator.

Needless to say, evacuees are influenced by various factors. Various elements can be considered, such as the disaster situation, information about the current situation and predictions, the behavior of others, and the knowledge that evacuees have about disasters. Considering previous studies, there have been attempts to reproduce some of these elements in simulators. These elements have been used as important parameters that determine the behavior of evacuees and have provided important insights for the analysis of evacuation behavior and evacuation planning. We follow these previous studies and have structured our framework so that these elements can be introduced into the framework in a way that can flexibly respond to parameters.

3.2 Framework structure

We investigate previous studies and classify the factors that determine evacuees' behavior into several types. For example, there are factors that evacuees internally possess, factors that serve as external stimuli, and changes in these factors. Evacuees comprehensively consider these factors and determine their actions. Fig. 1 shows the framework structure we have designed based on the above considerations. The structure in Fig. 1 represents the functions that describe the behavior of individual agents in the evacuation simulator. This framework consists of four components: the main loop, a set of modules, variable blocks, and interactions with the external environment.

3.3 Main Roop

Our main loop is a function that controls the state of the evacuees. We consider how we will act based on external situations and information from the outside, and then choose our actions. Several behaviors can be considered as part of the evacuation simulator, such as obtaining/not obtaining information, evacuating/not evacuating, selecting/not being able to select evacuation sites, etc. The main loop represents the state transition of evacuees in the simulation function. Since our framework assumes a simulation, the processing to determine the state of evacuees operates at each step of the simulation. The psychological state changes are updated in the Autonomy and Sensing processing blocks, and actions are determined in the Decision processing block. Then, in the Action processing block, the state of the evacuees is changed. The main loop takes a structure that repeats this process at each step.

The main loop consists of four processing blocks: Autonomy, Sensing, Decision, and Action. Each processing block is connected to a set of modules that are called at each step. Sensing is a processing block that receives information from the outside. When faced with the threat of a flood, we obtain and judge various information. This information ranges from the appearance of heavy rain, the flooding situation of rivers and roads, sensor values collected by IoT sensors, weather-related warnings, and how people in the neighborhood are acting. The Sensing module group inputs this information into the evacuation simulator and manages how that information affects the psychology of the evacuees, and the Sensing process in the main loop plays a role in centrally managing and controlling the Sensing module group.

The Decision processing block is a processing block for determining what actions to take by comprehensively judging the psychological variables representing the psychological state and the environmental variables representing the situation in which the evacuees are placed. For example, it determines whether to start evacuation behavior or not, and what actions to choose next from the current state of the evacuees. From the perspective of the simulator, it is a process for determining whether to change or maintain the current state. Research on decision-making during disasters has developed many models in previous studies, especially regarding the choice of evacuation behavior. This processing block assumes the application of those models. The variables required vary depending on the model, but this processing block is connected to the variables and is configured to allow each model to select and use the variables it utilizes.

The Action processing block controls the state of the evacuees. In the Decision processing block, an Action module is selected to determine what actions to take, and the Action module is executed. The types of actions are stored in the Action module, and this processing block manages the modules. When the Action processing block is completed, the main loop transitions to the Autonomy processing block.

The Autonomy processing block is a process that represents changes in the psychological state over time. The main loop circulates and executes at each step of the simulation execution. However, the Sensing process that receives information from the outside is not necessarily executed at every step. Weather forecasts and flood information are input into the simulation as data in the sensing process, and the psychological variables of the evacuees who receive it are updated. In reality, it is possible that such information gathering actions may not work well. For example, if information cannot be obtained due to a failure in information communication, it is thought that the psychological variables of the evacuees will change due to the anxiety of not being able to obtain information. The Autonomy processing block is responsible for updating the psychological variables over time, even if it cannot be triggered by external information.

3.4 Module Sets and Psychological / Environmental Variables

Module sets are a set of functions that represent specific processes executed in each processing block. The psychological state and current situation of the evacuees are represented by the psychological variables and environmental variables in the psychological variable block and the environmental variable block, respectively. These function sets describe the rewriting rules for these variables. The Autonomy module in the Autonomy processing block represents changes in the psychological state over time and updates the psychological variables. For example, psychological anxiety due to the inability to obtain information is represented in this module and rewrites the psychological variables over time.

The Communication module in the Sensing processing block has a set of modules for obtaining information from the outside and a set of modules for updating psychological variables according to that information. The module set for obtaining information from the outside is connected to other simulators. The mechanism of connection will be explained in the section on interactions with the outside. After obtaining this information, the next set of modules determines how to rewrite the psychological variables according to the content of the information.

The Decision processing block does not set up a module set, but it can obtain variables from the psychological variable block and the environmental variable block and use them for processing. Based on the psychological variables and environmental variables updated by the module sets of other processing blocks, it determines whether to change the state of the evacuees and, if so, selects the action.

The Action module in the Action processing block executes the processing of the action if an action is determined in the Decision processing block. For example, if the action to start evacuation is selected, this module set describes the detailed rules of the evacuation behavior, such as whether to evacuate to a shelter or to an upper floor. Furthermore, the Action module holds several options. For example, as a mobility option, choices such as the means of movement, whether on foot or using a car, are stored. Based on this action, the environmental variables of the evacuees (for example, location and information access environment at the current location) are updated.

3.5 Interaction with other simulators / systems

Interaction with other simulators / systems refers to the mechanism of inputting information calculated by simulators other than the evacuation simulator related to flood evacuation into the evacuation simulator. Aiming for a dynamic calculation mechanism, we believe that a mechanism to input the latest information updated with each calculation step of the simulation is necessary. The evacuation simulation calculation requires the results of flood analysis, but these flood analysis results are also constantly updated due to changes in precipitation conditions. In order to input the latest flood analysis results, it is desirable to connect with the flood analysis simulator and obtain the newly calculated results, rather than preparing the flood analysis results as data in advance within the evacuation simulator. To realize such interaction with other simulators / systems, we adopt the federation strategy that we have developed so far, which can simultaneously operate multiple systems and simulators [25]. The federation strategy consists of functions for physical data exchange and processing timing control between simulators and systems. The data exchange function, as the name suggests, is responsible for data exchange between simulators and systems. At each step, the simulator/system outputs its calculation results and simultaneously receives the results calculated by other simulators and systems, and uses them for its own calculations. The processing timing control function manages the processing timing and is a function for adjusting the calculation speed with other simulators and systems.

By adopting such a federation strategy, the calculation results from other simulators / systems are used in the evacuation simulator's calculations. The communication module is responsible for this interaction. Specifically, modules are prepared for each external simulator and system, such as the flood analysis simulator, the information service emulator for obtaining weather forecasts and warnings, and the smartphone emulator for evacuees to obtain information, and these modules handle the connection. This interaction has high affinity with global warming adaptation measures and smart cities. For example, if a new service is launched as part of a smart city strategy, our evacuation simulator can simulate the effect on evacuation strategies by simply preparing a module for that service.

4. PROTOTYPE IMPLEMENTATION AND PERFORMANCE STUDY

4.1 Overview

The purpose of this paper is to develop a structured evacuation simulator framework that incorporates various factors influencing evacuation behavior during flood disasters. The proposed framework consists of four main components: the main loop, module sets, variable blocks, and interactions with the external environment. The main loop controls the state of the evacuees and represents their state transitions. The psychological and environmental variables representing the evacuees' state and situation are stored in the variable blocks, and the module sets describe the rules for updating these variables. We have implemented a prototype of the module sets that update the psychological and environmental variables in this evacuation simulator framework. As another simulator, we prepared a flood analysis simulator and implemented the interaction. The flood analysis simulator uses flood data assumed to occur in the event of heavy rainfall in Joso City, Ibaraki Prefecture, Japan. The evacuee agents in the evacuation simulator are virtually placed and start evacuation behavior according to rules that consider the values of psychological and environmental variables. Although this prototype is only a part of our concept, the purpose of this test is to investigate whether the proposed framework operates as intended and to conduct a performance study.

4.2 Setup

For the flood analysis simulator setting, a specific single point is selected as the levee breach point, and time-series inundation data is used for the case when the maximum assumed flood occurs. In the evacuation simulator, 2,000 evacuee agents are randomly placed at locations on a trial basis. Alerts are regularly issued before the flood occurs, and evacuee agents who receive this information start evacuation according to the values of psychological and environmental variables. In the performance test, the following points were experimented and verified. Assuming a flood disaster in Joso City, a flood is generated, and it is investigated whether the psychological and environmental variables are updated and their impact is reflected in the behavior of the evacuee agents in the evacuation simulator. The flood analysis simulator and evacuation simulator realize interaction through the federation strategy we have developed.

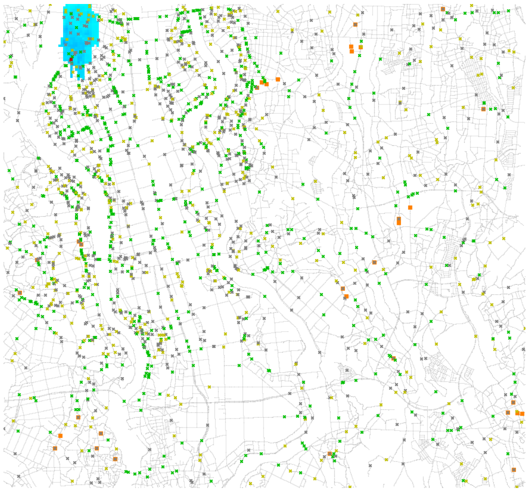

Fig. 2 a) Evacuation result after flood

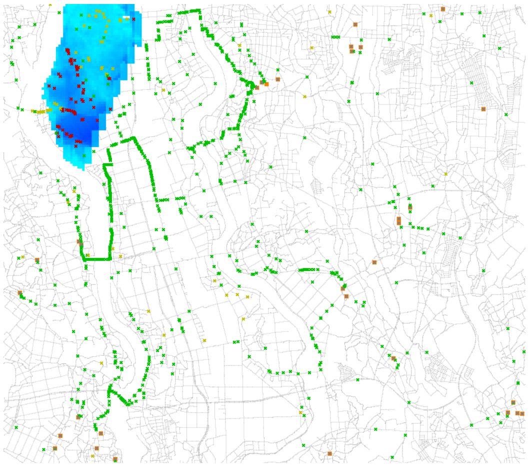

Fig. 2 b) Evacuation result after flood expand

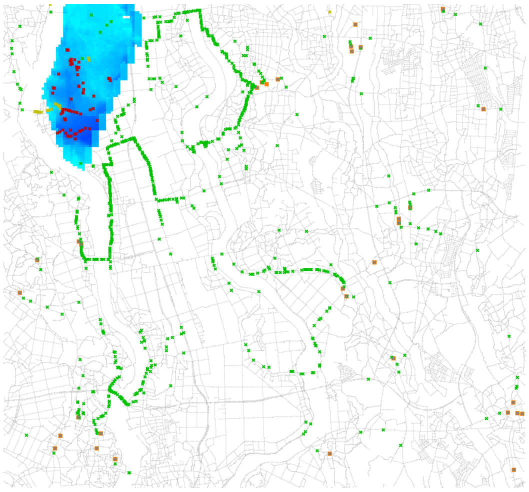

Fig. 2 c) Evacuation result after flood expand with safely configured psychological valuables

4.3 Evacuation result and discussion

Fig. 2 shows the results of the evacuation simulator, where evacuees start evacuation under the influence of flooding transmitted from the flood analysis simulator. Fig. 2 a) shows the situation of evacuee agents in the city immediately after the flood occurs. The green, yellow, and gray dots on the map represent evacuee agents. Green evacuee agents are agents who have started evacuation behavior, yellow agents are agents who are preparing to start evacuation behavior, and gray agents are agents who have not yet reached the decision-making stage to start evacuation behavior. Inundation has already started in the upper left of the figure. Agents near the inundated area start evacuation after judging the surrounding situation, but evacuee agents in areas far from the inundated area also perform evacuation behavior or prepare for evacuation. This is because they received information through the interaction with other simulators via the sensing block processing, and the psychological variables of the evacuee agents were updated based on the sensing results, leading to such decision-making. In other words, it shows that the updating of psychological variables through the interaction processing and sensing processing has been successful, as we expected.

Fig. 2 b) and Fig. 2 c) show the situation of evacuee agents when the inundation range further expands. Fig. 2 b) is the result of advancing the time progression of the evacuation simulation from Fig. 2 a). Many evacuee agents in the city have completed evacuation. On the other hand, agents indicated in red and yellow can be observed in the inundated area in the upper left of the figure. Red agents are agents that have become unable to move due to inundation and represent affected people. Yellow agents are moving agents, but since they are moving through the inundated area, they have a high possibility of encountering danger. Fig. 2 c) shows the result of conducting the evacuation simulation with the psychological variables set to have a safer way of thinking compared to Figs 2 a) and b). The evacuee agents in Fig. 2 c) observe the surrounding flooding situation more carefully compared to Figs 2 a) and b) and use it for decision-making. In Figs 2 b) and c), the number of evacuee agents remaining in the non-inundated area is almost the same, but when comparing the inundated area in the upper left, Fig. 2 b) has a larger number of evacuee agents remaining in the inundated area. This indicates that the setting of psychological variables influences the outcome of evacuation behavior. In other words, psychological variables are used for decision-making and are processed as actions in the subsequent main loop processing. This result affects the disaster status of the evacuees.

As described above, in this paper, we developed a structured evacuation simulator framework that incorporates various factors influencing evacuation behavior during flood disasters and conducted a performance investigation of its prototype. As a result, it was confirmed that the processing blocks of the main loop function as we expected, updating the variables. It was also confirmed that the operation of utilizing variables for decision-making worked as expected, and that the difference in these variables manifested as a difference in the amount of damage. The current performance investigation is a simple functional verification of the structured evacuee simulator, and it does not reach the level of generating evacuation scenarios or analyzing results that can be utilized for evacuation planning. However, by structuring the framework, we were able to build it as a framework capable of incorporating various functions, and we believe that we were able to bring flexibility and extensibility that can be utilized for cyber-physical systems, such as interactions with other simulators.

5. CONCLUSIONS

In this paper, we proposed a structured evacuation simulator framework that incorporates various factors influencing evacuation behavior during flood disasters. The framework consists of four main components: the main loop, module sets, variable blocks, and interactions with the external environment. The main loop controls the state of the evacuees and represents their state transitions. The psychological and environmental variables representing the evacuees' state and situation are stored in the variable blocks, and the module sets describe the rules for updating these variables.

To evaluate the effectiveness of the proposed framework, we implemented a prototype and conducted a performance study. The prototype included a flood analysis simulator and an evacuation simulator, which interact through a federation strategy. The flood analysis simulator used flood data assumed to occur in the event of heavy rainfall in Joso City, Ibaraki Prefecture, Japan. The evacuee agents in the evacuation simulator were virtually placed and started evacuation behavior according to rules that considered the values of psychological and environmental variables.

The performance study results confirmed that the processing blocks of the main loop functioned as expected, updating the variables. It was also verified that the operation of utilizing variables for decision-making worked as intended, and that the difference in these variables manifested as a difference in the amount of damage. Although the current performance investigation is a simple functional verification of the structured evacuation simulator and does not reach the level of generating evacuation scenarios or analyzing results that can be utilized for evacuation planning, the proposed framework demonstrates the potential for flexibility and extensibility in modeling evacuation behavior.

The structured nature of the proposed evacuation simulator framework allows for the incorporation of various functions and the ability to interact with other simulators and systems. This flexibility and extensibility make it suitable for use in cyber-physical systems, where the integration of multiple models and the ability to adapt to different situations are crucial.

In conclusion, the proposed structured evacuation simulator framework contributes to the development of comprehensive and dynamic evacuation simulators for flood disasters. By incorporating various factors influencing evacuation behavior and enabling interactions with other simulators and systems, the framework facilitates the analysis and planning of evacuation strategies in the context of cyber-physical systems for disaster damage reduction. Future work will focus on further enhancing the framework, incorporating additional factors, and applying it to real-world case studies to validate its effectiveness in supporting evacuation planning and decision-making.

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