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Medium-sized city pedestrian evacuation in a flood context: simulation using an agent based model.

Cyril Orengo*

Laboratory for Sciences of Risks, IMT Mines Alès, France. E-mail: cyril.orengo@mines-ales.fr

Florian Tena-Chollet

Laboratory for Sciences of Risks, IMT Mines Alès, France.

Sophie Sauvagnargues

Laboratory for Sciences of Risks, IMT Mines Alès, France.

This paper proposes a numerical simulation of a preventive pedestrian evacuation process in response to an imminent risk of dam failure. The simulation is performed in a flood context and four flooding scenarios of the involved river (the Gardon d'Alès, France) are analyzed. The aim is to evaluate the impact of such a flood on the pedestrian walkability of the road network and therefore on the time required to evacuate the population in such a context. The simulation is supported by the multi-agent platform GAMA (Taillandier et al. 2021), to which was integrated a simplified Social Force Model (Helbing and Molnár 1995). The study case is the French town of Ales, middle-sized city threatened by a dam failure and prone to heavy rainfall.

Keywords: multi-agent system, evacuation, risk, systems, rainfall, flooding.

1. Introduction

To ensure stakes protection during hazards, risk management relies on two main approaches. One named as “structural”, as it relies on civil engineering infrastructures. Dauphiné (2001). In addition to which a more flexible approach focus on human stakes and involve these in their own saving.

The real or assumed failure of a hazard mitigation structure leads to an inevitable rise in the exposure of the stakes. If this failure has not been thought of beforehand, as is frequently the case in risk prevention plans, a crisis may emerge. Crisis test territory response capacities. Lagadec (2003). In this context, a process of adaptation and safeguarding of the stakes must be set up quickly, under the leadership of a crisis command post (CCP). CCP takes a series of decisions in order to save the stakes, of which evacuation or confinement are examples.

Due to logistic and cost consideration, evacuation process is hard to exercise in real life. Massive evacuation, involving several thousands of people

even more. So numerous research has contributed to evacuation simulation. Bangate (2020); Takabatake et al. (2020). Nonetheless, few simulations adapt to a massive evacuation during a hydrometeorological hazard.

This paper proposes a numerical simulation of a preventive evacuation process in the context of a hydrological event using a multi-agent system. It is applied to an evacuation of Alès municipality (Gard, France) a medium sized city under the threat of a dam-failure (Sainte-Cecile d'Andorge, France). The aim is to study and assess the possibility of evacuating a large amount of population in a reduced amount of time in a flood context.

To do so, section 1 presents a literature review on evacuation simulations. Section 2 introduces the global approach of the process. Section 3 presents the simulation of it on a multi-agent framework and its application in the study case. Section 4 presents the indicators and mapping of the evacuees on the network across time.

1.1. Scope of research: preventive evacuation under intense rain

The decision to evacuate has to be taken prior to the onset of the hazard. There is a near scientific consensus on the division of population evacuations process into several different stages. These stages imply various problematics, knowledge, and methods. The least detailed partitioning mentions three main stages: decision making by the authorities, preparation of evacuees and transportation out of the area Barendregt et al. (2005). The transmission time of the alert can be added. Leone et al. (2017). The verification phase may be taken into account. Baker (1991). This article focuses on the clearing time phase. The evacuation is also regarded as fully pedestrian. It is thus a question of considering only the process of moving the evacuees to the gathering points envisaged by the prefecture of the Gard.

The study case context is a potential dam failure. Therefore, the evacuation is supposed to take place prior to the hazard. It is however certain that an intense pluvial event will be part of the process. Moreover, the overflowing of the Gardon is likely and may slow down the progression of the populations attempting to reach safety. The aim of this paper is to study the impact of a flood event on the preventive evacuation process of the Alès municipality.

1.2. Existing evacuation simulations

Several works on evacuation simulation have been conducted in recent years. The development of artificial intelligence technologies and Multi-agents Systems (MAS) has allowed researchers from various disciplines to bring new perspectives to the subject. The objective here is to build a simulation model of a pedestrian evacuation in the specific context of a hydrological event.

The evacuation of large-scale populations (city, conurbation, and region) involves a large influx of people to drain and a more complex travel environment. The first models used a graph and attempted to answer the question of how to share the road network between individuals during an event. These graphs represented the population as a potential that is carried from point to point. Tweedie et al. (1986). Some models use a weighting on road sections according to different parameters, congestion in NETVACI, for

example. Sheffi, Mahmassani, and Powell (1982). These models introduced the problem of evacuee routing. The Dijkstra algorithm used then is the most widely used method still.

Other models, mainly in the field of distributed artificial intelligence, using agents with more or less extensive cognitive characteristics, operate based on individual strategies. Multi-Agent System (M.A.S.) technology has brought the opportunity to observe complex systems emergence from simple individual behaviors. Drogoul (1993).

The problem of pedestrian evacuation on large scale implies a multiplicity of individuals self-organizing on a network to reach shelters. These individuals are socially and physically interacting through the process, these interactions tend to modify their trip. Chaib-draa (2001) identify two characteristics of MAS that makes it appropriate to use. First, they are situated. They have a position, at any time, in the environment. This position evolves through time according to rules. The position changes of the evacuees is essential to understand pedestrian evacuation dynamics, especially in an urban context, high densities being highly probable. The second characteristic is flexibility. An agent is meant to be non-deterministic; it can adapt its behavior to its environment. In a pedestrian evacuation context, it is materialized by collision avoidance and velocity adaptation according to the density of evacuees on a route.

2. Global approach

Numerous documentation on the population evacuation process exists. On the one hand, experience feedbacks, reporting on the stages and forms of previous processes (the south of Rhône valley in 2003, Nijmegen in 1995). On the other hand, scientific literature also develops knowledge on the process. Lindell et al. (2020). Feedbacks allow assessing the process complexity. The scientific literature highlights the impact of the surrounding context. Various elements influence evacuation processes such as organizational factors, temporal context or the focus of this paper, the hydrometeorological context. Indeed, this paper deals with an evacuation as a response to an imminent dam failure. It implies heavy rains and eventual raise of the river level. This article is divided into two

contributions. The first one is a simulation of a pedestrian evacuation in an urban environment. The second is an integration of a flooding context to this simulation.

2.1. From a reality to a simulation: a systemic approach

In this paper, preventive evacuation is regarded as a system of actors interacting. The desired outcome is the safeguarding of the threatened population in a minimum amount of time. The number of actors (especially civilians), the uncertain nature of their behaviors and the potential emergence of system-wide properties such as herding effects and stop& not observable at the level of an individual make it a complex system. Moussaïd et al. (2009) ; Moussaïd, Helbing, and Theraulaz (2011).

As shown in (Fig. 1), the research approach entails to understand key factors of the process, an abstraction of the latter through modeling, and finally its simulation via the use of a multi-agent platform. Identifying and quantifying key elements of the evacuation process precede their characterization.

Figure 1: Illustration of the global approach.

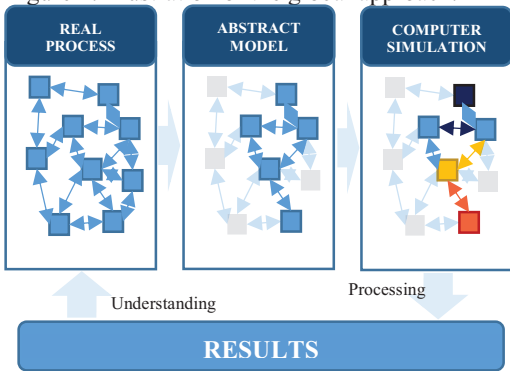


Fig. 1. Illustration of the global approach.

In order to test this model, it has been implemented as a simulation in a multi-agent framework. Elements of the evacuation process abstract model got values assigned. The simulation is then run. However, results are quite far from what an evacuation can be. In fact, these initial conditions do not correspond to anything tangible.

Indeed, the evacuation process is subject to several external influences (Fig. 2). It is chosen on

this article to focus on the case of a possible (and likely) hydrological hazard (flooding of the Gardon river, Gard, France) occurring in parallel to the evacuation process. In a dam-breaking risk context, taking eventual flood and its effects on the evacuation process into account appears logic.

2.2. Evacuation system and related systems

Once the framework of the evacuation system has been defined, and these elementary parts have been prioritized and characterized, the context surrounding this system must also be considered. Indeed, an evacuation takes place in a particular and unique geographical and temporal context. The functioning of a set of related systems thereby influences its course. Fig. 2 is a schematization of what it is intended by “surrounding systems”, it is of course not exhaustive.

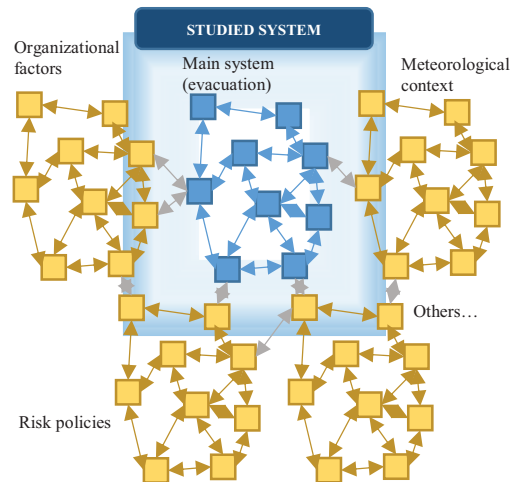


Fig. 2. Systems surrounding.

Among various bordering systems known as affecting the evacuation process system, it is carried a specific focus on the hydrological system during the specific time of the network clearance. Intense rainfall, in addition to threatening the structural integrity of the dam, can also contribute to an overflow of the Gardon. This overflow could occur in the middle of the evacuation process, and thus, in the case of a pedestrian evacuation, slow down the operation. One of the multiple effects that a flood can have on an evacuation process, the attention is specifically focused on the slowdowns caused by

a rise in the water level, and hence a progression of the evacuees in a difficult environment.

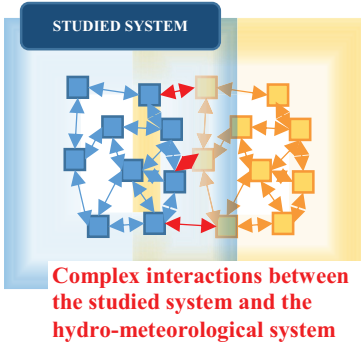


Fig.3.Impact of a bordering system (hydro-meteorological) on the studied system (evacuation).

The hydro-meteorological system can have several consequences on our study system. For instance, well before the rising of the river level, the onset of rain can influence individual and collective decision-making. The degradation of the meteorological conditions can thus push people not to evacuate or to do so in an anticipated way. Schematically, Fig. 3 illustrates these interactions between the two systems. These interactions are numerous and complex, and are not discussed here. However, it is proposed to analyze the influence of one of the consequences of the operation of the hydrometeorological system (Fig. 4), the overflow of the Gardon, through the implementation of water level values in the simulation.

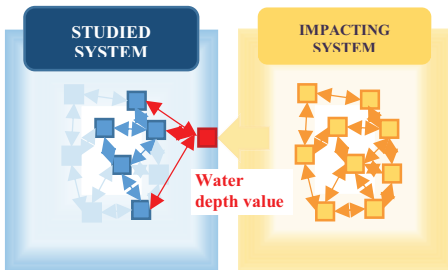


Fig. 4.Use of water depth as the outcome of the hydro-meteorological system

2.3. Specific flood force and pedestrians

A series of experimental studies conducted on large population samples have established a robust relationship between the amount of water

on a transect and the walking speed of individuals. Bernardini et al. (2017); Dias, Abd, and Zaiter (2021). Such experiments are performed in a closed environment on a valid population. The equation Eq. (1) characterizes the impact of water depth and flood force on pedestrian locomotion.

$$V_i = a \cdot M \cdot b \quad (1)$$

Here M represents the specific flood force while previously mentioned. The work of (Bernardini et al. 2017) has highlighted two constants (a and b in Eq. (1)). The specific flood force is given by the Eq. (2) (Dias, Abd, and Zaiter 2021).

$$M = \frac{D \cdot v \cdot f}{g} + \frac{D^2}{2} \quad (2)$$

The walking speed has been measure on a sample for several water depths (0.08, 0.43 and 0.90 meters). Dias, Abd, and Zaiter (2021). The results obtained show a significant impact of the water depth on the walking speed starting from 0.43cm. The walking speed in normal conditions of practicability is considered 1.34m/s (consensus).

3. Material and method

The simulation is developed on the open-source software GAMA. GAMA is a multi-agent platform with a dedicated development environment. Widely used in research, the development language (GAML) allows the creation of agent species, the integration of executable functions by these same agents. These executable functions or "skills" are themselves coded in Java by the platform operators. Besides, the construction of spatial models is facilitated by the ability to read files in shapefile format. This makes the GAMA platform an optimal solution for the construction of an evacuation simulation.

3.1. Simulation architecture

An environment and a set of pedestrian agents, which represents the population living in the survey area, constitute the simulation. The spatial environment is set as the study area. Within this survey area are all the buildings included, the road network, the Gardon river layout and the maximum threat zone as identified by the Flood Risk Territories (TRI in French). These components are imported via a geographic database. GAMA platform read and displays them. The buildings contain a variable

corresponding to the number of inhabitants counted inside (data built from INSEE statistics), the road network is used to build a graph.

Pedestrian agents are the only species of "active" agents. They possess a speed of movement as well as a direction in space. The direction they adopt is relative to the destination they choose. They also have an "objective" which determines the behavior they adopt and thus the choice of a destination. They use the network in order to move, when they have to reach a new destination. Destinations in the simulation are gathering point defined in the 'Plan Particulier d'Intervention (PPI)' related to the dam. They are pictured as red dots on (Fig. 6).

The building agents have two purposes in the simulation. The first one is to generate pedestrian agents. This function concerns only residential buildings. To do so, they hold a population variable, which allows to generating a reliable number of pedestrian agents. In addition, buildings used as shelters are included as destinations (red dots on fig. 7). The shelters used in the simulation are those specified by the public administration.

The road sections are also agents. Together they form a graph. They carry information about their length, information that the pedestrian agent can retrieve when building its route. They are imported into the simulation as segments. However, they also have information about their width. This information determines the maximum distance of the agent from the center of the road and thus allows reproducing a realistic navigation behavior.

Fig. 5 (a) presents a view of the environment generated into GAMA platform. Fig 5. (b) shows pedestrian agents walking in the environment.

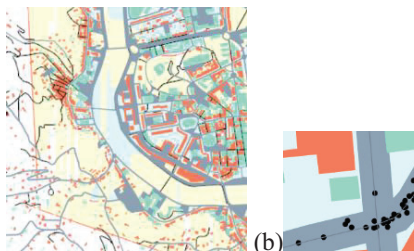


Fig 5. (a). View of the environment simulated with GAMA (b). Pedestrian agents.

3.2. Agents interactions.

At the beginning of the simulation, building

agents are set to create pedestrian agents. To do so, each building hold the information of the number of inhabitants living inside. This data is obtained by crossing census data at 200-meter scale to buildings characteristics. Residential buildings are isolated, and for each 200-meter tile, volume ratio, number of floors and housing type are used to allocate population. Once pedestrians are generated, they set their objective as "NULL" value. In this state, they are supposed to stay at their living place. When the objective is set as "Leave", they leave their living place to join the network.

Following data on evacuation preparation times, each agent as a probability to begin to start the evacuation. The probability is set to evolve according to a curve. Once on the network, each pedestrian agent set the nearest gathering point as his destination. The pedestrian agent computes the shortest past between its starting location and the final destination chosen. The graph, composed by agents roads serves as support to path construction.

Pedestrian agents may also go out of their way if another pedestrian is on their path. This deviation has to respect the width of the road it is on. Each cycle of the simulation, the whole pedestrian agent set check rather if there is water on their location or not. If not, they keep their standard speed. If yes, they also check for D and V_f . They adapt their speed to the returned values following Eq. (1) and Eq. (2).

3.3. Study case

The study area is the municipality of Alès. Situated in the Gard district of France, the municipality of Alès has a population of 39500 and is close to a dam (Sainte Cecile d'Andorge). In case of dam breaching, few exact measurements on the flood wave exist, but its spatial extension is known and is used as the evacuation zone (represented in yellow on the Fig. 6), and it is considered that it would take nearly an hour to reach the municipality of Alès. The speed of the phenomenon pushed the municipality of Ales to refuse the evacuation, unlike the prefecture of the Gard, which prepared the latter. The prefecture has decreed eleven gathering points outside the potentially impacted area (represented in red on Fig. 6).

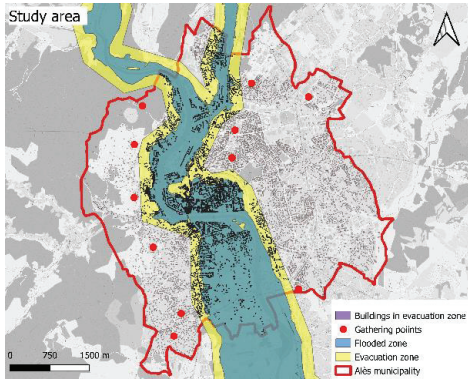


Fig.6.Study area

Shown in blue on (Fig. 6) the potential flood zone remains large in relation to the total area to be evacuated. This zone is the result of a study conducted during the elaboration of the TRI. The zone can be subject to cumulative water levels between 0.50m and 2m. Depending on the intensity of the rainy event. This zone will be given water level values D in the simulation. Counting people living in single-storey houses as well as on the ground and second floor of the buildings, around 3'500 people would be concerned. Lacking reliable local measurements, V_f is fixed at 0.10 m/s . This makes it possible to include the parameter without giving it too much weight, given the simplification it is subject to.

3.4. Values implementation.

MAS allows a set of agents to collect information of their environment and thus adapt their behavior according to rules. "People" agent is moving through the network adopting a speed considered as average regarding the specific literature review (1.34 meters per second following a normal distribution with $\sigma = 0.25$). It is here about a standard speed adopted by agents when there is no obstacle on the network.

Three values of water depth (D) will be tested and compared to a scenario without flooding ($D=0$): 0.08, 0.43 and 0.90 meters.

4. Results

For each of the scenarios, several runs of the simulation have been launched. The maximum, minimum and average values as well as the standard deviations are analyzed.

4.1. Cumulative evacuation completion curve comparison.

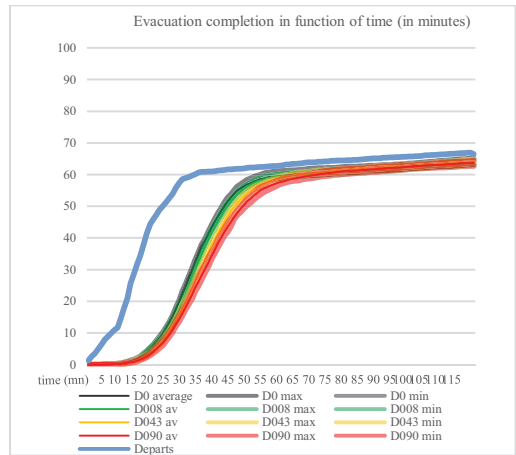


Fig.7.(a) Evacuation completion curves for every scenario.

The departure curve in Fig. 7(a) takes into consideration eventual reluctance of a part of population to evacuate. It leads to a curve flattening once after compliant people are gone. Fig. 7(b) uses a regular departure curve which has been observed in (Mas, Adriano, and Koshimura 2013), in a tsunami event, which go along with a higher emergency level.

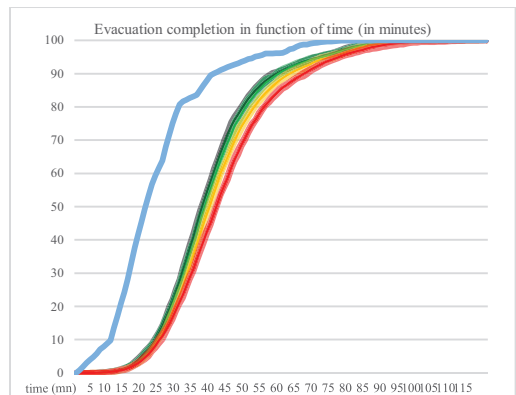


Fig.7.(b) Evacuation completion curve for every scenario.

Fig. 8(a) and (b) gives a first information. It shows the importance of the departure curve shape. With the first curve in Fig.8(a), the evacuation is not completed in two hours. With the second Fig. 8(b), it takes more than one hour.

The increase of water depth delays the process

slightly. Accumulation of evacuees is delayed by a small margin during the first hour. However, in the second hour, the curves logically merge afterward. The majority of evacuees have left the flooded areas.

Scenarios $d = 0.43$ point out significant delays overall evacuation. As for the previous one, the delay is more consistent in the first hour and reduces in the second.

The last scenario shows little difference with the previous one, the curve for $d = 0.90$ does not mark a more significant delay than the previous scenario.

4.2. Evacuees mapping

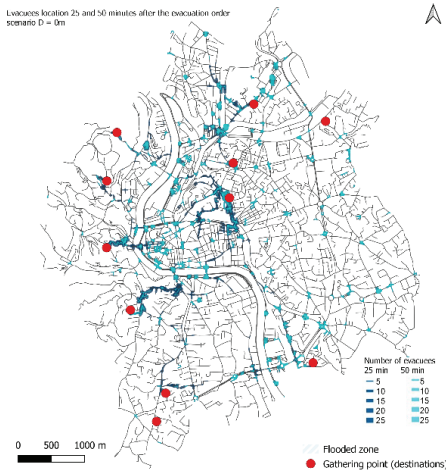


Fig. 8.(a) Evacuees position 25 and 50 minutes after the start of the evacuation (scenario $d = 0$).

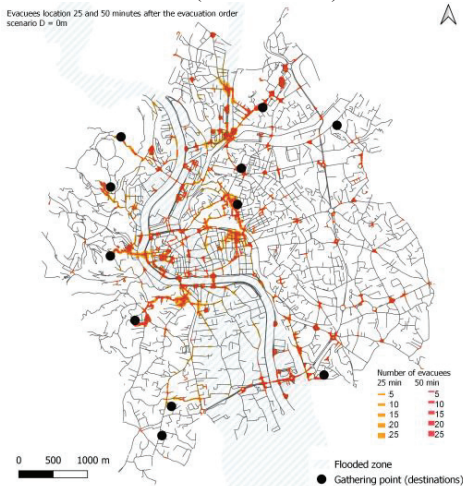


Fig. 8.(b) Evacuees position 25 and 50 minutes after the start of the evacuation (scenario $d = 0,90$).

For the two extreme scenarios ($d = 0$ and $d = 0.90$), Position of the evacuees has been mapped at 25 minutes and 50 minutes of the evacuation, using the second preparation time curve. This curve assume that the whole population within the area will evacuate in less than two hours. According to Fig. 7(a) and Fig. 7(b) number of people on the network increase on this period of time. The differences between the two maps is noticeable. In Fig. 8(a), density of people at 25 and 50 minutes are different which is a clue of a better network clearance performance. Fig.8(b) shows a more difficult progression of the evacuees within the time-period.

5. Discussion

According to the simulation results, a flooding event would have a moderate impact on the evacuation process. However, the differences between the scenarios seem more noticeable around twenty-five minutes after the start of the evacuation. It is at this point that the maximum number of peoples are on the network. It is also at this moment that a majority of them is in the flooded zone. The curves appears to be close one each other. Two facts explain the small difference between different curves. A non-negligible part of the population is in the evacuation zone but not in the flood zone (about 1400 peoples). The position of the gathering points relatively far from the flooded zone area means that the evacuees are only in the water on part of their path.

On the other hand, these results point out the importance of population compliance in the evacuation process. This comes as a reminder of an important matter about evacuation and crisis management in general. A large part of the evacuation performance is due to organizational factors. Crisis management exercises and training are thus a perspective to enhance decision making (Hamon et al. 2022). According to maps in Fig. 8 shows also a high density of pedestrians at the exits situated close to the city center

6. Conclusion

The evacuation of populations is a difficult process to test in reality. The development of digital technologies has allowed a multiplication of simulations of such a process. This contribution attempts to bring understanding in the context of a pedestrian evacuation in a hydrological event. To do so, the use of a multi-

agent system allows to couple autonomous agents and a cellular automata, in order to integrate the effects of different water depths on the movement of a population. The results show a moderate impact. The integration of the water depth in the simulation can still be improved, with the addition of the temporal parameter. The addition of a real hydrological model would allow a local consideration of the parameter (V_f), and thus more accurate results. It is also possible to add a risk parameter in the calculation of the pedestrian route. This would make the flooded roads less attractive in their choice of travel. The integration of these psychosocial parameters can be done using a BDI (Belief, Desire, and Intention) module. Bratman and Mele (1987). The real time simulation of the flood can be integrated in the form of a cellular automaton and linked to agents people properties. These two aspects are in the perspective of this contribution.

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