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Simulation of the evacuation of passengers and crew from aircraft during a fire on the ground

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Abstract. *Background* Currently, incidents, including fires on board of aircrafts during takeoff and landing, are becoming more frequent. To address this issue, we introduce new models of fire propagation dynamics and the evacuation process for aircraft passengers, accounting for their physical interactions, along with an integrated model combining such processes as the spread of fire, smoke, and temperature. Nowadays aviation incidents involving onboard fires occur regularly, often resulting in traumas among passengers, as well as material damage. *Purpose* The main purpose of this study is to create integrated models that enable analysis of aircraft evacuation under various fire hazard scenarios. Much attention is given to using these models to analyze the process of leaving the aircraft, taking into account various scenarios of the spread of damaging fire factors, which will allow us to develop an optimal sequence of actions for each particular situation. *Method* It uses mathematical apparatus of the multi-dimensional cellular automata to describe fire spread, dividing the aircraft into cubic cells with 4 states: burning, burned, consisting of combustible, and non-combustible materials. Calculation of the probabilities of combustion is based on the influence of the neighboring cells, while evacuation models incorporate multi-agent approaches considering passengers' movements, physical contacts, and hazardous factor distributions. The model was created, and graphs were obtained using Python 3.12. *Results* The results indicate that the integrated model accurately simulates fire dynamics and evacuation interactions, allowing us to analyze different scenarios to make scenario-based predictions of optimal post-accident exit routes. The model was implemented for two scenarios: a fire in the left engine of the Embraer E-190 and Airbus A320-100 aircraft. *Conclusions* Based on the findings, it can be concluded that this approach facilitates decision support systems for enhancing safety during ground-based aircraft fires, providing the model for analyzing and minimizing risks in sudden emergencies.

Key words and phrases: multi-agent model, passenger evacuation, fire, aircraft

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1. Introduction

Aviation incidents involving fires on board of aircrafts are regularly recorded in Russia and worldwide [1–3]. Such incidents often result in injuries and even victims among passengers and crew members. Nevertheless, in nearly all cases, they cause substantial material damage [4].

Strict guidelines exist [5] that regulate the actions of the crew and passengers during aircraft evacuation. However, these guidelines are typically applicable in certain key details only to specific aircraft types and cannot be effectively implemented in a general context [6].

At the same time, it is important to note that analysis of statistical data reveals a notable trend driven by the increasing adoption of onboard decision support systems [7]. The relative proportion of “sudden” accidents, where there is virtually no time for decision-making, has been rising over the years compared to “anticipated” accidents, which allow sufficient time for preparing the aircraft for landing and subsequent evacuation [8].

In this field of research, we cannot ignore works about crowds in confined spaces [9, 10] and their behavior dictated by people’s psychological features [11–13]. However, these works don’t take into account the features of enclosed spaces such as the cabin of the aircraft.

Both domestic and international researchers conducted studies on modeling fire dynamics in confined spaces [14–17]. However, these works are primarily useful for analyzing individual hazardous factors. Some of the models considering people’s interaction neglect the effects of physical connection and inertial forces between agents [18, 19]. This limitation can be addressed through the application of integrated model research findings [20–23], although these models, in turn, do not account for the unique characteristics of fires occurring on board of aircrafts.

This determines the relevance of research focused on developing integrated models that allow simultaneous consideration of diverse hazardous factors during emergency landings (e.g., the spread of carbon monoxide, high combustion temperatures, flooding in water landings, and others). Such models can be employed to analyze the aircraft evacuation process under various scenarios of hazardous factor spreading, thereby allowing the development of optimal action sequences for each specific situation.

1.1. Structure of the paper

The article includes several sections, each addressing a specific aspect of the research:

The section “Theoretical Basis” defines models of spreading fire and carbon monoxide, and mathematical model of people evacuation from the plane.

The section “Results” presents the graphs obtained by application of the model in specific conditions.

The section “Discussion” summarizes the experimental findings.

The section “Conclusion” outlines the main outcomes and discusses directions for future research.

2. Theoretical Basis

2.1. Problem statement

The specific problem addressed in this study is the development of new models for the dynamics of fire propagation and the evacuation process of aircraft crew and passengers, taking into account their physical interactions. It also includes development of the integrated model that combines the processes of fire, smoke, and temperature spread with evacuation.

2.2. Proposed mathematical models of the spread of fire hazards on board an aircraft

2.2.1. Fire propagation model

We propose to use the mathematical framework of multidimensional cellular automata for describing the fire propagation process.

The aircraft, including the volume of the passenger cabin and the cockpit, is discretized into cubic cells. This yields a three-dimensional grid $A = \{a_{ijk} \mid 0 \le i < n,\ 0 \le j < m,\ 0 \le k < l\}$, where n, m, l denote the number of cubes along the horizontal, vertical, and height axes, respectively; c_{ijk} represents the elementary cube (EC) at coordinates (i, j, k).

Let

- F_t be the set of ECs where combustion is occurring at the given time instant.
- V_t be the set of ECs where the material has fully burned out, preventing any further combustion.
- M_t be the set of ECs where combustion is fundamentally possible due to the presence of combustible material but has not yet initiated at time t.
- N be the set of ECs where fire is impossible (non-combustible material).

The direction of fire propagation at time $t + 1$ is governed by the ignition probability P^t_{ijk} of an EC in state I_t (a state that subsequently assumes values from the aforementioned sets). The ignition probability of an EC can be determined via the expression:

$$P^t_{ijk} = \upsilon_{ijk} f^t_{ijk}\, dt/8l, \tag{1}$$

where υ_{ijk} is the fire propagation velocity of the material composing EC c_{ijk}; f^t_{ijk} is a parameter characterizing the state of neighboring ECs; and dt is the model time step.

The parameter f^t_{ijk} is calculated using the formula:

$$f^t_{ijk} = 3q^t_{ijk1} + 2q^t_{ijk2} + q^t_{ijk3},$$

where q^t_{ijk1} is the number of ECs sharing a face with the considered EC, where combustion is occurring at time t. Their coordinates (see Table 1): $(i, j, k+1)$, $(i-1, j, k)$, $(i, j-1, k)$, $(i, j+1, k)$, $(i+1, j, k)$, $(i, j, k-1)$;

q^t_{ijk2} is the number of ECs sharing an edge but not a face with the considered EC, where combustion is occurring at time t. Their coordinates (see Table 1): $(i-1, j, k+1)$, $(i, j-1, k+1)$, $(i, j+1, k+1)$, $(i+1, j, k+1)$, $(i-1, j-1, k)$, $(i-1, j+1, k)$, $(i+1, j-1, k)$, $(i+1, j+1, k)$, $(i-1, j, k-1)$, $(i, j-1, k-1)$, $(i, j+1, k-1)$, $(i+1, j, k-1)$;

q^t_{ijk3} is the number of ECs sharing a vertex but neither an edge nor a face with the considered EC, where combustion is occurring at time t. Their coordinates (see Table 1): $(i-1, j-1, k+1)$, $(i-1, j+1, k+1)$, $(i+1, j-1, k+1)$, $(i+1, j+1, k+1)$, $(i-1, j-1, k-1)$, $(i-1, j+1, k-1)$, $(i+1, j-1, k-1)$, $(i+1, j+1, k-1)$.

The parameter f^t_{ijk} can take one of the values 0, 1, 2, ..., 50, determined according to the following principle (see Fig. 1 and Table 2).

Each non-boundary elementary cube has:

- 6 ECs sharing a common *face* with the considered EC, and each of these six takes the value 3.
- 12 ECs sharing a common *edge but not a face* with the considered EC, and each of these 12 takes the value 2.
- 8 ECs sharing a common *vertex but not a face or edge* with the considered EC, and each of these 8 takes the value 1.

Table 1

Coordinates of neighboring elementary cubes to the considered one

Upper row of EC			**Middle row of EC**			**Lower row of EC**		
(i-1, j+1, k+1)	(i, j+1, k+1)	(i+1, j+1, k+1)	(i-1, j+1, k)	(i, j+1, k)	(i+1, j+1, k)	(i-1, j+1, k-1)	(i, j+1, k-1)	(i+1, j+1, k-1)
(i-1, j, k+1)	(i, j, k+1)	(i+1, j, k+1)	(i-1, j, k)	(i, j, k)	(i+1, j, k)	(i-1, j, k-1)	(i, j, k-1)	(i+1, j, k-1)
(i-1, j-1, k+1)	(i, j-1, k+1)	(i+1, j-1, k+1)	(i-1, j-1, k)	(i, j-1, k)	(i+1, j-1, k)	(i-1, j-1, k-1)	(i, j-1, k-1)	(i+1, j-1, k-1)

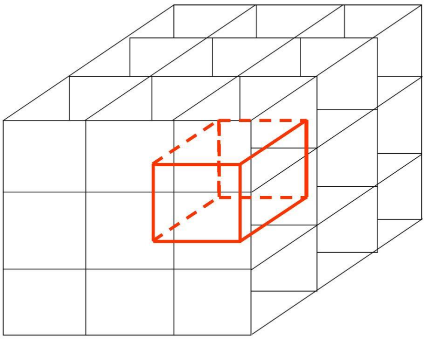

Figure 1. Graphical representation of the EC (highlighted in red) and all its neighboring elementary cubes

f_{ijk}^{t} will be equal to the sum of the values of neighboring burning ECs.

This value is chosen based on the fact that the distance between the centers of ECs sharing a common *face* with the considered EC is smaller than the distance between the centers of ECs sharing a common *edge*. At the same time, it is still smaller than between the centers of ECs sharing a common *vertex* with the considered EC.

For edge ECs, the parameter f_{ijk}^{t} can take a value from the set $\{0, 1, 2, \dots, 35\}$, and for corner ones — from $\{0, 1, 2, \dots, 24\}$.

The elementary cube transitions from the burning state at moment t to the burned state at $t+1$, if no combustible mass remains in it. For each EC a_{ijk}, the mass of combustible substance m_{ijk} and burning speed v_{ijk} are specified.

The mass of the combustible substance of the combustible material m_{ijk} is determined as follows:

$$m_{ijk}^{t+1} = m_{ijk}^{t} - v_{ijk}\, dt.$$

Figure 2 shows an example of fire propagation on board a twin-engine aircraft.

2.2.2. Carbon monoxide propagation model

In the proposed model, the mass of combustible material in each burning EC changes according to the relation

$$m_{ijk}^{t+1} = m_{ijk}^{t} - v_{ijk}\, dt.$$

Table 2

Values of the terms in the parameter f_{ijk}^t for neighboring elementary cubes

Upper row of EC			**Middle row of EC**			**Lower row of EC**		
1	2	1	2	3	2	1	2	1
2	3	2	3	EC	3	2	3	2
1	2	1	2	3	2	1	2	1

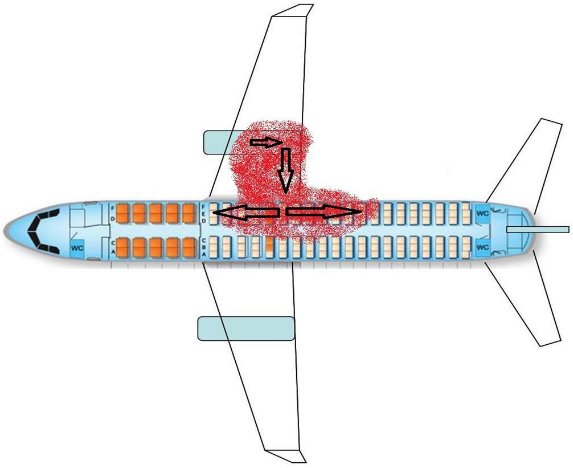

Figure 2. Dynamics of fire propagation on board an aircraft during an engine fire

During combustion, carbon monoxide is emitted. The volume of this emission depends on the type of material being burned. The density of carbon monoxide μ_{ijk} in the elementary cube a_{ijk} increases according to the relation:

$$\mu_{ijk}^{t+1} = \mu_{ijk}^{t} + U_{ijk} v_{ijk}\, dt/h^3,$$

where U_{ijk} is the CO emission coefficient of the burning material, h^3 is the cell volume.

The propagation of carbon monoxide is determined by the expression:

$$\mu_{ijk}^{t+1} = \mu_{ijk}^{t} + d'_{ijk} \sum_{s \in S'_{ijk}} d'_s(\mu_s^t - \mu_{ijk}^t),$$

where d'_{ijk}, d'_s are coefficients regulating the rate of carbon monoxide propagation; μ_s^t is the density of carbon monoxide for EC.

2.3. Mathematical model of the evacuation process of people from the aircraft

In the proposed mathematical model of the evacuation process, the following objects will be considered:

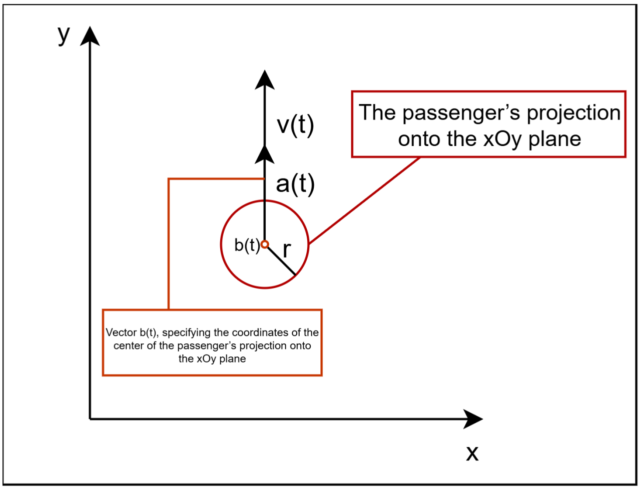

Figure 3. Model of the passenger projected onto the xOy plane

1. A finite set of obstacles in the aircraft cabin, each represented by parameters: (x_W, y_W) are the coordinates of the lower left corner, x_{WW} and y_{WW} — their length and width, respectively.
2. A finite set of exits from the aircraft, specified by the coordinates of the lower left corner (x_E, y_E), width and length of the opening x_{WE} and y_{WE}. The exit zone outside of the aircraft should be located at some distance from the door opening, as after exiting the aircraft, the passenger in some cases still influences the evacuation process.
3. A finite set of evacuating passengers, which we will consider as a set of their projections onto the xOy plane in the form of circles (see Figure 3). The coordinates of these passengers are the centers of the corresponding circles.
4. A finite set of evacuation zones, each specified by parameters: (x_Z, y_Z) are the coordinates of the lower left corner of the evacuation zone, x_{WZ} and y_{WZ} — its length and width, respectively. It is assumed that passengers are located within these zones at the initial moment of evacuation.

The parameters considered in the model for passengers (or agents in terms of multi-agent systems theory):

- vector $b(t)$, specifying the coordinates of the center of the passenger's projection onto the xOy plane.
- r — projection radius.
- m — human mass.
- $v(t)$ — velocity vector of movement.
- $a(t)$ — acceleration vector of movement.
- $v_{\max}$ — maximum possible speed.
- $a_{\max}$ — maximum possible acceleration.

Figure 3 shows the passenger's projection onto the xOy plane.

In the proposed model, the law of motion for passengers is determined by the relations:

$$b(t+\Delta t) = b(t) + v(t)\Delta t,$$
$$v(t+\Delta t) = v(t) + a(t)\Delta t,$$

where Δt is the model time step.

Passenger speeds change during collisions. We will consider collisions as partially elastic impacts. To describe a partially elastic collision, we introduce a restitution coefficient $0 \le R \le 1$. We calculate the normal components of the motion velocities to the common tangent plane to the surfaces of the colliding bodies at their contact point (collision plane) after the impact in a partially elastic impact using the formulas:

$$p_{1n} = -Rv_{1n} + (1+R)\frac{m_1 v_{1n} + m_2 v_{2n}}{m_1 + m_2}, \qquad p_{2n} = -Rv_{2n} + (1+R)\frac{m_1 v_{1n} + m_2 v_{2n}}{m_1 + m_2}. \tag{2}$$

Here, v_{1n} and v_{2n} are the normal projections of the passengers' motion velocities to the collision plane before the impact, and p_{1n} and p_{2n} are the normal projections of the passengers' motion velocities to the collision plane after the impact; m_1 and m_2 are the masses of the colliding agents. We assume that the tangential projections of the velocities to the collision plane do not change during the impact.

When a passenger collides with an obstacle, the projection of their motion velocity that is in parallel to the obstacle does not change. The other projection changes its sign to the opposite and decreases its value depending on R.

Let us determine the direction of the acceleration vector $a(t)$ for each passenger, assuming that each strives to reach the nearest aircraft exit as quickly as possible. For this, let us introduce the concept of the optimal (from the passenger's perspective) velocity vector $v_{\text{opt}}(t)$, approximating the passenger to the chosen exit and allowing avoidance of collisions with obstacles such as the other passengers and obstacles. Also, the actual speed and direction of the agent's movement $v(t)$ may change due to these collisions. Then, it can be considered that passengers move with acceleration $a(t)$, whose absolute magnitude depends on physical capabilities: $|a(t)| = a_{\max}$, and the direction matches with the direction of $v_{\text{opt}}(t) - v(t)$. If $v_{\text{opt}}(t) = v(t)$, it is considered that the agent moves without acceleration. The absolute magnitude of acceleration is always at its maximum value, except in the cases when the passenger is already moving with maximum speed. It can be explained by the *stressful* situation and the passenger's desire to leave the aircraft as quickly as possible.

The absolute magnitude of the optimal velocity $v_{\text{opt}}(t)$ is bounded above by the agent's physical capabilities, namely the speed $v_{\max}$. If there are no obstacles ahead along the route, then $|v_{\text{opt}}(t)| = v_{\max}$. To avoid collision with other agents along the route, the absolute magnitude $|v_{\text{opt}}(t)|$ may decrease.

Let us consider the approach to choosing the vector $v_{\text{opt}}(t)$. Let w be the vector specifying the direction to the nearest exit, accounting for the cabin layout. The vector w is an attribute of the space cell where the agent is located and is determined by the positions of obstacles and exit zones. Let h_γ be the distance from the agent's center to the nearest obstacle in the motion direction at angle γ to w, B is the given critical distance, r is the radius of the passenger's projection onto the xOy plane.

Consequently, the absolute magnitude of the optimal speed $v_{\gamma\text{opt}}(\gamma)$ of the passenger in the motion direction at angle γ to the vector w can be calculated by formula:

$$v_{\gamma\text{opt}}(\gamma) = \begin{cases} v_{\max} & \text{if } h_\gamma \ge B + r, \\ \frac{v_{\max}(h_\gamma - r)}{B} & \text{if } r \le h_\gamma \le B + r, \\ 0 & \text{if } h_\gamma \le r. \end{cases}$$

Passengers' physical capabilities vary, so each passenger must have individual values of $v_{\max}$ and $a_{\max}$.

Let us introduce the function $g(\gamma)$:

$$g(\gamma) = v_{\gamma\text{opt}}(\gamma)\cos(\gamma), \quad \gamma \in [-\pi/2, \pi/2]. \tag{3}$$

It can be inferred from formula (3) that the angle α between the vectors v_{opt} and w is defined as the angle at which the function $g(\gamma)$ is maximal.

The absolute magnitude of v_{opt} determined as:

$$|v_{\text{opt}}| = v_{\gamma\text{opt}}(\alpha).$$

The presented method for choosing v_{opt} allows the agent to maneuver between other agents, aiming to avoid collisions and approach the nearest exit faster (assuming the passenger knows where the exit is).

Thus, the choice of the optimal velocity vector v_{opt} accounts for the cabin layout and the positions of other agents. This vector must be recalculated for each passenger at each model time step Δt. Agents also exhibit additional properties such as heterogeneity due to differences in their mass and projection radius, as well as goal-directedness, since all presented passengers strive to exit the aircraft cabin.

Furthermore, we have to consider the impact of carbon monoxide spreading on the velocity of agents. This impact can be calculated by formula:

$$v'_{\max} = \begin{cases} v_{\max}, & \text{if } \mu_{ijk} \le 0.1, \\ v_{\max} \cdot \max\left(0.6,\ 1 - 1.1 \cdot \mu_{ijk}\right), & \text{if } \mu_{ijk} > 0.1. \end{cases}$$

It should be noted that the presented model also includes known attributes such as the angle and range of the agent's view of the surrounding space, moment of inertia, and head rotation angle. The direction leading the agent to the exit (considering obstacles) is determined by the vector w. The agent's view angle can be considered equal to 180°, since $\gamma \in [-\pi/2, \pi/2]$, i.e., the agent analyzes all possible alternatives for movement in the plane ahead.

Since the agent calculates the optimal speed values based on analyzing the situation within the critical zone, the agent's view range is at least B.

Part of the energy during impact transfers to rotational motion. In the model, these energy losses are accounted for by the restitution coefficient.

2.4. Algorithm for modeling the evacuation process

We created an algorithm for modeling emergency situations (an event of fire on the ground in our case) consisting of such steps:

1. Input initial data: cabin dimensions, coordinates of obstacles, exits from the cabin, number of agents and their parameters.
2. Generate agents inside evacuation zones according to seating positions.
3. Calculate v_{opt} for each agent.
4. Calculate a for each agent.
5. Calculate v for each agent.
6. Calculate b for each agent.
7. Check for collisions for each pair of agents. If a collision occurs, recalculate velocities.
8. Check collisions with obstacles for each agent. If a collision occurs, recalculate velocities.
9. Check the condition for reaching the emergency exit for each agent. If the agent has reached the exit, exclude them from the list.

10. Collect and store statistics. If no passengers remain in the cabin, proceed to step 12.
11. Proceed to the next model time step. Go to step 3.
12. Display the results of the experiments (graphs of functions).
13. Go to step 1 (upon user request).

The model is created according to this algorithm.

3. Results

The model was built using Python 3 according to the proposed theoretical basis, the application of the mathematical apparatus of multidimensional cellular automata, and the rules of mathematical models of fire and carbon monoxide propagation. Also, a mathematical model of the evacuation of passengers was implemented.

All of the mentioned models were integrated into the program according to the algorithm suggested in Section 2.4.

The results include graphs of the dependence between the time and passengers evacuated, as well as of the dependence between the time and burned cubes.

The scenario of the model is the combustion of the left engine of an aircraft. One of the model conventions is the fact that the fire begins its propagation from the cabin (exactly from the part of the cabin in front of the left engine).

The graphs introduced for the aircraft models, such as the Embraer E-190 with 100 seats and a full load of passengers and the Airbus A320-100 with 150 seats and also a full load of passengers.

Let us introduce the common parameters of the model for Airbus A320-100 and Embraer E-190. (see Table 3).

As we can observe, the parameters in question are primarily relevant to passengers and the general model configuration. A uniform distribution is set for the parameters that are calculated at each step of the algorithm.

Also, there are differing parameters to consider (see Table 4).

Figures 4 , 5 display the dynamic of evacuation from the aircraft and fire propagation via displaying the cubic cells that have been burned.

In comparing the scenarios for the Embraer E-190 and Airbus A320-100, it is noted that the bigger A320, accommodating 50% more passengers and featuring a broader cabin, requires approximately 50 seconds longer for total evacuation (140 seconds against 90 seconds). Meanwhile, the fire extends to 43 additional burned cells, and the time increases to 140 seconds, illustrating how larger cabin volume and passengers' capacity affect the model. The uniform distribution applied for parameters like v_{max}, a_{max}, r and m makes this model and the result more realistic. These findings highlight the vital role of right exits and evacuation zone locations.

4. Discussion

The results obtained from the integrated model show that combining cellular automata for fire and carbon monoxide propagation with the dynamics of agent evacuation provides a method to predict the evacuation process from aircraft in the event of a fire on the ground.

For example, in the Embraer E-190 case (Fig. 4), 100 passengers could evacuate in about 90 seconds when only 94 cubic cells was burned. As the maximum count of burning EC is 528, and for this time only 94 of them were burned, this time is enough to evacuate all of the passengers without injuries.

Table 3

Common parameters of the E190 and A320 models

Parameter	**Value**	**Description**
Cell size	0.5 m	Size of elementary cube (EC) in meters
Time step Δt	0.05 s	Model time step
Restitution coefficient R	0.2	Coefficient for collision handling
Critical distance B	2.0 m	Distance for optimal velocity calculation
Initial temperature	20°C	Initial EC temperature
Maximum agent velocity $v_{\max}$	1.2–1.8 m/s (uniform distribution)	Maximum speed of agents
Maximum acceleration $a_{\max}$	2.0–4.0 m/s^2 (uniform distribution)	Maximum acceleration of agents
Reaction time	0–8 s (uniform distribution)	Delay before agent starts moving
Agent radius r	0.20–0.28 m (uniform distribution)	Radius of projection for agents
Agent mass m	50–90 kg (uniform distribution)	Mass of agents

Table 4

Differing parameters of the E190 and A320 models

Parameter	**E190 Value**	**A320 Value**
Aircraft model	Embraer E190	Airbus A320-100
Number of passengers	100	150
Cabin length	25.0 m	27.5 m
Cabin width	2.74 m	3.70 m
Cabin height	2.0 m	2.22 m
Grid size	52 x 7 x 6	57 x 9 x 6
Engine fire position	(26, 0, 0)	(28, 0, 0)
Max. burning EC	528	682
Number of exits	4	6
Seat configuration	2+2	3+3

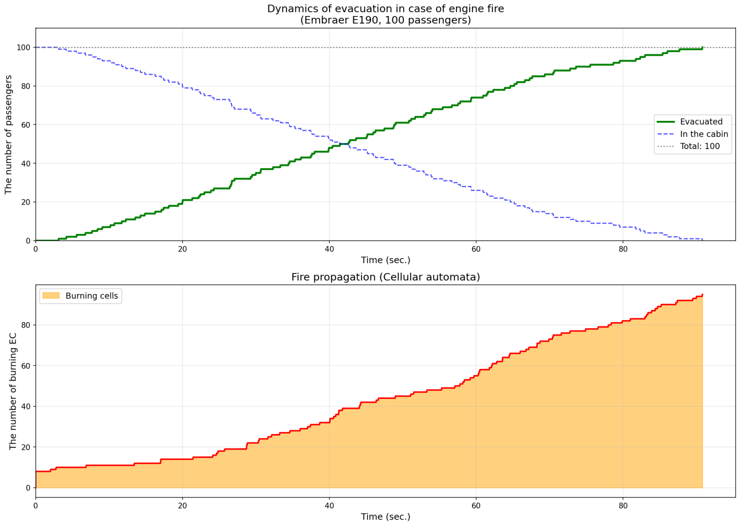

Figure 4. Dynamic of evacuation from the aircraft / fire propagation for Embraer E-190

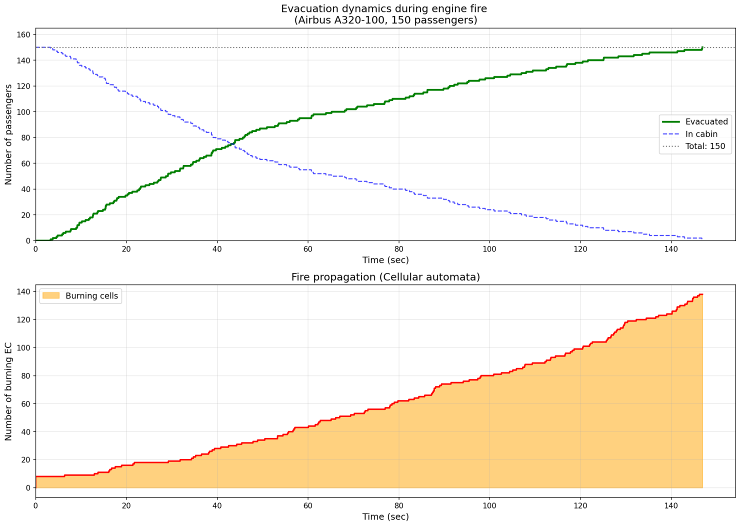

Figure 5. Dynamic of evacuation from the aircraft / fire propagation for Airbus A320-100

At the same time, the Airbus A320-100 scenario (Fig. 5) took longer, around 140 seconds for 150 passengers with 137 cells affected. These results are obtained because of the larger cabin and more people involved.

The fire spread follows a smoothly growing curve due to the mechanism of neighbor influences in the automata, as does the curve of evacuation in both cases. It follows from this that physical interactions, like passenger collisions handled through restitution coefficients (Eq. (2)), and hazard progression (Eq. (1)) lead to accurate and realistic results of the model.

There are no major deviations in the graphs. The variability of the random starting conditions (e.g., reaction times 0–8 s) confirming the model's stability. The suggested approach stands out by its simple adaptation to aircraft specifics and could feed into real decision-support tools to cut down on casualties in the "sudden" incidents.

There is a perspective for the future work, as could be added more data for the output in the model, such as detailed temperature maps, a map of cabin and burned cubes etc. Overall, this research enhances the importance of comprehensive models for aviation safety. This research could reduce sudden accidents by generating results for different scenarios and considering them when designing aircraft.

5. Conclusion

A complex of mathematical models and algorithms has been developed that enables the simulation of situations arising during aircraft fires, the calculation of the dynamics of hazardous fire factors, and passenger evacuation under the spread of these factors.

The integrated model of the dynamics of hazardous fire factors development and the process of evacuating passengers and crew from the aircraft is built on the basis of the mathematical apparatus of cellular automata and multi-agent systems.

It is proposed to use the integrated model for analyzing the process of leaving the aircraft, taking into account various scenarios of the spread of fire's hazardous factors, which will allow developing optimal lists of actions for each specific situation.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. Conceptualization, Aleksandr S. Baklashov and Leonid Yu. Filimonyuk; methodology, Leonid Yu. Filimonyuk; software, Aleksandr S. Baklashov; validation, Aleksandr S. Baklashov and Leonid Yu. Filimonyuk; formal analysis, Leonid Yu. Filimonyuk; investigation, Aleksandr S. Baklashov and Leonid Yu. Filimonyuk; resources, Aleksandr S. Baklashov; data curation, Aleksandr S. Baklashov; writing—original draft preparation, Leonid Yu. Filimonyuk; writing—review and editing, Aleksandr S. Baklashov; visualization, Aleksandr S. Baklashov; supervision, Leonid Yu. Filimonyuk.; project administration, Leonid Yu. Filimonyuk. All authors have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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References

1. *Report of the Interstate Aviation Committee on the Results of the Investigation of the Aviation Accident. Airbus A-310 Catastrophe* tech. rep. (Interstate Aviation Committee, 2006).
2. Suharev, A., Šestakovs, V. & Vinogradov, L. Estimation of evacuation time of passengers in aircraft accidents with fire in airfield areas. *Aviation* **24,** 72–79. doi:10.3846/aviation.2020.12653 (July 2020).
3. *Report of the Interstate Aviation Committee on the Results of the Investigation of the Aviation Accident. An-24RV Catastrophe* Russian. Tech. rep. (Interstate Aviation Committee, 2011).
4. Wang, J., Tao, Z., Yang, R., Gao, Z., Shan, D. & Wang, W. A review of aircraft fire accident investigation techniques: Research, process, and cases. **153.** doi:10.1016/j.engfailanal.2023.107558 (2023).

5. Butcher, N., Barnett, J. & Buckland, T. *Emergency evacuation of commercial passenger aeroplanes* June 2020.
6. Choochart, P. & Thipyopas, C. Study of Passenger Evacuation from the Airbus A330-300 Aircraft. *Proceedings* **39.** doi:10.3390/proceedings2019039025 (2019).
7. Lv, W., Xing, L., Li, J., Zhao, C. & Yang, Y. Evaluating personnel evacuation risks under fire scenario of Airbus wide-body aircraft: A simulation study. English. *Frontiers in Public Health* **10.** doi:10.3389/fpubh.2022.994031 (Sept. 2022).
8. Boyd, D. D. & Howell, C. Accident Rates, Causes, and Occupant Injury Involving High-Performance General Aviation Aircraft. *Aerospace Medicine and Human Performance* **91,** 387–393. doi:10.3357/AMHP.5509.2020 (May 2020).
9. Winter, H. Modelling Crowd Dynamics During Evacuation Situations Using Simulation, 20 (2012).
10. Beklaryan, A. Exit Front in the Model of Crowd Behavior in Emergency Situations. Russian. *Bulletin of Tambov University. Series: Natural and Technical Sciences* **20,** 851–856 (2015).
11. Cherif, F. & Chighoub, R. Crowd simulation influenced by agent's socio-psychological state. *Journal of computing* **2,** 48–54 (2010).
12. Henderson, L. F. The statistics of crowd fluids. *Nature* **229,** 381–383 (1971).
13. Helbing, D., Farkas, I. & Vicsek, T. Simulating dynamical features of escape panic. *Nature* **407,** 487–490 (2000).
14. Fedosov, S., Ibragimov, A., Solov'ev, R., *et al.* Mathematical Model of Fire Development in a System of Premises. Russian. *Vestnik MGSU,* 121–128 (2013).
15. Drysdale, D. *Introduction to Fire Dynamics* Russian. 424 pp. (Stroyizdat, 1990).
16. Apiecionek, L., Zarzycki, H., Czerniak, J., *et al.* The Cellular Automata Theory with Fuzzy Numbers in Simulation of Real Fires in Buildings. *Advances in Intelligent Systems and Computing* **559,** 169–182 (2018).
17. Zhang, Y., Yang, Z. & Sun, Z. A dynamic estimation method for aircraft emergency evacuation based on cellular automata. *Advances in Mechanical Engineering* **11,** 12. doi:10 . 1177 / 1687814019825702 (2019).
18. Akopov, A. S. & Beklaryan, L. A. An agent model of crowd behavior in emergencies. **76,** 1817–1827. doi:10.1134/S0005117915100094 (Oct. 2015).
19. Korepanov, V. O. Simulation models of agents' tactical behavior. *Management of large systems: collection of works,* 145–157 (2009).
20. Samartsev, A. *et al.* Mathematical Model of the Dynamics of Fire Development in Premises. Russian. *Large-Scale Systems Control,* 42–62 (2018).
21. Samartsev, A. *et al.* Fire and Heat Spreading Model Based on Cellular Automata Theory. *Journal of Physics: Conference Series* **1015,** 5 (2018).
22. Göttlich, S., Kühn, S., Ohst, J. P., Ruzika, S. & Thiemann, M. Evacuation dynamics influenced by spreading hazardous material. *Networks and Heterogeneous Media* **6,** 443–464. doi:10.3934/nhm.2011.6.443 (2011).
23. Korolchenko D.A., P. S. Introduction of a flame suppression pattern into integrated and zone models used to analyze the dynamics of hazardous factors of indoor fires. Russian. *Fire and Explosion Safety* **30,** 78–87. doi:10.22227/PVB.2021.30.02.78-87 (May 2021).

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Моделирование эвакуации пассажиров и экипажа из воздушных судов при пожаре на земле

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Аннотация. *Предпосылки* В настоящее время происшествия, в том числе пожары на борту самолёта при взлете/посадке, возникают всё чаще. Для исследования этой проблемы в статье представлены новые модели динамики распространения пожара и процесса эвакуации пассажиров воздушного судна с учётом их физического взаимодействия, а также интегрированная модель, объединяющая процессы, такие как распространение огня, дыма и температуры. *Цель* Основная цель данного исследования заключается в создании комплексных моделей, позволяющих анализировать процесс эвакуации из воздушного судна при различных сценариях. Особое внимание уделяется использованию этих моделей для анализа процесса покидания самолёта с учётом различных сценариев распространения поражающих факторов пожара, что позволит разработать оптимальную последовательность действий для каждой конкретной ситуации. *Методы* Для описания распространения огня используется математический аппарат многомерных клеточных автоматов, разделяющих воздушное судно на кубические ячейки, которым присваиваются 4 различных состояния: горения, выгоревшего, состоящего из горючего и негорючего материалов. Вероятности возгорания рассчитываются на основе влияния соседних ячеек, а модели эвакуации объединяют в себе мультиагентные подходы, учитывающие движения пассажиров, физические контакты и распределения опасных факторов. Модель была создана и графики получены с использованием языка программирования Python 3.12. *Результаты* Результаты показывают, что интегрированная модель точно симулирует динамику пожара и действия пассажиров при эвакуации. Также она позволяет анализировать различные сценарии для прогнозирования оптимальных путей эвакуации после аварии. Модель была реализована для двух сценариев: возгорания в левом двигателе самолётов Embraer E-190 и Airbus A320-100. *Заключение* В заключение можно констатировать, что предложенный подход способствует разработке систем поддержки принятия решений, необходимых для повышения безопасности при пожарах на воздушных судах на земле, предлагая модель для анализа и минимизации рисков в условиях внезапных чрезвычайных ситуаций.

Ключевые слова: мультиагентная модель, эвакуация пассажиров, пожар, воздушное судно