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SYSTEM DYNAMICS VERSUS CELLULAR AUTOMATA IN MODELLING PANIC SITUATIONS

Provitolo Damienne
Chargée de recherche CNRS
UMR 6049 ThéMA, CNRS, Université de Franche-Comté
32 rue Mégevand, 25 030 Besançon
UMR 6526 Géosciences Azur, CNRS, UNSA
250 rue A. Einstein, 06560 Valbonne
damienne.provitolo@geoazur.unice.fr

Daudé Eric
Chargé de recherche CNRS
UMR 6266 IDEES, Université de Rouen
7 rue Thomas Becket, 76 821 Mont Saint-Aignan
eric.daude@univ-rouen.fr

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ABSTRACT

In this paper we face system dynamics modelling and cellular automata to model panic processes. We compare both models using phase plans. The results of simulation confirm our hypotheses: First, a collective behaviour is not the arithmetical sum of the individual behaviours. Secondly the crowd causes the emergence of collective panic from individual panic. Both types of methodology produce the emergence of panic and identical curves for different values of initial conditions and parameters. But the effects of thresholds vary according to these values.

INTRODUCTION

Frequently, technological or natural disasters create panic behaviours. If these behaviours are not the most frequent, they are the most dreaded (Crocq 1994) and this for three reasons: they increase the number of victims, they are difficult to stop, and they have impact on disaster relief, and on the evacuation of the population.

The studies of the behaviour of panic during disasters are based essentially on the analysis of documents (archives, account of events, press cuttings) and on the observations realized by rescuers, medical profession and psychologists. Some agent based models study the evacuation of the panicking population (Helbing et al. 2000, 2002). These models are mostly applied to enclosed spaces. But few researches are interested in the processes of self-organization and in the emergence of the collective panic from individual panic.

In this paper, we compare two methods of simulation of the emergence of the collective panic from individual panic. These two methods are the system dynamics modelling and the cellular automata. The results of simulation based on these two approaches are different, although the structure and the hypothesis of the models are identical. We wish to defend the idea that the different results are not inevitably a limit of the modelling. According to the methodology and thus according to the scale of analysis of the phenomenon, the different results of simulation contribute to the knowledge of the emergence of panic.

UNDERSTANDING THE PANIC BASED ON INDIVIDUAL INTERACTIONS

The collective panic propagates in a crowd from behaviours of imitation (Dupuy 1991; Quarantelli 1954). It is indeed easier to follow his neighbours and the group than to think. In situation of stress, individuals who do not know which behaviour to adopt, adapt their behaviour according to their neighbours. In other words, the individuals imitate the others. The crowd is the support of contagion of the panic (Le Bon 2003). The collective panic emerges without concerted action. The collective panic would thus appear from the diffusion of individual panic, without a leader who would call to the panic, or prevent it.

We put forward three hypotheses to explain the propagation of the panic in a crowd:
Hypothesis 1: The panic spreads by behaviour of imitation. The imitation is based on the pattern of interactions between the individuals.
Hypothesis 2: A collective behaviour is not the arithmetical sum of the individual behaviours.
Hypothesis 3: The crowd causes the emergence of collective panic.

The models, presented in section *Two models to simulate emergence and diffusion of panic* are based on the epidemiological models of W. Kermack and A. McKendrick (1927). Three state variables describe the system of panic: the *population susceptible to panic* (*Psp*), the *panicking population* (*Pp*) and the *non panicking population* (*Npp*). These three state variables constitute the crowd, i.e. the *total population*. The *total population* is a fixed population of size *N*. The three populations (*Psp, Pp, Npp*) meet each other and interact. *Transmission rate* apprehend the contagion of the panic between both human populations in contact. *Interactions* between human populations indeed do not necessarily lead to contagion. This *transmission rate* is a coefficient which varies from 0 to 1, i.e. a low to a high contamination. After a certain period of time, people will stop panicking and resume normal behaviour. The *non-panicking population* is proportional to the numbers of *panicking population* and the *return time to normal behaviour* (*Rtn*).

TWO MODELS TO SIMULATE EMERGENCE AND DIFFUSION OF PANIC

We study the emergence and the spread of panic from two different methods of modelling: the System Dynamic (SD) and the Cellular Automata (CA). With the system dynamics modelling, the system in whole is the object of study. The systemic approach allows us to search the principles of organization and functioning of the system of panic. With cellular automata, individual behaviours and their interactions are the studied objects. The conditions of a possible organization and the relations between a micro level and a macro level are studied.

A system dynamics model of panic

The dynamic modelling of the system is found originally in the General System Theory of Ludwig Von Bertallanfy (Von Bertallanfy 1973). A system consists of several components connected by flows of material, energy or information. System dynamics is a methodology used to understand how systems change over time. The mathematical formalism of the system dynamics modelling is based on differential equations. The "Stella Research" software solves differential equations as difference equations. The graphical formalism is based on stocks, flows, converters and connectors. The stock or state variables are the reservoirs of the system. The flow variables correspond to the processes. Converters are rates; they connect different types of flows. Finally connectors are the relations and the feedback between the elements of the system.

Figure 1 shows the graphical formalism of panic model (Provitolo 2007) built with the "Stella Research" software. The model was presented during the *European Conference Complex Systems -EPNACS'07*. The aim of this paper is different. We compare the results of simulation obtained by both methods of modelling. The aggregate model includes three stocks of population: the *population susceptible to panic* (*Psp*) (1), the *panicking population* (*Pp*) (2) and the *non-panicking population* (*Npp*) (3), i.e. people will stop panicking and resume normal behaviour; *interactions* (4) between these three types of population, *transmission rate of panic* (*Tr*) and *return time to a normal behaviour* (*Rtn*). "Adoptions" (5) and "normal behaviour" (6) flows connect the three stocks of population. These three stocks constitute the *total population* (7).

The corresponding equations are:

$$Psp\ (t) = Psp\ (t - dt) - (adoptions) * dt \qquad (1)$$

$$Pp\ (t) = Pp\ (t - dt) + (adoptions - Normal\ behaviour) * dt \qquad (2)$$

$$Npp\ (t) = Npp\ (t - dt) + (Normal\ Behaviour) * dt \qquad (3)$$

$$Interaction\ PspPpNpp = (FractionPsp * Fraction\ Pp * Fraction\ Npp) * Total\ Population \qquad (4)$$

$$Adoptions = Interaction\ PspPpNpp * Tr \qquad (5)$$

$$Normal\ behaviour = Pp / Rtn \qquad (6)$$

$$Total\ Population = Psp + Pp + Npp \qquad (7)$$

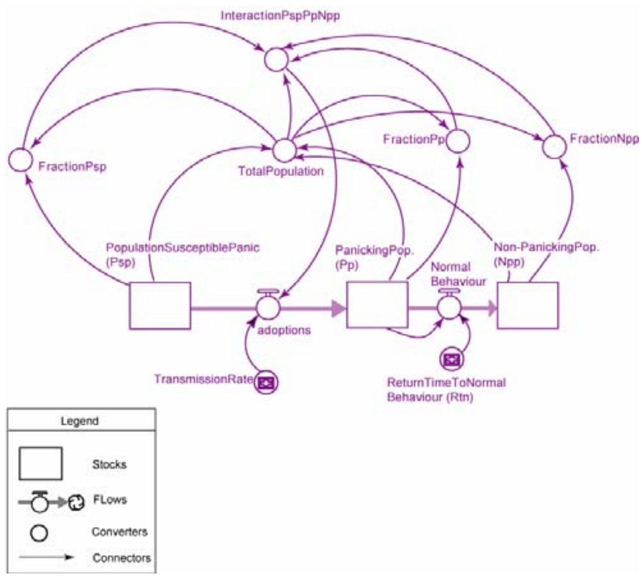


Figure 1 A system of panic based on the interactions between populations

With the system dynamics (SD), we compute how population of agents behaves as a whole. With the cellular automata (CA), individual agents are not processed as a stock but as individuals.

A cellular-automata based model of panic

A second step of this research uses cellular automata to build the same model, i.e. a model of panic based on interaction between individuals.

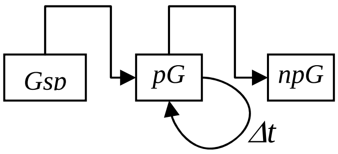
We identify three main differences between system dynamic and cellular-automata. First is the spatial component of cellular-automata, defined in this model by a two-dimension grid of $l*c=n$ cells. This spatial structure defines local interactions in cellular-automata and not global as in system dynamic, which means that a cell is only connected with its neighbour's cells, 4 (von Neumann neighbourhood) or 8 (Moore neighbourhood) for example. Second is the nature of the dynamic, performs by transition rules *T*. In cellular automata, the future state $S(t+1)$ (8) of one cell depends of its actual state $S(t)$ and of its environmental state (Ev). We can then define cellular automata as a discrete and local dynamic system where:

$$S(t+1) = T(S(t), Ev(t)) \qquad (8)$$

is the transition rule applied at each time and for all cells. A third difference is more implicit, it is based on the local and distributed nature of CA compared to the global and centralised nature of SD: we use to view cells as micro-structures or micro entities. In this way, it's accurate to express this alteration by changing the name of the different states in the model. A cell represents a group of individuals which can takes three different states. The state space (9) is:

$$S = \{Gsp, pG, npG\} \qquad (9)$$

where transition is not symmetric, $Gsp \rightarrow pG \rightarrow npG$.



In this way, population of susceptible *(Psp)* is the sum of groups of susceptible *(Gsp)*. Then and to be in accordance with the system dynamics model, we use three variables (10, 11, 12) to observe the dynamic of the model:

$$Psp_i = \sum_{i,j} Gsp_{i,j}(t) \quad (10)$$

$$Pp_i = \sum_{i,j} pG_{i,j}(t) \quad (11)$$

$$Npp_i = \sum_{i,j} npG_{i,j}(t) \quad (12)$$

The environment *Ev* of a cell c_{ij} is composed of it's 8 neighbours cells, where *v* (13) gives the coordinates of the cells centred on the cell c_{ij} :

v = ((0, -1), (1, 0), (0, 1), (-1, 0), (-1, -1), (1, -1), (1, 1), (-1, 1)) (13)

The transition from the state *Gsp* - the *group susceptible to panic* -, to the state *pG* - the *panicking group* -, depends on the proportion ν_i of panicking groups in the spatio-temporal neighbourhood of the cell, which is the average of panicking groups in this vicinity (14):

$$< \nu_i(t) >_{V\times T} = \frac{1}{n_R} \sum_{j\in V(i)} \nu_j(t) \quad (14)$$

where n_R is the density of all groups in the neighbourhood. As the global density is equal to $l*c=n$ in this model, n_R is equal to 8 for each cell. This parameter ν_I represents the probability to interact with a group of panicking people. But it is not sufficient to interact with a panicking group to be panicked. The transition probability from the state *Gsp* to the state *pG* for the cell *i* (15) is then:

$$p\left(s_i = pG \middle/ s_i = Gsp \right) = t_r \cdot < \nu_i(t) >_{V\times T} \quad (15)$$

where t_r is a continuous parameter representing the *transmission rate* of the model, the probability that an interaction transmitted the panic. This *transmission rate* varies from 0 to 1. A main difference with the system dynamic's model is the result of this process: the result is discrete (panicking or not) whereas with system dynamic the result is continuous (a proportion of panicking people at each round). With cellular automata, we then have to choose a way to transit from the state *Gsp* to the state *pG,* depending of this probability. We use the algoritm (16):

to Panic
  if (pG / (Gsp+pG+npG)) ∗ tr > random-float 1
    [si(Gsp) → (pG)]
end (16)

where random-float reports a uniform random floating point number included in [0;1[. Once in the state *pG*, the group *i* stay in this panicking situation a certain laps of time *Rtn*, and then pass on the state *npG*, the panic is off in this group and the transmission to the neighbours is off as well (17).

$$s_i(t) = \begin{cases} pG \;\; if \;\; \tau_i(t) \in [0, Rtn[\\ npG \qquad else \end{cases} \quad (17)$$

where *τi(t)* represents the time passed since the panic is on, which is linked with the *Rtn* in the system dynamic model. We have tried a probabilistic method to smooth the transition between the *pG* to the *npG* but results do not give new interesting facts.

SIMULATIONS TO PREDICT EMERGENCE AND DIFFUSION OF PANIC

According to the values of initial conditions and of parameters, we observe qualitative modifications of the trajectories for both methodologies. On the other hand, according to the methodology, i.e. the system dynamics modelling or the cellular automata, the results differ for identical values. These results will be analyzed in the section *Discussion* .

Results of simulation with system dynamics modelling

We present results of simulation for different values of *panicking population* and of parameters (*transmission rate* and *return time to normal behaviour*) related to the model. We will focus more particularly our attention on the spread and the emergence of panic. The *population susceptible to panic* is always equal to 3721 individuals. The phase plans (Figures 2-3) allow us to analyse the various trajectories of the system.

Two cases are presented.
Case 1: the *population susceptible to panic* is equal to 3721 individuals and the *panicking population* is equal to 50 individuals. We study the system evolution by making vary the *transmission rate* of the panic (between 0 and 1, i.e. a low to a high contamination.) and the *return time to normal behaviour* (between 1 and 10). Nine tests are realized with values of *Tr* equal to 0.1; 0.5 or 0.85 and values of *Rtn* equal to 1, 5 or 10 (Figures 2a, 2b, 2c).

Case 2: the *population susceptible to panic* is equal to 3721 individuals, the *panicking population* is equal to 200 individuals. As in the case 1, we study the system evolution by making vary the *transmission rate* of the panic (between 0 and 1). The *return time to normal behaviour* is equal to 22 units of time (Figure 3).

Case 1 :
Psp = 3721
Pp = 50
Npp = 0 (at the beginning of the simulation, this stock is equal to 0 because the panicking persons have not yet found their normal behaviour)
Transmission rate (*Tr*) = 0.1; *Tr* = 0.5; *Tr* = 0.85
Return time to a normal behaviour (*Rtn*) = 1 units of time, *Rtn* = 5, *Rtn* = 10

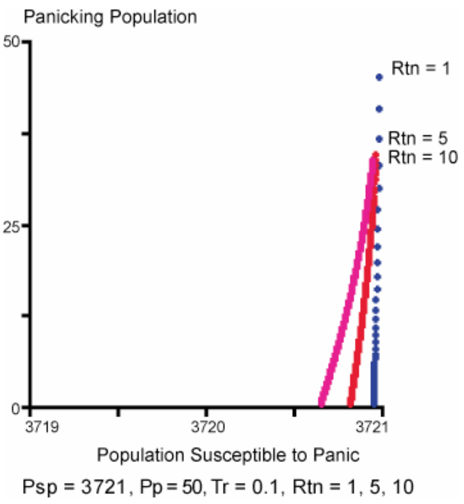


Figure 2a Panic cannot spread over

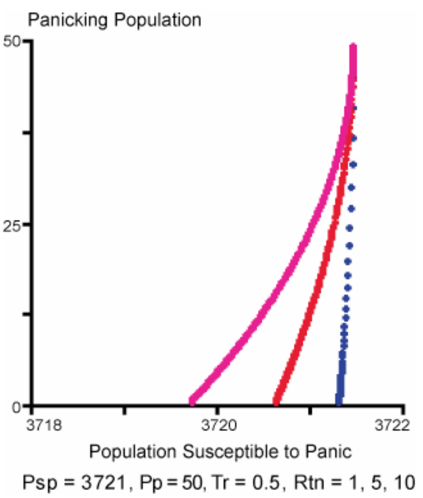


Figure 2b Panic cannot spread over

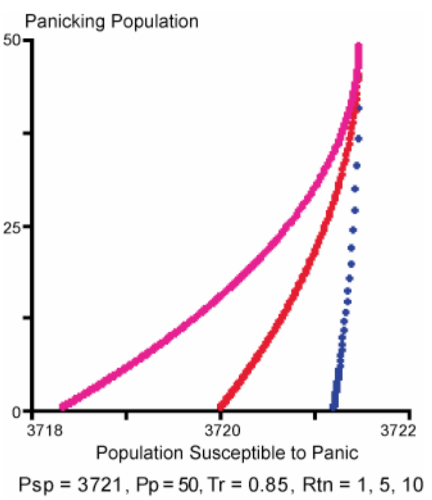


Figure 2c Panic cannot spread over

For different values of *Tr and Rtn* (Fig. 2a,b,c.), there is no emergence phase of panic. The *panicking population* tends to disappear. We do not observe qualitative modification of the model. Whatever the values of the *rate of transmission* and the *return time to normal behaviour*, the trajectories have the same shape with less than 2% of the *panicking population*. On the other hand, for these same conditions, the results of simulation with cellular automata differ.

Case 2:
Psp = 3721
Pp = 200
Npp = 0
Transmission rate (*Tr*) = 0.1; *Tr* = 0.5; *Tr* = 0.85
Return time to a normal behaviour (*Rtn*) = 22 units of time

The trajectories converge to an equilibrium point (coordinated 0, 0) where *Psp* and *Pp* are zero (Fig. 3). This equilibrium point with coordinates (0, 0) can be explained by the flow *normal behaviour* which tends to empty the stock *panicking population* and to feed that entitled *non-panicking population*.

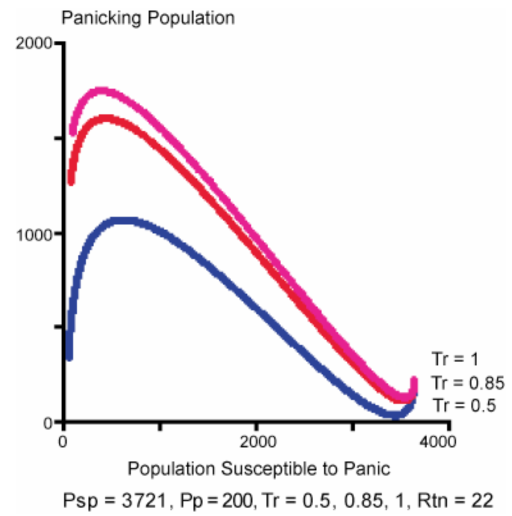


Figure 3 Diffusion and emergence of panic

But contrary to the case 1, the collective panic emerge. The *population susceptible to panic* and the *panicking population* decrease at first, and then increase. There is a bifurcation and the emergence of the panic before reaching a new bifurcation bringing the system to another state of equilibrium where *Psp* and *Pp* are zero. The modification of the initial condition of the *panicking population* and *Rtn* influence the proportion of population susceptible to panic and panicking population. There is a threshold, with *Pp* = 200, *Rtn* = 22 and *Tr* ≥ 0.5.

Results of simulation with cellular automata

We use the same initial conditions as previously (case 1) with the system dynamic model, defined for each simulation by the set {*pG*; *Rtn*; *Tr*}. The domain is composed of 3721 cells in a regular grid.

Figure 4 shows two very different simulations with for the upper one the set of initial conditions equal to {50; 10; 0.85} and the lower one initial conditions equal to {50; 7; 0.2}. These simulations show the importance of parameters in the spread of the panic, especially transmission rate.

This suspicion fits with the study of parameters space built with the set {50; 1,..., 10; 0.05,…, 0.85} (Figure 5). When *transmission rate* is lower than 15%, a high period of transmission cannot expand the volume of *panicking population*. On the contrary, when *transmission rate* is high, up to 70%, even a small period of panic activity at the group's level produces a high level of collective panic. The most interesting zone here is the small part of the system where panic can go up or go down, in the area of 50% people panicked. A small difference in one or other parameter can make the system go from one attractor to the other.

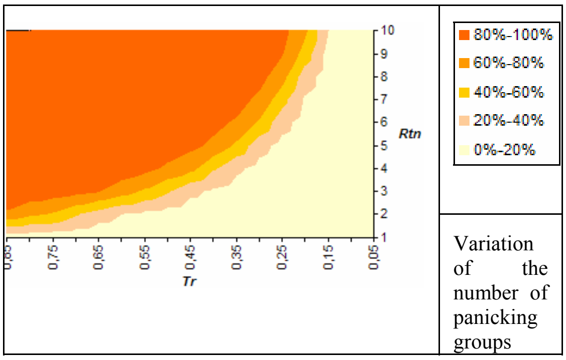


Figure 5 Parameter space of panic's diffusion: from low diffusion (yellow) to global diffusion (red)

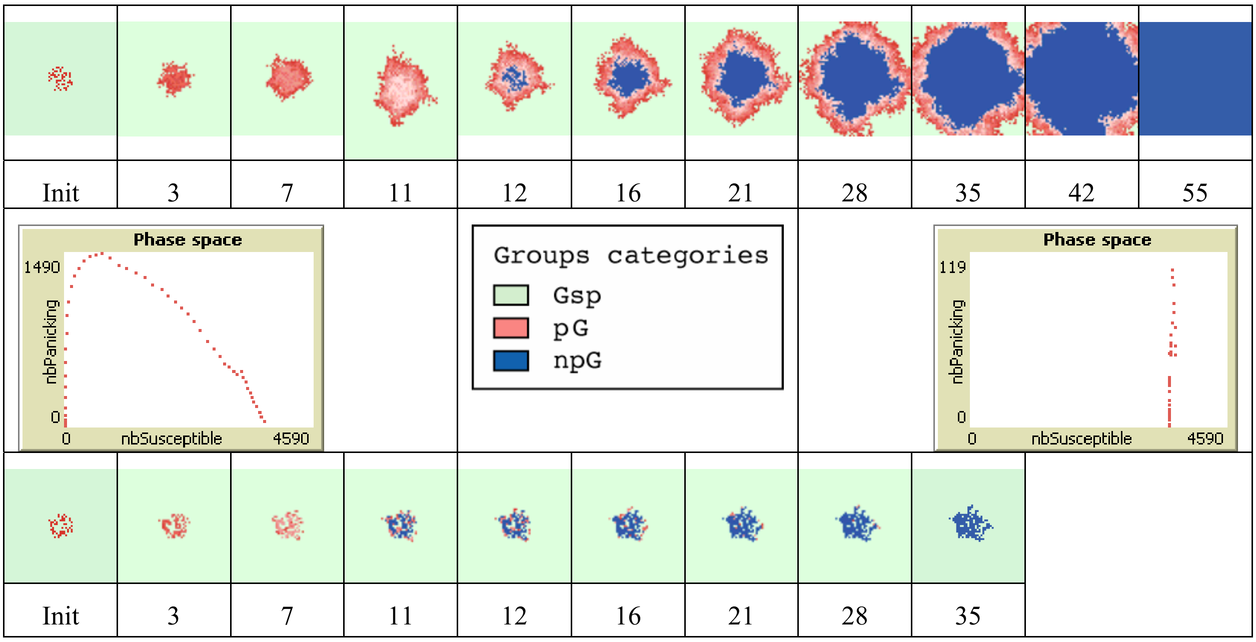


Figure 4 Phases space and screen-shoot of 2 simulations

DISCUSSION

The study of panic enables to put human vulnerability in the foreground of the analysis of disasters. But the three hypotheses simplify the real situations. For example, the sensitivity of the population is not included in the model. This sensitivity depends on the age of the population, on the social structure (Granovetter 1978), or others factors. The models, in the same way, do not integrate the shape of the environment, for example the shape of building or of road.

Another limitation of this work is the quantitative prediction. We cannot predict the number of *panicking population* for three reasons: At first, experimentations *in situ* are few. These experimentations, when they are carried out, give an uncertain estimation of the behaviour that could be effectively chosen in the emergency of the situation. It is difficult to predict what will happen. Secondly, the data to calibrate the models do not exist. Thirdly, it is difficult to quantify, at the beginning of the event, the number of *panicking population*, population who contaminate the others.

These two methods give us a global understanding of the spread of the panic in the population. It is indeed possible to predict qualitatively the dynamics of the phenomenon and to identify the bifurcation. Panic is not a fate. Modifying the panic, and thus the vulnerability of the population, requires planning and preparedness: Implementation of a variety of measures such as prevention, evacuation before an event occurs, knowledge of the preventive measures in order to avoid the collective behaviour of panic.

The various methods of simulation show that different results are not inevitably a limit of the modelling. Several models represent the same reality (Israël 1998). And it is difficult to decide which of these two models give the best representation of the collective panic. According to the methodology and thus according to the scale of analysis of the phenomenon, the different results of simulation represent certainly a contribution of knowledge on the studied system. Whatever the methodology will be, the results confirm our hypotheses: First, a collective behaviour is not the arithmetical sum of the individual behaviours. Secondly the crowd causes the emergence of collective panic from individual panic. There is indeed a repetition of the behaviour in the crowd.

Both types of methodology produce the emergence of the panic and the forms of identical curves for different values of initial conditions and parameters. But the effects of thresholds vary according to the values. For example, with cellular automata, the panic spread with 50 *panicking population* in a total population of 3721 people. With the system dynamics modelling, 200 persons are needed to observe the emergence of the panic.

A difference between the SD and the CA model is that $\tau i(t)$ is turned down of one unit at each round, and a group quit the panic situation only if $\tau i(t)$ is equal to zero. Whereas panicking is submitted to a probability, stop panicking is deterministic in this model. With the system dynamics modelling, at each step, the value of inflow is added to stock. For example, the value of inflow *normal behaviour* is always the previous value of stock *panicking population* times a coefficient, here the *return time to normal behaviour*.

CONCLUSION

The emergence of the panic does not appear in every situation. This emergence depends on three elements: the *transmission rate*, the *return time to normal behaviour*, but also the number of *panicking population* at the beginning of the simulation. The results of simulation of these two methods confirm our hypotheses: a collective behaviour is not the arithmetical sum of the individual behaviours and the crowd causes the emergence of collective panic from individual panic. To conclude, the models of simulation are a representation of the reality (Israël 1998) and not the representation of the reality. Whatever the methodology will be, the modelling and the simulation of many agents in interaction ask the question of the emergent properties.

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