The personal space and the collective behavior of crowd disasters

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Abstract

The concept of the personal space in crowd dynamics is commonly underestimated. However, the self-awareness of it can prevent and handle risk situations in human crowds. The aim of this study was to explore theoretically the use of the personal space as an interdisciplinary concept and design a computational model based on cellular automata for modeling collective behaviors related to crushing events. We generated transitional rules based on the Shelling's spatial proximity model of segregation. Based on an explorative data analysis and model validation, we found that the dynamics of crowd events showed dependencies between similar or dissimilar individual preferences and their interpersonal distances. These results suggests that crushing events in social gatherings are highly probable and that the initial space between attendees is the key for delaying the presence of crowd disasters.

Introduction

The dynamics of extremely dense crowds or crowd turbulence is a deeply worrying phenomenon in which people have been hurt and lost their lives in different places and cultures. It is characterized by sudden variations in all directions among people that push others around generating uncontrollable and unpredictable large-scale events [1, 2]. Such events can be triggered by a small group of individuals in close proximity to one another. Unfortunately, the most recent well-known events in Etah, Uttar Pradesh, India, July 2, 2024, during a religious event, or in South Korea on October 29, 2022, during a Halloween celebration, showed a disturbing lack of knowledge required to understand and prevent fatal injuries. In particular, the event in South Korea showed the crush of crowd without an ex-ante mass panic [2]. Contrasting with these lamentable events, there are other examples in which the overcrowding did not result in tragedy. For example, the celebration of the winning of the soccer world cup by Argentina, at December 20, 2022. In this event, we could see an auto-organized crowd across the country without fatal crush events. Both incidents were separated by two months apart, and they showed completely different outputs. Therefore, our investigation proposes a theoretical approximation for modeling the dynamics of crowd crushing in social gatherings. We are particularly interested in studying one specific cultural driver that can explain the individual reaction in a crowd situation: the personal space (PS). To

achieve this, we shall use the cellular automata (CA) as our main formulation for modeling and showing complex and emergent behaviors in crowed situations.

Based on the sociocultural approach and the complex systems perspective [3–6], we propose to associate a possible cultural driver with the concept of the PS. This concept is commonly use in studies of human behavior [7, 8], and it can be understood as the surrounding area for social interactions of an individual [7, 9, 10]. In addition, this area can be associated with levels of comfort or discomfort [10, 11]. Consequently, we aim to translate this conceptual idea into the CA modeling by generating simple local rules that can replicate the conditions and dynamics in crowd situations [12]. Then, if we consider the PS as a key to understand the collective and individual psychology—which depends on the cultural context, such as family, friends, communities, and religion—of crowds, we can describe the instinctive reaction of a person within a crowd [13]. Therefore, we are interested in the following questions: What is the situation in which the crushing is unstoppable? How probable are the crushing events? What are the levels of comfort or tolerance for being surrounded by similar persons? We shall answer these questions by using an interdisciplinary approach in science. Just as we mentioned before, we use the sociocultural approach for indicating how the daily interpersonal interactions affect our natural instinct for self-preservation in different crowd situations [9, 14, 15]. That is, social interactions guide and teach individuals how to react instinctively to harmful events. In addition, we use the complex systems perspective by applying its basic concepts, methods, and tools [16]. In particular, we use the Shelling's model of segregation for generating our CA because CAs show advantages for modeling non-linear dynamics and applying them in diverse scientific fields [16–18]. In addition, we shall use an explorative data analysis and model validation for evaluating if the model outputs agree with empirical data and determine if our assumptions are justifiable [19, 20].

Therefore, we hypothesize that fatal crushing events can be related to cultural aspects of some regions. Societies that are related to high tolerance thresholds of being surrounded by people in near-body proximities are more vulnerable to fatal crushing in overcrowded events. That is to say, if a person tolerates the violation of the PS, it is more probable the presence of fatal crushing. On the other hand, societies that are related to less tolerance thresholds of the PS are less vulnerable to crushing. That is, if a person has less tolerance of the discomfort associated with the violation of the PS, the presence of fatal crushing is less probable. Therefore, the cultural context affects the presence of fatal or non-fatal cases of crowd crushing. This is important because we can understand and prevent uncontrollable crowd turbulences and their fatal crushing events.

The remaining part of the article proceeds as follows: Literature review, Material, Methods, Results, and Discussion. The Literature review shows the main references about studies of collective behaviors and crowds in different disciplines, as well as their computational approximation. The Material section describes the transition between particular concepts of those studies and their implementation of building our CA model. The Method section explains our CA based on the Shelling's model of segregation and the transitional rules that describe different situations related to the PS. Furthermore, we describe the initial conditions and the data analysis. The Result section displays our findings based on the model validation and sensitivity analysis. Finally, the Discussion section shows our final remarks and conclusions.

Literature review

In the diverse and extended literature related to collective behaviors and crowds, we identify important distinctions about the type of coordinations and their trigger events. In particular, studies of collective behavior in the biology field, such as flocking of birds,

point out the dynamics behind the effect of local actions and the formation of large-scale patterns within groups [21]. A feature that is highlighted in these studies is the efficient information transfer for preventing crushing events [22]. This is because there is an enough space between each individual and its near neighbors at the level of the group that communicates effectively the sudden changes of direction and prevents any type of crushing incidents. Even if those changes were generated by warning sings of possible predator around the group, the type of group reaction is to avoid the dangerous situation by impulsive but coordinated dispersion. Therefore, the physical space between individuals in animal groups stands as the key for coordinating movements and prevents crashing or crushing events.

On the contrary, collective behaviors related to a massive group of people show singular attributes of crowd turbulence [2, 23]. In particular, we are interested in the chaotic and uncoordinated movements and their unknown trigger events. In this respect, there are studies that have considered empirical and theoretical approaches to describe the dynamics in the motions of extremely dense crowds. The work of Helbing et. al., [2] analyzed video recordings of the crowd disaster in the "Muslim pilgrimage in Mina/Makkah, Saudi Arabia." They identified turbulent flows that are similar to earthquakes because they initiated as sudden changes of pressure, and these changes generated unstoppable and chaotic movements in the crowd. In addition, the work of Helbing et. al., [12] studies the evacuation dynamics of classrooms by experiments and simulations. They identified jamming of students at the exit door that affected the evacuation dynamics. In this study, the trigger event was a signal alarm shouted by the cameraman. In addition to these findings, the study of Nakayama et. al., [24] analyzed two-dimensional formulation of pedestrian and granular flows. They suggested the presence of instabilities in pedestrian flows. Therefore, in this type of approximation, it is obvious by now that people were densely packed, and this condition suggests that the PS is completely filled.

With respect to the method, there are few studies related to the use of cellular automata in collective behaviors of crowd events. For example, the work of FukuiIshibashi [25] suggested the use of CA models for understanding pedestrian flows and "the high density crowd behavior in overcrowding places." Moreover, the work of Muramatsu and Nagatani [26] and Burstedde et. al., [27] showed the application of the CA in pedestrian dynamics. They used the dynamics of the traffic flow for describing the pedestrian movements. They identified that the jamming transitions emerge from an increased density. However, these studies have not considered and modeled explicitly the PS among people as a condition for generating chaotic movements in the crowd.

In line with the analysis of the PS applied to collective behaviors, there are very few published studies that point out the need to carefully consider its local effect in different groups of people. For example, Welschetal [10] used a field-theoretical framework for showing the response of the violation of the PS. They found that such a violation is immediate. Then, if your PS constantly changes, there is no tolerance for violations. Compare to this results, the work of Thompson et. al., [11] suggested the existence of a comfort or tolerance zone, around 180–240 cm. Finally, the work of Lugo and Alatriste-Contreras [18] used the PS concept to validate the application of the classic Moore neighborhood in the CA. They suggested that the PS is a fundamental concept for modeling the interpersonal distance in spatial interactions. Therefore, these studies show the potential to complement the findings of collective behaviors by including explicitly the PS in theoretical and empirical analyses.

Thus far, these references indicate the importance of considering the physical space between individuals to describe difference outputs in overcrowded events. It seems that the PS is a fundamental concept with a possible measure for understanding the crushing events. In the section that follows, we present the materials related to particular studies

of collective behavior and programming libraries for converting concepts into our CA modeling.

Materials

To build our theoretical CA model, we used different studies for defining the configuration of a matrix, the attributes of each cell, and the shape of the neighborhood of a cell. In this study, we are interested in modeling two-dimensional CAs because they can represent a wide variety of dynamic systems related to crowd modeling and its geographical and temporal scales [28]. In particular, CAs consist of grid cells that can take different values and are updated in discrete time steps based on transitional rules depending on the neighborhood of a cell [29]. Then, the configuration of the grid cells or matrix matters for defining and describing different spatial and temporal situations, for example local environments related to indoor locations or large scale movements associated with transport systems [17, 18]. In this case, our matrix shall show a closed boundary that represents real life situations in which the crowd is limited by physical boundaries, such as walls, buildings, and natural structures. These type of boundaries are closely related to locations and areas—indoors and outdoors—of crowd events, such as mass gatherings and festivals.

Next, attributes of each cell are directly related to the Shelling's model of segregation [16]. This model shows the emergence of social segregation as a result of relative and modest decisions of individuals who act in their self-interest and group preference [30]. In addition, we considered the concept of "phycological crowd" that describes the presence of different groups of people within a physical crowd linked by a clear social coherence [13, 31]. Then, in our case, we can define cells as crowd members who are identified with each other based on their similar opinion or preference [32]. This preference can be associated with two values of occupied cells that define which cell shows the attribute of "tolerance" or "intolerance" of being surrounded by others. In addition, each cell shows the attribute of movement around its unoccupied cells. This attribute considers the possibility of evading the formation of a self-overpopulated neighborhood or staying with similar ones. Therefore, each cell attribute can be set by one of the following three integer values: $tolerance = 0$, $intolerance = 1$, and $unoccupied = 3$

Let us now consider the neighborhood of a cell. In particular, we used the Moore neighborhood to describe the PS. Because the PS can be seen as a "circular area surrounding the person" [10], the Moore neighborhood can be a good approximation for modeling the interpersonal distance around a person in near-body or extreme close interactions [29, 33]. Furthermore, using this type of neighborhood and the Shelling's model of segregation about the decisions of individuals based on similar surrounding preferences [16], we can associate the concept of "social psychology" with the "sociocultural approach" in crowd situations [4, 13]. In particular, the behavior and thoughts of an individual to move or stay in place in a crowd can be influenced by the cultural context—family, friends, communities, and religion. Then, the socio-cultural environment of the place in which the crowd is gathering shall affect the instinctive reaction of people to move or stay in place. Therefore, based on these ideas, we can identify and set the number of neighbors who shall affect the preference of a cell of being surrounded by its similars or moving to other unoccupied cell duo to its preference of avoiding near-body proximities with other cells. These situations can describe the individual psychology behind the physical reaction of a person within a crowd.

Turning now to other type of materials used in this study, we apply the Python programming language and its third party libraries for generating our CA model, analyzing its outputs, and showing its results. In particular, we used NumPy,

matplotlib, and SciPy libraries. For making all our data, code, and results as open and accesible as possible, we place them in the Open Science Framework (OSF). The name of the project associated with the OSF is Cultural drivers for understanding crowd crushing.

Methods

As we mentioned before, we use the Shelling's model of segregation for generating our CA [16]. Compared with the classic model in which the individual changes its preference while staying in the same location, our CA describes individuals who change location or stay in the same place according to the presence of individuals with different or similar levels of tolerance. Tolerance is defined in terms of the PS and change of location is associated with the number of individuals with similar levels of tolerance within each neighborhood. Therefore, our CA describes a spatial model of segregation in which a cell will change its location as a response of the sense of discomfort associated with the presence of surrounding and occupied cells, or a cell will stay in place as a response of aligning common preferences. The following subsection describes in detail these behaviors as transitional rules.

Rules

Following the notation in Batty [30], we defined each cell in a NxN matrix, m_{NxN}, as $C_{ij}(t)$ in which each cell, C, shows the location (i, j) at time t. The notation (i, j) is referred as a tuple of values related to the coordinates of m, and t is related to the number of iteration for updating m. Each $C_{ij}(t)$ has the attribute of occupied or unoccupied cells. Occupied cells are related to the attribute of tolerance or intolerance as $C_{ij}^{tol} = 1$ or $C_{ij}^{intol} = 0$. On the other hand, unoccupied cells are defined as $C_{ij}^{unocc} = 3$. As we have just mentioned, the attributes of tolerance and intolerance will not change as t moves forward. The change of each cell will be in its location (i, j) based on its neighbors. We defined a neighborhood of eight cells in which the number of neighbors related to tolerance or intolerance cells are the following:

$$\bar{C}_{ij}^{tol}(t) = \sum_{\substack{k_{ij} \in \Omega \\ k_{ij} = tol}} C_{k_{ij}}(t) \quad \text{and} \quad \bar{C}_{ij}^{intol}(t) = \sum_{\substack{k_{ij} \in \Omega \\ k_{ij} = intol}} C_{k_{ij}}(t) \tag{1}$$

where k_{ij} is a cell location in the neighborhood Ω, and k_{ij} shows the attribute of tolerance or intolerance.

Then, the movement of a cell is related to the number of unoccupied cells and the number of similar cells around it. Therefore, we updated each cell as follows:

$$C_{ij}(t+1) = \left\{ \begin{array}{ll} C_{k_{ij}}(t) & \text{if } C_{k_{ij}}(t) = C_{ij}^{unocc} \text{and } \bar{C}_{ij}^{tol}(t) < \text{tol_cells} \\ & \text{elif } C_{k_{ij}}(t) = C_{ij}^{unocc} \text{and } \bar{C}_{ij}^{tol}(t) = \text{tol_cells} \\ C_{k_{ij}}(t) & \text{if } C_{k_{ij}}(t) = C_{ij}^{unocc} \text{and } \bar{C}_{ij}^{intol}(t) < \text{intol_cells} \\ & \text{elif } C_{k_{ij}}(t) = C_{ij}^{unocc} \text{and } \bar{C}_{ij}^{intol}(t) = \text{intol_cells} \\ C_{ij}(t) & \text{if } C_{k_{ij}}(t) = C_{ij}^{tol} \text{or } C_{k_{ij}}(t) = C_{ij}^{intol} \end{array} \right\} \tag{2}$$

where $C_{k_{ij}}(t)$ is a neighbor cell; $\bar{C}_{ij}^{tol}(t)$ and $\bar{C}_{ij}^{intol}(t)$ are the sum of the values of neighbors related to a cell of tolerance and intolerance attributes respectively; and *tol_cells* and *untol_cells* are parameters for specifying different levels of tolerance and intolerance—i.e., high and medium levels. Following the ideas of Thompson et. al., [11]

and Welsch et. all, [10] that there is an immediate discomfort associated with a near-body or extreme close proximity presence, we describe equation 2 as follows. The first and second situations in equation 2 set the rules of movement and immobility of a cell based on the existence of unoccupied cell and similar ones around it. In particular, the first and second rules describe situations in which a cell with a tolerance or intolerance attribute will move its location around its neighborhood or stay in place based on the number of available cells and the number of similar cells around it. The third rule describes a situation in which a cell does not move due to the lack of empty space around it.

Based on the parameters tol_cells and $untol_cells$, we can define three types of criteria related to similar number of cells around it, and each of them described levels of tolerance or intolerance. The first criterion is related to a similar level—medium level—of tolerance and intolerance among cells (Algorithm 1). This criterion describes a situation in which the discomfort associated with the violation of the PS is the same for the two types of cells. In particular, in equation 2, we set the parameters as follows: $tol_cells = 4$ and $untol_cells = 4$.

Algorithm 1 Rules for moving or staying in place based on similar tolerant and intolerant cells

Require: $m = matrix$
Ensure: $C_{ij} = Occupied\ cell$
  if C_{ij} has unoccupied neighbors > 1 **then**
    list neighbors to move

    if $C_{ij} == 1$ and similar neighbors < 4 **then**
    move new location ▷ Tolerant
    else if $C_{ij} == 1$ and similar neighbors $== 4$ **then**
    stay in location

    else if $C_{ij} == 0$ and similar neighbors < 4 **then**
    move new location ▷ Intolerant
    else if $C_{ij} == 0$ and similar neighbors $== 4$ **then**
    stay in location

    end if
  end if

The second criterion is related to different levels of tolerance and intolerance among cells (Algorithm 2, see the Supporting information). In particular, for tolerant cells, we specify the variable $tol_cells = 7$, and for intolerant ones, we set $untol_cells = 4$. This situation describes the case of high levels of tolerant cells who will move their location or stay in place until they are almost caught by neighbors. Meanwhile, the intolerant cells show a medium level.

The third criterion is associated with extream levels of tolerance and intolerance among cells (Algorithm 3, see the Supporting information). In particular, for tolerant cells, we specify the variable $tol_cells = 7$, and for intolerant ones, we set $untol_cells = 2$. This situation describes the case of high levels of tolerant and intolerant cells.

Therefore, we shall use these criteria for exploring three scenarios that set initial conditions and may identify the dynamics for the presence of crowd crushing in overcrowded events.

Data analysis and model validation

In line with the possible outputs associated with the rules above, we identify and compute the level of overcrowding or "crowd density" that surrounds each cell by measuring the number of neighbors in a neighborhood of 12 cells [34]. This measure is computed by a function named *cnt_neighbors*. This is the key to identify a dangerous and potentially fatal situation because a cell can be jammed by its 8 or 12 nearby and occupied cells. This reflects the possible crushing situations; no matter if your neighbors are similar or dissimilar, you are in a dangerous location position.

We use this measure for our exploratory data analysis and model validation [19, 35]. In particular, the exploratory data analysis aims to search for trends and relationships between our main measurement and the public perceptions and scientific knowledge about the crushing events. For example, how true is the public perception of an increasing concern about the dangers of overcrowding events? and how accurate is our crushing measure for preventing harmful effects in overcrowded events? Then, to determine whether our model describes the crowd behavior, we should evaluate our overcrowding measure using a conceptual validation—if "the theory and assumptions underlying the model are justifiable" [20]. Based on this type of validation, we use a sensitivity analysis that determines the relative influence of the initial conditions and the parameters on our model output. We are interested in exploring which combination of those parameters are related to the current public perceptions and scientific knowledge. To do this, we used a Monte Carlo formulation that tests how probable is the presence of crushing events in certain overcrowding situations. We set our number of trials in $1,000$. To determine this number, we computed the measure of the Monte Carlo sampling: $n = [z_{\alpha/2} S/E]^2$ [36]. In this sampling n is the minimum number of trials, $z_{\alpha/2}$ is the the critical value of the normal distribution, S is the estimated standard deviation, and E is the desired margin of error, in units. To find the estimated value of S, we generated our overcrowding measure 100 times. Furthermore, we use the Kolmogorov-Smirnov (KS) goodness-of-fit test for identifying the statistical distributions that best describe the data [37].

Next, we selected three cases of those sensitivity analyses that answer our main questions mentioned in the Introduction section. These cases present a best-fit analysis that aims to identify the statistical distribution that best describes our overcrowding measure in particular updated results.

Initial condition and scenarios

Based on the above processes, we explore different initial conditions related to the proportion of occupied and unoccupied cells. As we mentioned in the previous sections, occupied cells are related the proportion of tolerant and intolerant individuals, and unoccupied cells are associated with empty spaces. For simplicity, the total number of cells is set by a matrix with fixed dimension equal to (50, 50), that is 2500 cells. We should recall that this matrix shows a closed boundary that represents physical obstacles for free movements.

To set the proportion of tolerant and intolerant individuals, and unoccupied cells in the initial matrix, we generated a random sample of those cell attributes based on probabilities associated with each of them. For example, if we start with similar proportions of each type of cell, we can use probabilities associated with 1/3 of tolerant, intolerant, and unoccupied cells respectively. Therefore, we define the following set of tuples related to different scenarios based on the proportions of tolerant, intolerant, and unoccupied cells respectively: $(0.33, 0.33, 0.34)$, $(0.2, 0.2, 0.6)$, and $(0.4, 0.4, 0.2)$. The first scenario is related to similar proportions between occupied and unoccupied cells; the second is associated with decreasing and similar proportions of occupied cells, but

an increasing proportion of unoccupied cells; and the third is related to increasing and similar occupied cells, but a decreasing proportion of unoccupied cells. Finally, the number of iterations is fixed to a total of 60. We set this value as a reference to time, in minutes. In particular, we assumed that the presence of crushing events can happen within a range of 60 minutes, in a window of 15 min. [34, 38, 39].

Results

In this section, we present our findings obtained from the explorative data analysis. In particular, we display graphical and statistical results based on a conceptual approximation of model validation. This approximation uses the sensitivity analysis for exploring the behavior of our overcrowding measure in different sets of initial conditions and parameters. These sets aim to identify the current public perceptions and scientific knowledge about the importance of being tolerant or intolerant to similar ones and the consequence of the interpersonal distance in overcrowding events (Fig 1). In addition, we select particular cases for drawing attention to the most representative of cases (Fig 2, 3, and Table 1).

Fig 1 shows the general results of the sensibility analysis that point out the importance of similar or dissimilar behaviors and the interpersonal distance. It seems that the proportion of unoccupied cells affects considerably the dynamics that generate crushing events. For example, if we select the first row of the table, which is characterized by similar behaviors of cells, we can see that increasing the proportion of unoccupied cells affects the number of cells with overcrowding values. That is, the first entry in this row shows the lowest overcrowding values. This indicates that if we control the number of people in a crowd by giving more space or areas in which people can move without jamming, the probability of generating crushing is lower (see Fig 2).

Fig 1. Sensitivity analysis. The random seeds were set to obtain the same initial values of the matrix. For exemplifying the results of a total of $1,000$ realizations, each subfigure display three realizations per case. Subfigures in rows show variations in the tolerance and intolerance parameters, and columns show variations in the proportion of occupied and unoccupied cell parameters. The x axis in each subplot shows the number of iterations, and the y axis shows the values of the overcrowding measure based on cells of 12 surrounded neighbors). The shaded boxes represent the cases that we use for an in-depth analysis in Fig 2 and Fig 3

Now, if we see the third row, which is characterized by dissimilar behaviors of cells—i.e., extremist positions of tolerant or intolerant cells—we can see a sharp drop in the proportion of cells with overcrowding values. This result is particularly important because it suggests that even if there is an extreme preference of being surrounded by others, the drastic position of being intolerant produces lower proportion of overcrowding values. That is, the crushing events are less probable (see Fig 2).

The columns 2 and 3 in Fig 1 display the presence of unstoppable crushing events. All of these cases show a marked increase in the proportion of overcrowding cells. Even if there is a similar proportion between occupied and unoccupied cells, as well as the presence of extremist preferences of being tolerant or intolerant, the proportion of overcrowding values rapidly and dangerously increase. These results suggest that crushing events are more probable than we have thought at the beginning (see Fig 2).

With respect to our fourth particular case, we can see the behavior of cells in different time periods. Fig 2 and Table 1 display the KS test per time period related to the overcrowding measure, Fig 3. Fig 2 reveals that there is a clear difference between the best-fit statistical distributions of the initial conditions and the rest of the periods.

Fig 2. Best-fit analysis of fourth selected cases of the sensitivity analysis at particular given time step. Subfigures are the visual results of the KS test (see Table 2, supplementary material, for seeing the probability density functions, PDF). These results are based on a Monte Carlo simulation of a total of $1,000$ realizations per case. Subfigures in rows show particular time in minutes, and columns shows the selected cases of the sensibility analysis. The x axis in each subplot shows the number of neighbors related to our overcrowding measure, and the y axis shows the likelihood of occurrence of the overcrowding measure.

Table 1. KS test, estimated parameters, and first moments of the selected cases. KS test: (stat, p-value), estimated parameters based on the KS test: (parameter1, loc, scale), first moments: (median, mean, variance, skewness, kurtosis). These results are based on a Monte Carlo simulation of a total of $1,000$ realizations per case.

It suggests a differentiated behavior of cells that produce a marked transition between statistical distributions. Furthermore, this Fig shows that there has been a marked presence of the beta distribution in most of the periods of time. The preponderance of these results suggests the presence of highly skewed statistical distributions behind the collective behavior.

Fig 3. Overcrowding measures of selected cases of the sensitivity analysis at particular time. We use the "coolwarm" palette to display the result. From dark blues to bright reds, we can see the range of number of neighbors, from zero to 12 neighbors. These results are based on a Monte Carlo simulation of a total of $1,000$ realizations per case. Subfigures in rows show particular time in minutes, and columns shows selected cases of the sensibility analysis.

Finally, we emphasize that the case with the lowest probability of generating crushes is the one where there are dissimilar behaviors of occupied cells and a higher proportion of unoccupied cells. This result is clearly displayed in column two of Fig 2 and 3. In particular, Fig 3 shows a small number of dispersed clusters of cells in all periods of time. It suggests that this particular situation delays the process of crushing events.

Therefore, it seems that the interpersonal distance related to the proportion of unoccupied cells matters the most. An increased proportion of unoccupied cells is more preferable than an increase proportion of cells with extreme preferences among them.

Discussion

As previously stated in the Introduction section, our main questions aimed to identify situations in which the crushing is unstoppable, to show how probable are the presence of crushing events, and to differentiate levels of tolerant and intolerant cells surrounded by similar ones. Based on our findings, we reach the following interpretations.

Depending more on the initial space related to unoccupied cells than the extremist preferences of cells of being surrounded by similars, the crushing events are unstoppable and highly probable in overcrowding, social gatherings. The number of unoccupied cells can diminish the presence of crushing events, meanwhile the tolerant and intolerant preferences control how fast the crushing events can develop. Contrary to expectations, the only presence of extreme preferences of being tolerant or intolerant does not ensure an effective control of crushing incidents in social gatherings. Therefore, our hypothesis is partially true, this would imply that differences in preferences for being surrounded

by people in near-body proximities may explain the generation speed of crushes, but unfortunately they cannot prevent or stop them.

These findings have implications for understanding the dynamics behind crowd events. In particular, no matter the type and scale of social gatherings, it is indisputable the presence of uncontrollable factors that can cause severe personal injuries. Social gatherings, indoor or outdoors, such as music concerts, religious meetings, and sport events can represent the perfect situation for a fatal crushing. Therefore, every person should know the risks of being in overcrowding events.

Despite these promising results, questions remain. In particular, what are the effective practices for communicating the risks of social gatherings? How the current technology of mobil applications can prevent possible crushing in social gatherings? Future work is needed to generate an application for predicting fatal situations. We are considering to explore the generation of a warning signal in which every mobil device can be used to prevent fatal crushing. Similar to the warning signal of earthquakes, it is possible to generate a mobile application that indicates a warning signal of probable crushing events in real time.

0.1 Conclusion

Different types and scales of social gatherings in progress might show high probability of occurrence of crushing events. The self-awareness of your personal space plays a vital role for preventing risky situations and reacting during overcrowding. An initial situation in which there is more space than attendees in a social gathering is preferable, and it could reduce the risk of crushing events. When this condition is not feasible, there are high probabilities of harmful incidents and fatal crushing events. Therefore, every coordination committee of those type of social events should communicate the risk of being hurt due to the lack of enough room for moving freely.

Supporting information

S1 Appendix. Rules for moving or staying in place based on high tolerant and medium intolerant cells.

S2 Appendix. Rules for moving or staying in place based on high tolerant and high intolerant cells.

S3 Appendix. Statistical distributions of the KS test and their probability density functions (PDF). Name of the statistical distributions and their PDF used for the KS test.

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Appendix

Algorithm 2 Rules for moving or staying in place based on high tolerant and medium intolerant cells

Require: $m = matrix$
Ensure: $C_{ij} = Occupied\ cell$
  if C_{ij} has unoccupied neighbors > 1 **then**
    list neighbors to move

    if $C_{ij} == 1$ and similar neighbors < 7 **then**
    move new location ▷ Tolerant
    else if $C_{ij} == 1$ and similar neighbors $== 7$ **then**
    stay in location

    else if $C_{ij} == 0$ and similar neighbors < 4 **then**
    move new location ▷ Intolerant
    else if $C_{ij} == 0$ and similar neighbors $== 4$ **then**
    stay in location

    end if
  end if

Name	PDF
exponential	$f(x) = exp(-x)$, for $x >= 0$
gamma	$f(x,a) = \frac{x^{a-1}e^{-x}}{\Gamma(a)}$, for $x >= 0$ and $a > 0$
beta	$f(x,a,b) = \frac{\Gamma(a+b)x^{a-1}(1-x)^{b-1}}{\Gamma(a)\Gamma(b)}$, for $0 <= x <= 1$, $a > 0$, $b > 0$
Weibull minimum	$f(x,c) = cx^{c-1}exp(-x^c)$, for $x > 0$, $c > 0$

Table 2. Statistical distributions of the KS test and their probability density functions (PDF). Name of the statistical distributions and their PDF used for the KS test.

Algorithm 3 Rules for moving or staying in place based on high tolerant and high intolerant cells

```
Require: m = matrix
Ensure: C_ij = Occupied cell
  if C_ij has unoccupied neighbors > 1 then
      list neighbors to move

      if C_ij == 1 and similar neighbors < 7 then
      move new location                                   ▷ Tolerant
      else if C_ij == 1 and similar neighbors == 7 then
      stay in location

      else if C_ij == 0 and similar neighbors < 2 then
      move new location                                   ▷ Intolerant
      else if C_ij == 0 and similar neighbors == 2 then
      stay in location

      end if
  end if
```

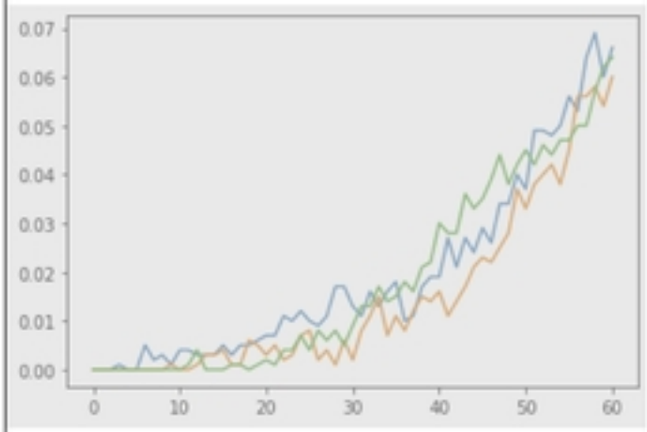
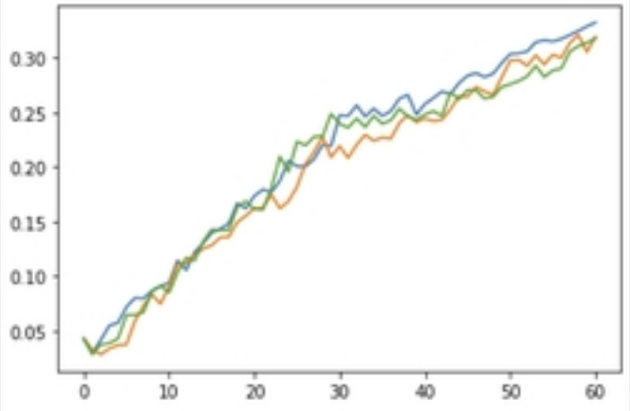
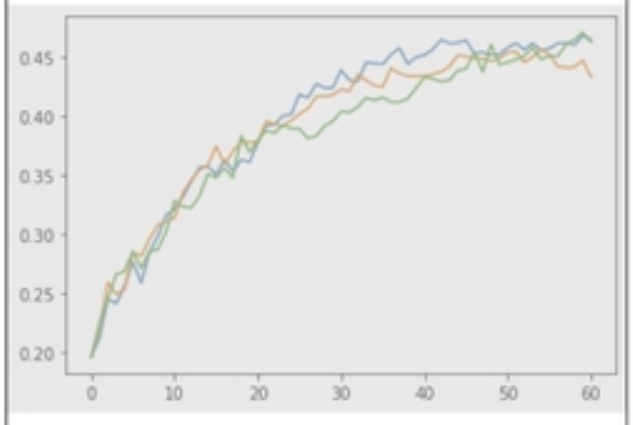
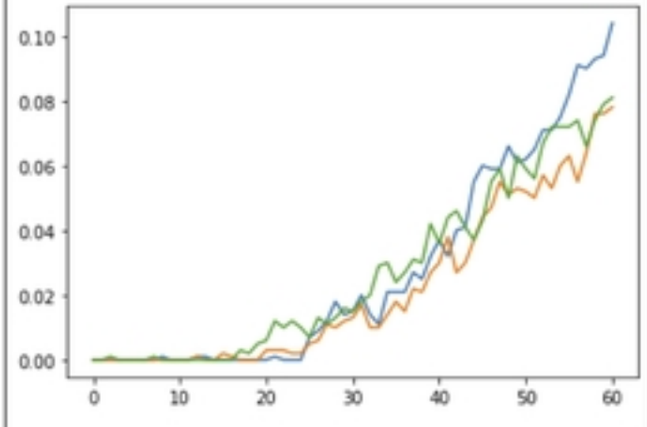
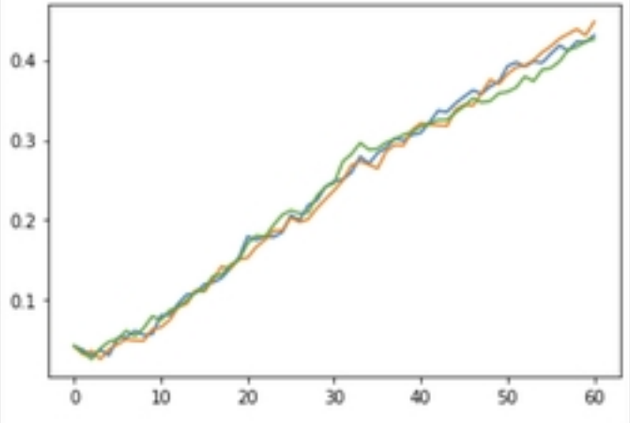
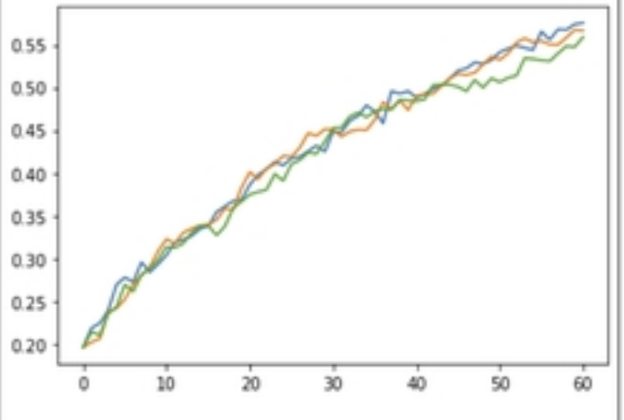
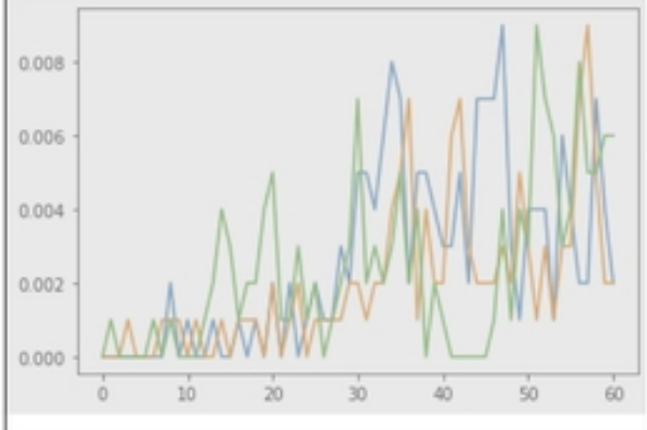
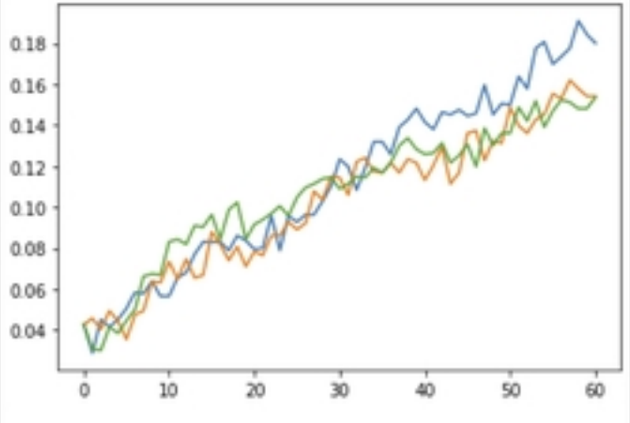
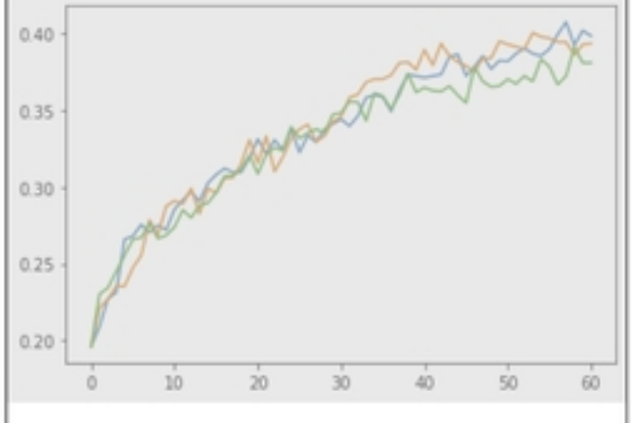
	(0.2, 0.2, 0.6)	(0.33, 0.33, 0.33)	(0.4, 0.4, 0.2)
(tolerance <=4 , intolerance <= 4)			
(tolerance <=7 , intolerance <= 4)			
(tolerance <=7 , intolerance < = 2)			

Fig01

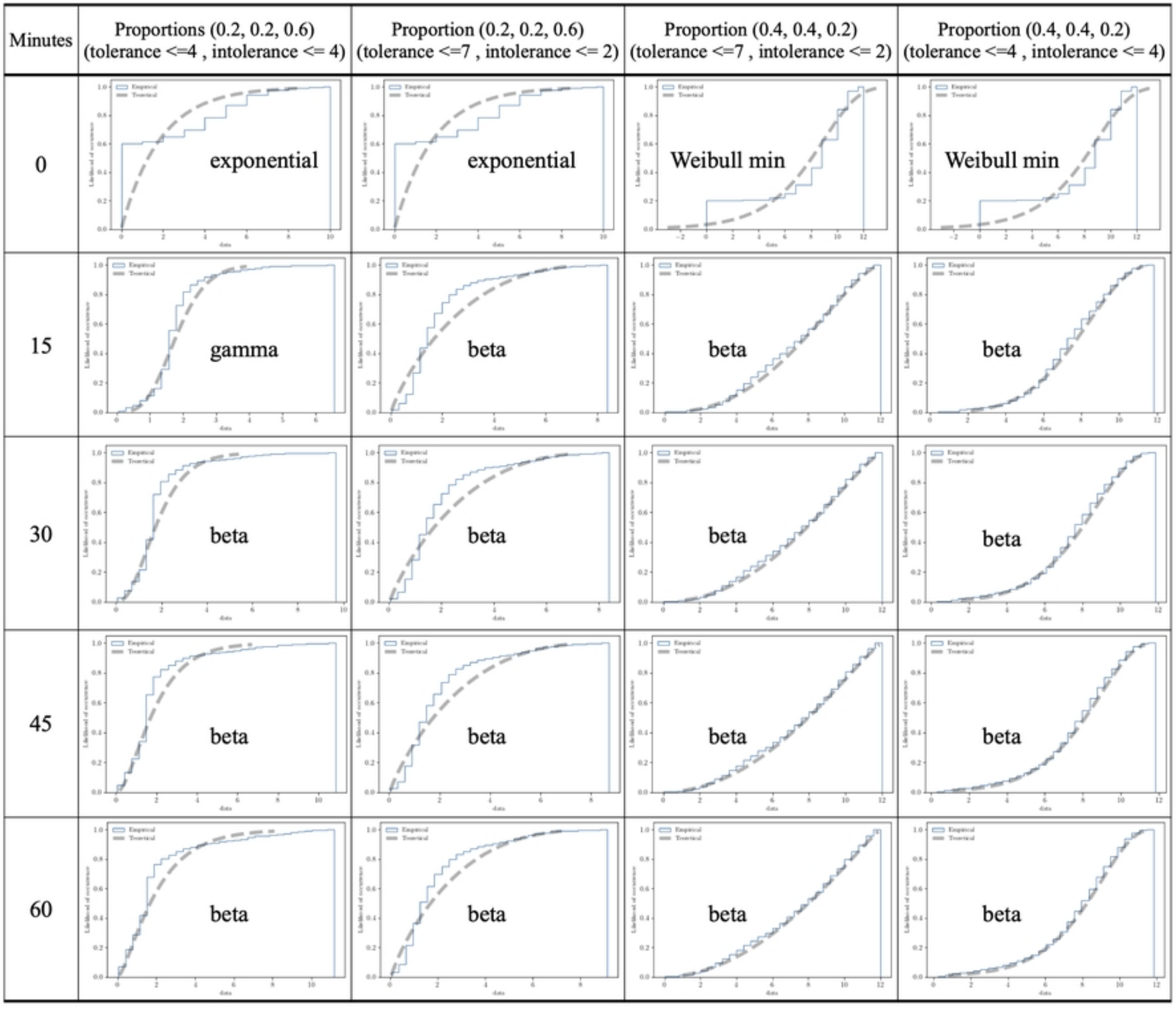

Minutes
Proportions (0.2, 0.2, 0.6) (tolerance <=4 , intolerance <= 4)
Proportion (0.2, 0.2, 0.6) (tolerance <=7 , intolerance <= 2)
Proportion (0.4, 0.4, 0.2) (tolerance <=7 , intolerance <= 2)
Proportion (0.4, 0.4, 0.2) (tolerance <=4 , intolerance <= 4)
0
exponential
exponential
Weibull min
Weibull min
15
gamma
beta
beta
beta
30
beta
beta
beta
beta
45
beta
beta
beta
beta
60
beta
beta
beta
beta

Fig02

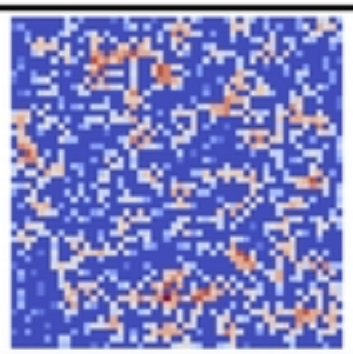
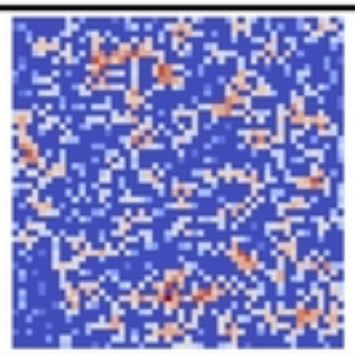
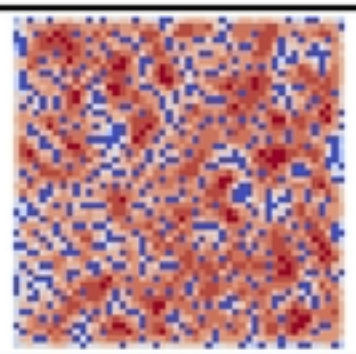
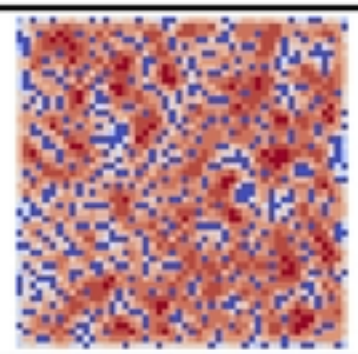
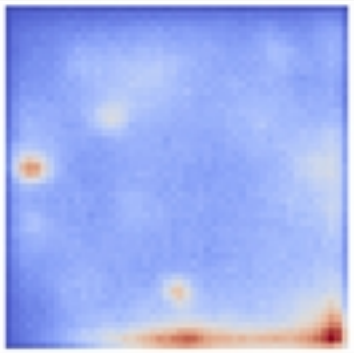
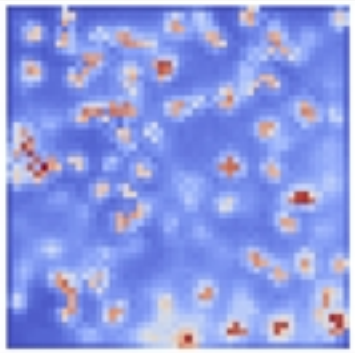
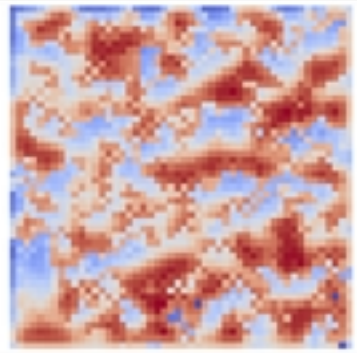
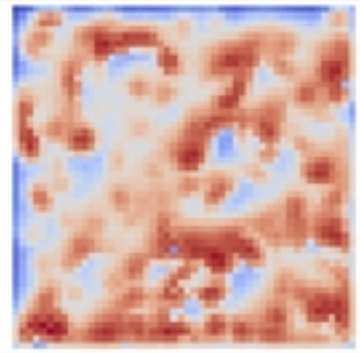
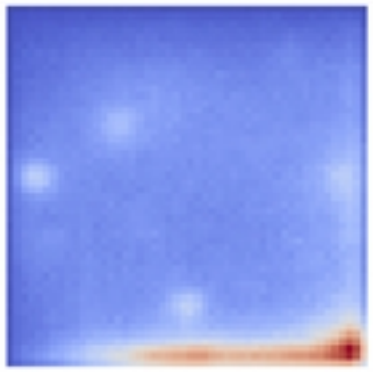
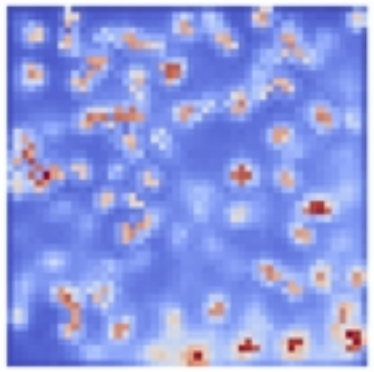
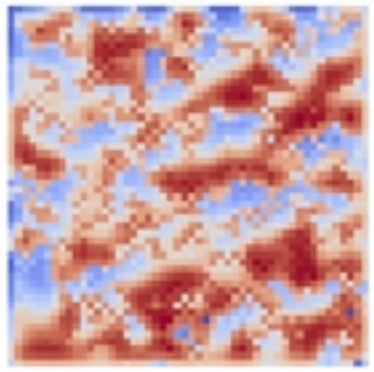
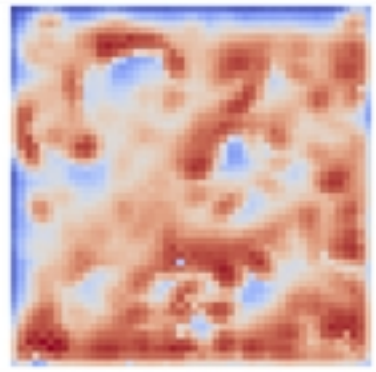
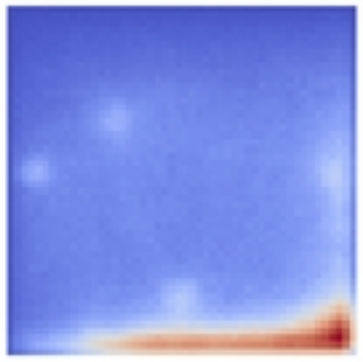
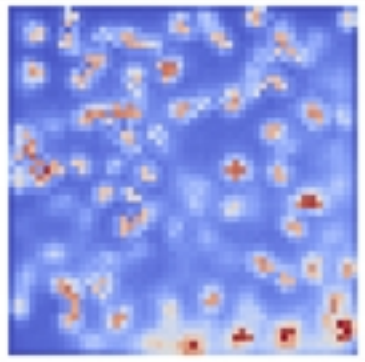
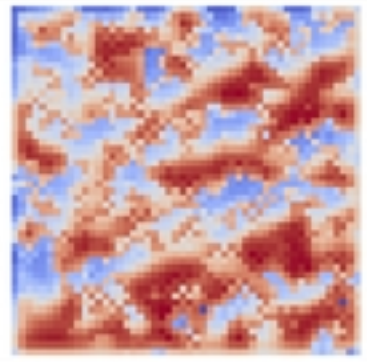
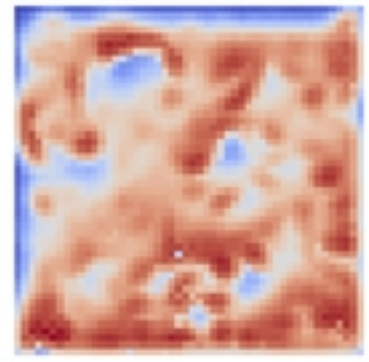
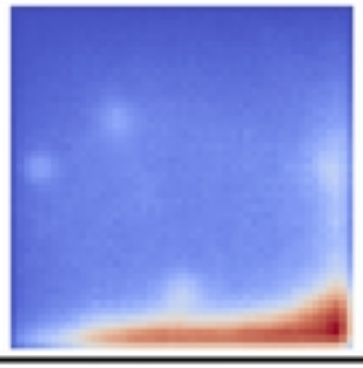
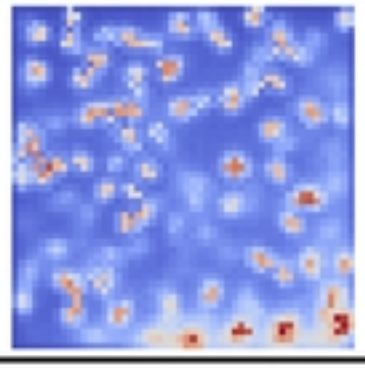
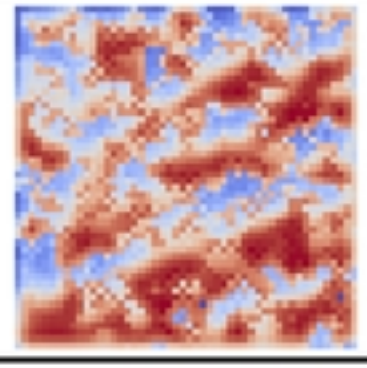
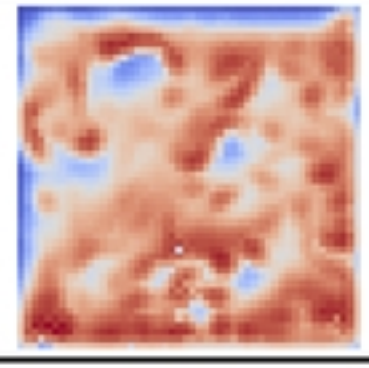
Minutes	Proportions (0.2, 0.2, 0.6) (tolerance <=4 , intolerance <= 4)	Proportion (0.2, 0.2, 0.6) (tolerance <=7 , intolerance <= 2)	Proportion (0.4, 0.4, 0.2) (tolerance <=7 , intolerance <= 2)	Proportion (0.4, 0.4, 0.2) (tolerance <=4 , intolerance <= 4)
0				
15				
30				
45				
60				

Fig03

Minutes	Proportions (0.2, 0.2, 0.6) (tolerance <=4 , intolerance <= 4)	Proportion (0.2, 0.2, 0.6) (tolerance <=7 , intolerance <= 2)	Proportion (0.4, 0.4, 0.2) (tolerance <=7 , intolerance <= 2)	Proportion (0.4, 0.4, 0.2) (tolerance <=4 , intolerance <= 4)
0	(0.0210, 0.2128) (0.0, 1.8592) (1.2886, 1.8592, 3.4566, 2.0, 6.0)	(0.0210, 0.2128) (0.0, 1.8592) (1.2886, 1.8592, 3.4566, 2.0, 6.0)	(0.0210, 0.2128) (118250608.8906, -307748410.8082, 307748419.8257) (8.0636, 7.5152, -21.0296, nan, nan)	(02109, 0.2128) (118250608.8906, -307748410.8082, 307748419.8257) (8.0636, 7.5152, -21.0296, nan, nan)
15	(0.0209, 0.2188) (10.6017, -0.6019, 0.2309) (1.7699, 1.8464, 0.5654, 0.6142, 0.5659)	(0.0131, 0.7721) (0.8556, 2.5635, 0.0269, 8.3657) (1.6922, 2.1204, 2.9713, 0.8947, 0.0789)	(0.0105, 0.9406) (2.5793, 1.5119, 0.1578, 12.1690) (7.7933, 7.5140, 6.7765, -0.4004, -0.6395)	(0.0126, 0.8150) (6.6547, 2.8432, -2.8025, 14.8092) (7.7891, 7.5735, 4.3816, -0.4938, -0.1435)
30	(0.0175, 0.4232) (3.1697, 6869783.3475, -0.0371, 4301611.1937) (1.7432, 1.9476, 1.2428, 1.1233, 1.8928)	(0.0190, 0.3187) (0.8744, 2.5981, 0.0469, 8.3648) (1.7341, 2.1533, 2.9474, 0.8838, 0.0637)	(0.0166, 0.4847) (2.2458, 1.2973, -0.1133, 12.1162) (7.8988, 7.5665, 7.4993, -0.4273, -0.6849)	(0.0111, 0.9126) (12.6099, 2.9417, -10.6884, 22.6715) (8.0005, 7.6946, 4.7630, -0.7359, 0.4451)
45	(0.0148, 0.6324) (1.9845, 22028825800.2849, 0.0278, 22327335176.8142) (1.7134, 2.0393, 2.0387, 1.4196, 3.0233)	(0.0189, 0.3279) (0.8756, 2.6628, 0.0369, 8.7179) (1.7590, 2.1942, 3.1185, 0.9004, 0.1125)	(0.0107, 0.9313) (2.0861, 1.1939, -0.0918, 12.0931) (7.9651, 7.5993, 7.9101, -0.4429, -0.7079)	(0.0111, 0.9102) (28.9740, 3.0586, -31.8220, 43.7754) (8.1404, 7.7735, 5.0102, -0.9298, 1.0885)
60	(0.0198, 0.2739) (1.4723, 2888033316146.783, 0.0316, 4148043505026.343) (1.6916, 2.1464, 3.0374, 1.6482, 4.0750)	(0.0161, 0.5271) (0.8646, 2.9059, 0.0489, 9.2105) (1.7034, 2.1611, 3.1427, 0.9748, 0.3286)	(0.0159, 0.5425) (1.9904, 1.1309, -0.0821, 12.0827) (8.0127, 7.6228, 8.1843, -0.4541, -0.7212)	(0.0163, 0.5107) (1723.2319, 3.2837, -2166.6281, 2178.6078) (8.2468, 7.8360, 5.2156, -1.0995, 1.8090)

Fig04