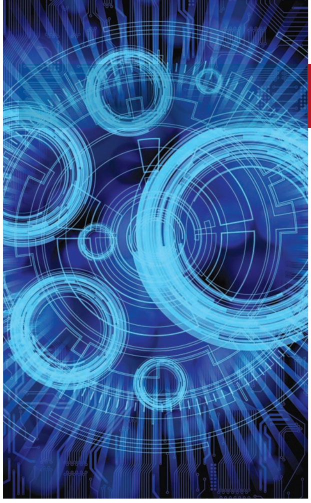

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A CPSS Approach for Emergency Evacuation in Building Fires

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Living with high-rise buildings or skyscrapers has raised important issues and huge challenges for occupant evacuation in fires or other emergencies. To alleviate casualties, it's important to have emergency evacuation plans in place before fire outbreaks occur. However, there are too many factors involving uncertainty, diversity, and complexity in evacuations. How, then, can we model human behaviors during evacuation processes? And how do we verify or evaluate those prearranged emergency plans? Furthermore, how can we guide evacuations timely and effectively under varied, changing scenarios?

To address these problems, we propose a cyber-physical-social systems (CPSS) approach based (ACP) methodology using artificial systems, computational experiments, and parallel execution.[1–3] CPSS is the extension of cyber-physical systems (CPS), which integrate with human and social characteristics and bridge the physical world, cyberspace, and human society together.[4] In a CPSS approach, building structures, fire scenarios, evacuees, and managers can be fully connected and interactive. To model the complex processes of evacuations, artificial evacuation systems are built and used to determine evacuation options for the physical evacuation systems. Based on the artificial evacuation systems, such prearranged emergency plans can be tested and evaluated by computational experiments. Then, constructing data-driven parallel mechanisms between the artificial evacuation systems and the physical evacuation systems is the ultimate way to achieve evacuation guidance in real time.

System Framework

As Figure 1 shows, the strategy database, artificial evacuation system, computational experiment platform, and visualization output are the main components. Various emergency evacuation strategies, static or dynamic, are included in strategy databases, and are applied to artificial evacuation systems. The computational experiment platform can be considered as the laboratory for conducting evacuation experiments.

As the counterparts of actual and physical evacuation systems, artificial evacuation systems are developed by three interactional components:

- *Building structures*. According to the needs of research, in the artificial evacuation systems we can flexibly construct different building spatial distributions and explore the influences of these different structures on evacuation efficiencies.
- *Fire scenarios*. Obviously, different fire scenarios will distinctly impact evacuees' psychology and physiology and change the evacuation efficiencies, even with the same strategy.
- *Evacuees*. It's been verified that agent-based modeling methods accurately imitate evacuees—from physiological and psychological characteristics to movements and behaviors.[5] To differentiate and distinguish among the evacuees, each individual agent should have some basic physiological and psychological attributes. Additionally, the agent needs capabilities for external fire environment perception and decision making.

After the use of artificial evacuation systems for modeling evacuation processes, we can design and perform controllable evacuation experiments with the computational experiment platform, which enables us to evaluate and quantitatively analyze various factors, especially human factors on evacuation efficiency, a difficult problem to address thus far. According to the problems and objectives of investigation, many existing experimental

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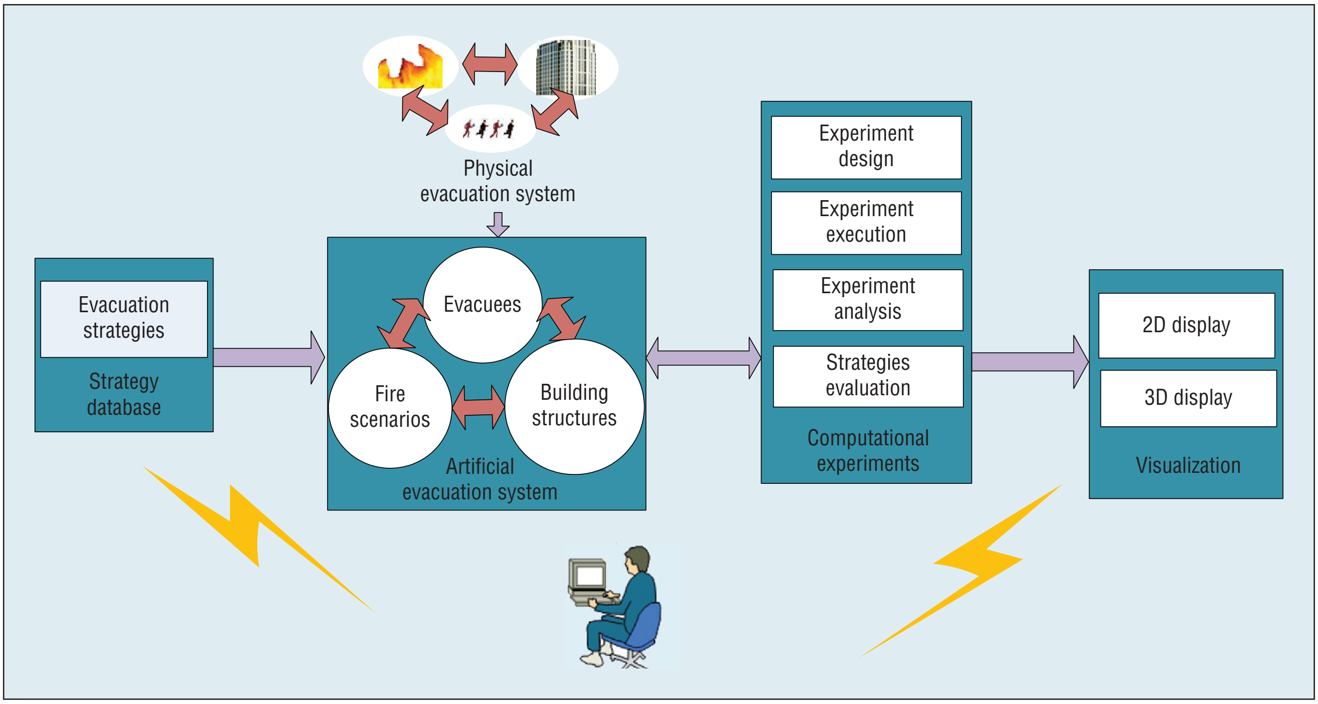

Figure 1. System framework. The main components are the strategy database, artificial evacuation system, computational experiment platform, and visualization output.

design theories and methods, such as single-factor or multifactor experimental design, orthogonal or uniform experiment design, and so on, can be utilized in evacuation computational experiments.[6]

The visualization is also an important part of our system. With the development of virtual reality technologies, visualization technologies can help us easily identify evacuation bottlenecks or congestion changes. That's helpful for improving or optimizing evacuation strategies.

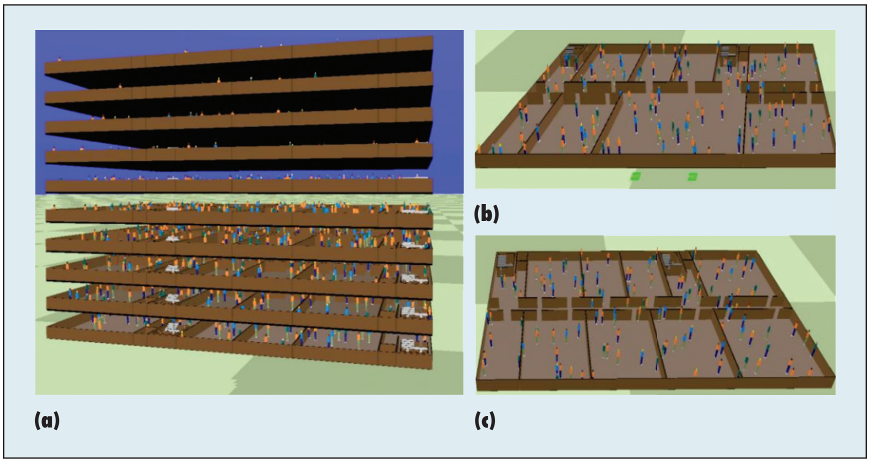

Figure 2. An artificial evacuation system with 3D display. (a) The whole building and evacuees, (b) the first floor, and (c) the second through tenth floors.

Strategy Evaluation

By integrating the agent, grid computing, and fire simulation technologies, we construct an artificial evacuation system (see Figure 2). The building structures, individual attributes, occupant distributions, and fire scenarios can be flexibly altered according to investigative needs or in reference to the actual evacuation systems. Figure 3 shows two representative fire scenarios to illustrate the developments of fire environments over time. Note that this environment information is perceived by individual agents and it affects their behaviors and movement capabilities in real time.

Evacuation strategies can by evaluated by applying them to artificial evacuation systems. Considering the strategies listed in Table 1, uncertainties or random factors are introduced by the Monte Carlo method and some statistical knowledge in experiments and evaluation.[7] With required safe egress time (RSET) as the key performance index, Figure 4 shows computational experimental results on two fire scenarios with different strategies. Clearly, the results show each strategy's evacuation efficiency while also revealing each fire scenario's effects.

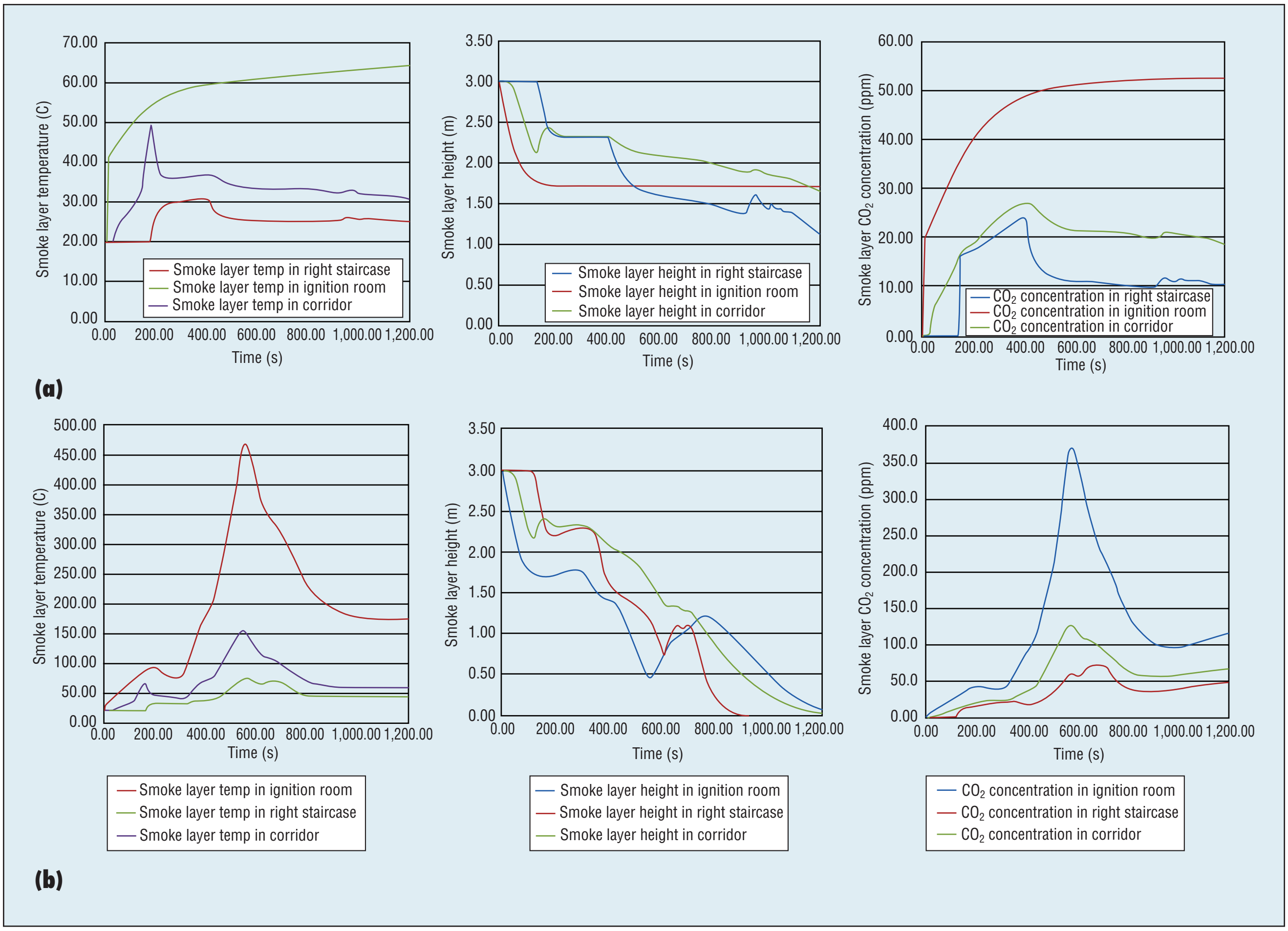

Figure 3. The evolution of smoke layer temperature, height, and carbon dioxide concentration in the ignition room, corridor, and nearby staircase. (a) The ignition location is set in the middle room on the third floor by main fire burning. (b) The ignition location is set on the left room near the staircase on the eighth floor by wooden panel burning. Here, ppm is the concentration unit (parts per million).

Table 1. Evacuation strategy database.

Strategy		Notes
Strategy1	The shortest-path evacuation	The shortest-distance export evacuation strategy.
Strategy2	Exit equal-density evacuation	Evacuee is evenly distributed to stairs or exits.
Strategy3	Fire floor prior evacuation	It combines with the shortest-distance export evacuation.
Strategy4	Fire floor prior evacuation	It combines with the exit equal-density evacuation.

Obviously, improved or optimal strategies can be obtained by such computational experiments and be used to train managers or drill occupants to alleviate the effect of disasters.

Evacuation Guidance

In our approach, the most significant function is to guide evacuation in real time. Considering the dynamics and uncertainties in evacuation processes, the data-driven parallel mechanism[8] between the actual evacuation systems and the artificial evacuation systems is important and useful.

In real-world applications, we can use the artificial evacuation systems to emulate the actual evacuation system for learning and training. Through analysis or evaluation of evacuees' behaviors on computers with artificial systems in advance, we can improve and optimize the actual evacuation process's performance. At the same time, various information and data collected by actual sensors can be used to calibrate the artificial

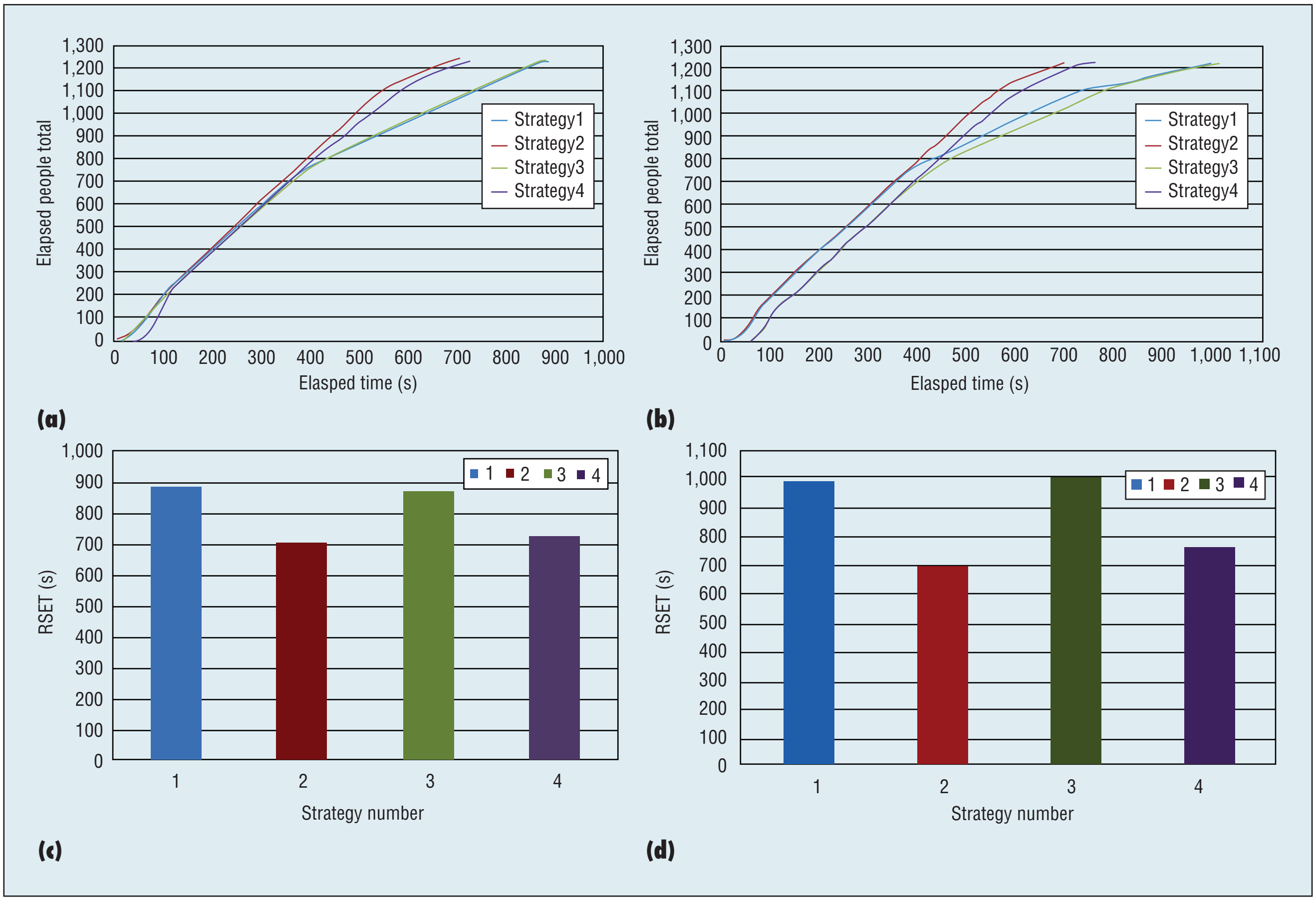

Figure 4. The results of a computational experiment, using four strategies in each scenario (refer to Table 1 for the strategies). (a) The relationship between elapsed time and the number of people who escaped in scenario 1. (b) The relationship between elapsed time and the number of people who escaped in scenario 2. (c) Required safe egress time (RSET) for the strategies in scenario 1. (d) RSET for the strategies in scenario 2.

evacuation systems and run them in parallel with actual evacuation processes in real time. Figure 5 shows the data-driven parallel mechanism.

The CPSS approach we proposed here provides a tool to verify or evaluate emergency evacuation plans. It enables operators to explore the possible consequences of decisions. In addition, by building a data-driven parallel mechanism between actual and artificial evacuation systems, this makes it possible to guide evacuation processes effectively in real time. We hope further work using this approach will significantly improve fire emergency management and public safety. ■

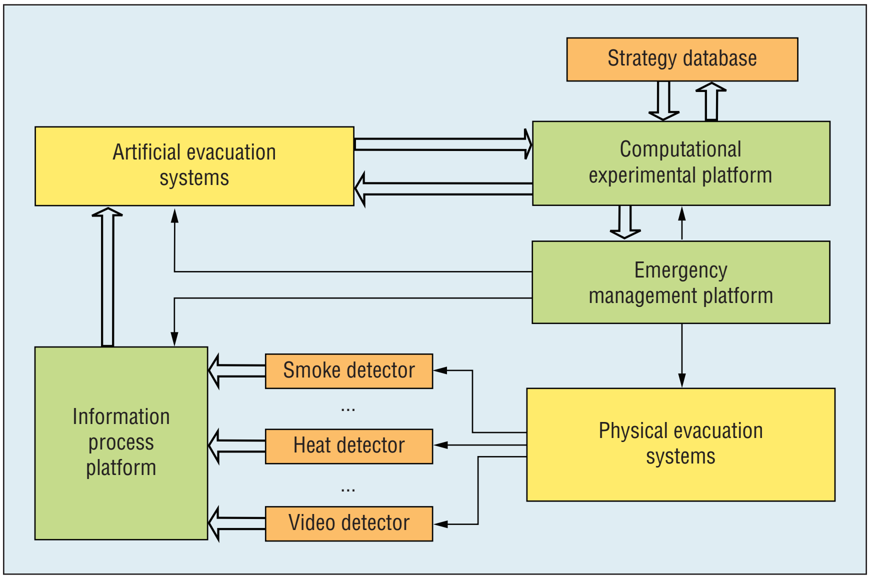

Figure 5. Data-driven parallel mechanism between artificial evacuation systems and physical evacuation systems.

Acknowledgments

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