Model of settlement evacuation based on the imitation modelling application

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Abstract. The relevance of the research is that despite the already studied method of evacuation modeling, it is not widely used, especially in Russia. There is also a tendency to an increasing destructive capacity of the heart rate, which increases the probability of complete evacuation of the population and material assets. The purpose of this article is to develop and test a simulation model that allows you to calculate the characteristics of a locality and transport infrastructure, allowing you to predict the process of evacuation in advance of the appearance of negative emergency factors. The model was developed based on the Anylogic software product. As a result of the experiments, indicators were obtained, which can be used to make a conclusion about the possibility of evacuation in the selected locality.

1. Introduction
The modern world can be characterized as the most exposed to emergencies era of humanity, because besides natural often occur quite powerful man-made disasters, which can cause great harm and kill many people [1]. When localizing the dangerous factors of an emergency or protect of the population are impossible, it becomes necessary to evacuate people to safe areas.

Determining the safe areas, to which evacuation will be made, is guided mainly by the absence of dangerous factors of an emergency there. At the same time, not enough attention is paid directly to the transport infrastructure, which will be followed by evacuation vehicles.

A number of methods have been found in foreign literature that allows us to consider the escape routes capacity [2, 3, 4, 5]. In most cases, the method of imitation modeling is used [2, 3].

Modeling is a method of studying a complex object by transferring its significant properties to an object that is easier to study [6, 7]. Thus, there is an abstraction from the set of small, but complicating characteristics of the system, leaving only the important ones.

Imitation modelling consists in recalculating the condition of system elements according to certain rules [8]. The choice of this method is conditioned from the fact, analytical method is that, the programmer creates the formula for each element, not for the entire system for all time of its work, which is quite a time consuming process.

The relevance of the study , despite the already studied method of modeling evacuation, is not widely used, especially in Russia, where there is not much research on the topic under consideration. There is also a tendency to an increasing destructive capacity of emergencies, which increases the probability of complete evacuation of the population and property. This requires a more complete approach to planning not only the evacuation process, but also urban planning.
The purpose of this article is developing and testing a method that allows to calculate the characteristics of localities and transport infrastructure, allowing to predict the process of evacuation in advance of the appearance of negative emergency factors.

2. Problem statement
The authors have formulated the modeling problem, which is presented in the form of a "black box" (figure 1).

![Figure 1. Formulating the modeling problem.](image)

The flow of cars with a certain intensity \( W \) considered as an input stream of events. The output parameters are the following variables:
- dam congestion, characterized by the number of vehicles per unit of time;
- queue length \( L \);
- number of evacuees \( N_{\text{evac}} \);

The object of the simulation is the evacuation of the city of Kronstadt. The choice is explained by the unusual transport infrastructure of the locality, that it is located on the island of Kotlin, from which there are only 2 roads.

The island is part of the complex of protective structures of Saint Petersburg. But it is not protected from the Western side, which leads to frequent flooding of this territory. The danger of flooding in the Eastern part of the island, where the city of Kronstadt is located, is minimized by earthen protective ramparts, some of which were built more than 100 years ago, and whose height does not exceed 11 m above sea level [9].

Will take for the population of Kronstadt (\( N \)) – 43687 people (2017 y.) [10]

This value will be taken as the number of people who are on the island at night, regardless of the time of year, as well as on weekends and holidays outside of the tourist season.

According to statistics, 8.2 million people visited Saint Petersburg in 2018 [11]. If we assume that a quarter of these tourists visited the city of Kronstadt, then, consequently, about 5.5 thousand people came to the city every day. (\( N_{\text{tour}} \)). Since no information was found for tourists depending on the time of year, \( N_{\text{tour}} \) is the average value for the entire year, but the main tourist flow is during the warm season.

Based on this, we take the average maximum number of people on the island (\( N_{\text{av}} \)) = 49000 people.

The road capacity is determined according to ODM 218.2.020-2012 "Guidelines for assessing road capacity" [12]. The model will use the maximum theoretical values provided in these recommendations.

As the transport involved for transporting evacuees, we will consider those vehicles that are used on routes on the island. Kotlin, as well as attracted from fleets on the continent.

Currently Kronstadt is served by the following vehicles: Golden Dragon XML6125CR (95 people), MA3-103 (98 people), JinA3-5292 (112 people), HeФA3-52994 (105 people), KАn3-4270 (84 people), Lotos 206 (72 people), Volkswagen Crafter (13 people) [13].

Take 90 people as the average vehicle capacity.

There is also a fleet 20 km away, where additional vehicles can be reached in 15 min. from.

Based on the calculation that the entire evacuation will be carried out by buses, about 540 vehicles will be required. Given the fact that other localities also be evacuated, the city will not be fully provided with this type of transport. Therefore, we should assume that some of them will be evacuated.
by private transport. Let's take 25,000 people as the new number of evacuees. Then about 270 buses are needed, which takes into account the presence of another bus fleet 40 km from the city. Kronstadt (the calculation of the number of buses in the fleets was performed from satellite images), vehicles removed from routes in the continental part of the city, also military vehicles, it is considered that the funds are sufficient for a complete evacuation of the population.

There will be no consideration of other modes of transport, since the most likely cause of evacuation will be a surge due to strong winds, which will interfere with the use of aircraft and water vessels.

3. Methods

To implement this task, the authors use the AnyLogic software product, which is developed on the basis of modern concepts in the field of information technology and research results in the theory of hybrid systems and object-oriented modeling. This is a comprehensive tool that covers the main areas of modeling currently in one model: discrete-event, system dynamics, and agent-based [14].

A imitation model in the AnyLogic environment is made up of blocks located in the "model components Palette", which consists of libraries for various thematic sections. In this paper, only the process modeling library will be considered. The elements used are described in table 1.

| Name         | Graphical representation | Description of the block's operation |
|--------------|--------------------------|-------------------------------------|
| Source       | out                      | Generates agents. Is usually a starting point of a process model. There is a number of ways to define when and how many agents should be generated. |
| Sink         | in                       | Disposes agents. Is usually an end point in a process model. |
| Delay        | in, out                  | Delays agents for a given amount of time. The delay time is evaluated dynamically, may be stochastic and may depend on the agent as well as on any other conditions. |
| Queue        | outPreempted, outTimeout | A queue (a buffer) of agents waiting to be accepted by the next object(s) in the process flow, or a general-purpose storage for the agents. Optionally, you may associate a maximum waiting time with an agent. You can also remove agents programmatically from any position in the queue. Routes the incoming agents to one of the two output ports depending on (probabilistic or deterministic) condition. The condition may depend on the agent as well as on any external factors. |
| SelectOutput | in, outF, outT           | Routes the incoming agents to one of the two output ports depending on (probabilistic or deterministic) condition. The condition may depend on the agent as well as on any external factors. |
| PedSource    | out                      | Generates pedestrians. Is usually used as a starting point of the pedestrian flow. Can produce pedestrians of a custom pedestrian type with arbitrary flow intensity. |
| Pickup       | in, outPickup            | Removes agents from a given Queue object and adds them to the contents of the incoming agent ("container"). The Queue block may be either connected to the inPickup port of Pickup or specified in the parameter queue (the latter has priority over connected object). When an agent arrives at in port, Pickup iterates through the contents of the queue and selects the agents according to the given mode, which can be: all agents, first N agents, an exact quantity of agents (the block will wait until the specified number is reached), agents for which the given condition is true. The whole operation takes zero time. |
Dropoff

Removes the agents contained in the incoming "container" agent and outputs them via out Dropoff port. Similarly to the Pickup block that is used to add agents to the container, here agents are removed according to the given mode: all, a given number, or all satisfying the given condition. The whole operation takes zero time.

PedSink

Disposes incoming pedestrians. Is usually used as an end point of the pedestrian flow.

Figure 2 shows the general view of the developed model.

Figure 2. Model of Kronstadt evacuation.

4. Results

When setting the modeling problem, the authors defined the input flow as a flow of cars with a certain intensity. The law of distribution of the input stream was also investigated, as a result of which it was determined as exponential. The main aspects of proof of ownership of the distribution law are shown below.

Since it is not possible to observe the actual evacuation process, an analysis of the time of departure of buses from the bus station was made. As a result, 50 values were obtained, which are used to calculate the Pearson criterion ($\chi^2$) using the formula [15]:

$$\chi^2 = \sum_{i=1}^{n} \frac{(n_i - np_i)^2}{np_i},$$

where $n_i$ – empirical frequencies, $p_i$ – theoretical frequencies, $i$ – measurement number, $n$ – total number of measurements.

$$n_i = \frac{n_n}{n},$$

where $n_n$ – result of the n-th measurement.

The theoretical frequencies were obtained from the exponential distribution function

$$F(x) = \begin{cases} 1 - e^{-\lambda x}, & x \geq 0, \\ 0, & x \leq 0, \end{cases}$$
where $\lambda$ – the frequency of departure of evacuation vehicles, equal to 0.2

$$p_i = F(\beta) - F(\alpha),$$

where $\beta$ и $\alpha$ – boundaries of time intervals in which random variables fall.

The intervals were defined as follows:

$$W^n ... W^{n+1} - x_{\min} ... n * \Delta x,$$

where $\Delta x$ is calculated using this formula:

$$\Delta x = \frac{x_{\max} - x_{\min}}{1 + 3.22 * \ln(n)} = \frac{14 - 3}{1 + 3.22 * \ln(50)} = 0.81.$$

As a result of calculations, the Pearson criterion was equal to 8.35, which is less than the table value with the same number of degrees of freedom and a significance level of 0.99.

Therefore, we can assume that the distribution of a random variable is exponential.

**Table 2. Values of interval borders.**

| Border number | Value    |
|---------------|----------|
| 0             | 3        |
| 1             | 3.809018998 |
| 2             | 4.618037996 |
| 3             | 5.427056994 |
| 4             | 6.236075992 |
| 5             | 7.04509499 |
| 6             | 7.854113988 |
| 7             | 8.663132986 |
| 8             | 9.472151985 |
| 9             | 10.28117098 |
| 10            | 11.09018998 |
| 11            | 11.89920898 |
| 12            | 12.70822798 |
| 13            | 13.51724697 |
| 14            | 14.32626597 |

**Table 3. Calculating the Pearson criterion.**

| Intervals | $ni$ | $pi$ | $n^*pi$ | $ni-n^*pi$ | $(ni-n^*pi)^2$ | $(ni-n^*pi)^2)/(n^*pi)$ |
|-----------|------|------|---------|-------------|----------------|------------------------|
| 0-1       | 0.04 | 0.081988 | 1.721749 | -1.68175 | 2.828278118 | 1.642677818 |
| 1-2       | 0.1  | 0.06974 | 1.464533 | -1.36453 | 1.861950875 | 1.271361322 |
| 2-3       | 0.18 | 0.059321 | 1.245744 | -1.06574 | 1.135809797 | 0.911752335 |
| 3-4       | 0.16 | 0.050459 | 1.05964 | -0.89964 | 0.809351624 | 0.763798874 |
| 4-5       | 0.08 | 0.042921 | 0.901338 | -0.82134 | 0.674596282 | 0.748438659 |
| 5-6       | 0.08 | 0.036509 | 0.766685 | -0.68669 | 0.471536938 | 0.615033094 |
| 6-7       | 0.08 | 0.031055 | 0.652149 | -0.57215 | 0.327354314 | 0.501962567 |
| 7-8       | 0.08 | 0.026415 | 0.554723 | -0.47472 | 0.225362007 | 0.406260373 |
| 8-9       | 0.06 | 0.022469 | 0.471852 | -0.41185 | 0.169622018 | 0.359481449 |
| 9-10      | 0.04 | 0.019112 | 0.401361 | -0.36136 | 0.130581822 | 0.325347505 |
| 10-11     | 0    | 0.016257 | 0.341401 | -0.3414  | 0.116554621 | 0.341400968 |
| 11-12     | 0.06 | 0.013828 | 0.290398 | -0.2304  | 0.053083432 | 0.182795182 |
| 12-13     | 0.06 | 0.011763 | 0.247015 | -0.18702 | 0.034974701 | 0.141589242 |
| 13-14     | 0.04 | 0.010005 | 0.210113 | -0.17011 | 0.028938487 | 0.137728105 |
A number of experiments were carried out on the constructed model, which allowed us to obtain the following statistics. Figure 4 shows the dependence of the load of the North and South dams on the evacuation time and the limit value. The figure shows that due to changes made to the input parameters of the program, it was possible to avoid traffic jams, which would have caused the evacuation process to stop for some time, which would have led to an increase in the total time of the population removal process.

![Figure 3. Distribution function of a random variable.](image)

![Figure 4. Function of congestion of the North and South dams.](image)

A function of the number of buses waiting in queue for people to board is on figure 5. It shows that this indicator reaches the value of 194 points.
Figure 5. Function of a queue of buses for people to board.

A function of a number of buses returning on the island is on figure 6. It shows that the first vehicle will return to the island after almost 1 hour. Therefore, for continuous export of people from the island it is necessary that there was such quantity of transport that it was enough that at a given intensity of arrival of people to fill in for 1 hour.

Figure 6. Function of a number buses returning on the island.

As a result of the experiment, 41454 people were evacuated from the 49,000 initially located in the city. In total, 84.6% of people were evacuated. Figure 7 shows a fragment of the model.

Figure 7. A fragment of the model that implements the calculation of evacuees.
5. Discussion
The simulation model developed by the authors allows us to develop a methodology for assessing the adequacy of transport infrastructure for carrying out evacuation measures. Based on the conducted experiments, we can conclude:
1. The slowest stage of the evacuation was observed. It is to fit people into buses. According to the distribution used when describing the time of arrival of people to the landing sites, evacuees arrive for all 4 hours, so it is impossible to evacuate in a shorter time. Due to this circumstance, a queue was noticed among the buses waiting to be filled.
2. The model data shows that people who are being evacuated by bus will be completely removed from the island. And 4359 people who wanted to use private transport will remain on the island. And another 3,187 people will be on the way when the wave approaches the island.
3. Thus, we can conclude that it is impossible to evacuate all people from the city in 4 hours. This can be explained by the fact that the assumptions that ensure the complete removal of the population cannot be implemented due to the transport infrastructure, and if they are corrected, the set time is not enough.

A number of approximations were used in the the work. since some of the necessary information is located under the column "For official use only". Therefore, the work does not calculate the time of evacuation of a locality, but on the contrary, all calculations are based on the normalized time in the event of a hydraulic structure breakout, equal to 4 hours.

The developed method allows calculating various characteristics of localities that should be used in the design of master plans in order to avoid problems during evacuation processes. For example, it is possible to estimate the necessary capacity of roads, the intensity of departure of evacuation vehicles, and others.

The development will allow avoiding cases of death of people, causing damage to material values which will not have time to evacuate from the dangerous zone, which can be created not only by the surge wave described in the work, but also by radiation, chemical, and biological factors.

6. Conclusion
1. A simulation model of evacuation of people by various transport from Kotlin island was built using the software product AnyLogic.
2. Based on the constructed model, the authors conducted a number of experiments that allow us to obtain the following output data: the congestion of the North and South dams in the evacuation process in time, the number of buses returning to the island, the number of buses in the queue for boarding people and the number of evacuated people.
3. Based on the experimental data, it can be concluded that with the existing transport infrastructure, it is impossible to make a complete evacuation of the population in 4 hours. This can be justified by the following restrictions: the number of buses used for evacuation measures; the speed of gathering people to the places of embarkation in transport; the low capacity of roads to withdraw all personal vehicles in a short period of time.

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