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Understanding and Simulation of Human Behaviors in Areas Affected by Disasters: From the Observation to the Conception of a Mathematical Model

By Nathalie Verdière, Guillaume Cantin, Damienne Provitolo, Valentina Lanza, Edwige Dubos-Paillard, Rodolphe Charrier, Moulay Aziz-Alaoui & Cyrille Bertelle

University of Le Havre, France

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UNDERSTANDINGANDSIMULATIONOFHUMANBEHAVIORSINAREASAFFECTEDBYDISASTERSFROMTHEOBSERVATIONTOTHECONCEPTIONOFAMATHEMATICALMODEL

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Keywords: human behavior, panic, disaster, systemic modeling, mathematical modeling, differential equation.

I. Introduction

When facing crises "beyond the scope" turns out to be no longer exceptional occurrences and becomes the common background for risk management (Lagadec, 2009), the assumption of responsibilities in major crises or disasters, regarding security concerns, makes focus on the safety of residents as well as the sustainability and resilience of societies.

Strategies have been thus introduced aiming at addressing threats, reducing vulnerabilities, and developing populations' capabilities for resilience and adaptation, all at once. On the latter concern, the purpose is to raise public awareness and prepare inhabitants to face the risk they might encounter, so that they can adapt their behaviors to the crisis.

Despite these efforts, it is clear that populations are often unaware of how they should act or take action to protect themselves against the threat or disaster they might face (CEPRI, 2013). This lack of awareness is not only limited to populations; it refers to the challenges of the research community in identifying the wide range of behaviors actually expressed in the case of a disaster (Crocq, 1994), their sequence, dynamics, and inter-dependence (Provitolo et al., 2015; Verdière et al., 2014).

These limitations relate especially to the relatively youthful works referred to, as well as the difficulties experienced in real-time observation and analysis of human behaviors facing a crisis or disaster. The scientist, who does not hold time series for human response analysis, can then proceed to simulations.

In mathematical and computer literature, scientists have focused essentially on the modeling of crowd dynamics and in case of a catastrophic event, on the modeling of collective panic (Helbing et al., 2000; Provitolo, 2009) or simulating movements inside buildings in order to model pedestrian evacuation (Yang et al., 2009). Several models have been developed at different scales.

Author α σ ω χ: Normandie Univ, France; ULH, LMAH, Le Havre; FR CNRS, ISCN, rue Philippe Lebon Le Havre, France.
e-mails: nathalie.verdiere@univ-lehavre.fr, gcmaths76@free.fr, valentina.lanza@univ-lehavre.fr, aziz.alaoui@univ-lehavre.fr
Author ρ: Univ. Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur, IRD, Géoazur UMR, Valbonne.
e-mail: damienne.provitolo@geoazur.unice.fr
Author ¥: Université Paris, Panthéon-Sorbonne, Géographie-Cités UMR 8504, Paris. e-mail: Edwige.Dubos-Paillard@univ-paris1.fr
Author § ν: Normandie Univ, France; ULH, Laboratoire d'Informatique, du Traitement de l'Information et des Systèmes (LITIS), Le Havre, ISCN, rue Philippe Lebon Le Havre, France.
e-mails: rodolphe.charrier@univ-lehavre.fr, cyrille.bertelle@univ-lehavre.fr

At microscopic level, cellular automate or agent based models have been proposed (Pan et al., 2007). They consist in modeling each individual of the population as a single entity. For the study of pedestrian flows, some microscopic models consider the pedestrians as particles subject to a mixture of socio-psychologically and physical forces (Helbing et al., 2000). Even if this approach permits to take into account the heterogeneity of the population, it requires high computational. Furthermore, the microscopic properties are sometimes difficult to transfer at a macroscopic level (Rahmandad et al., 2008).

At macroscopic level, partial differential equations are used to model the crowd dynamics. They permit to describe the evolution in time and space of the density and mean velocity of the crowd flow. In (Venel et al., 2008, Goatin et al., 2010), for example, the interactions of crowds and structures in panic situations are considered.

Finally, at mesoscopic level, a level between the microscopic and the macroscopic ones, the models exploit the approach of the kinetic theory, through the Boltzmann or Vlasov equations, depending on the different range of interactions (Bellomo et al., 2011).

However, all these models focus either on the modeling of crowd or/and on the panic reactions and they do not really take into account all the works done in Human Science and Social Science since the second half of the twentieth century (Janis, 1951; Tyhurst 1957, Whyte, 1978; Quarantelli, 2008). They have established that during a disaster, individuals can exhibit different concurrent reactions and they do not stay in the same behavior. Indeed, individuals adopt a sequence of behavioral responses depending on the regions of the brain processing information (Noto et al., 1994), the first one, instinctive and of short duration, the second reasoned. The aim of the paper is to gather the different types of knowledge from human sciences researchers, mathematiciens and computer scientists and to propose a mathematical model considering the panel of behaviors occurring during a disaster. The aim at long term will be to better understand the human reactions during a sudden disaster according to the place, the culture of risk of the population, etc...

Our model has been developed from the SIR based-models which are compartmental models widely used in epidemiology (Murray, 2002). In these models, the population, dense or not, can be decomposed in several subpopulations each of them corresponding to a compartment. Different types of transition can also be considered between each of them as imitation processes corresponding to contagion processes in epidemiology (Hatfield et al., 1994). A first work in this sense has been proposed in (Verdière et al., 2014). (Verdière et al., 2014) has developed a first SIR-based model, considering three different types of collective behaviors occurring in catastrophic events and their different interactions. In this paper, we propose to extend this work in completing both the investigation in the human science area and the mathematical model. About the latter, according to the advices of human sciences, the imitation terms have been changed in order to better describe the imitation between two concurrent behaviors. This change ensures us now to obtain positive solutions that is, for all values of parameters in the system, realistic behaviors. This positivity was not always guaranteed by the previous system and reduced the scenarios of disasters. In this paper, we also propose to incorporate, in the model, the possibility to take into account a succession of catastrophes and the mortality.

The paper is organized as follows. In section I, we explore the factors influencing the human behaviors in the context of disasters. From this analysis, we give, in Section II, our choices for the modeling of the behaviors in such event as the considered interactions between them. In Section III, we present the mathematical model from a graphical representation. Several simulations are proposed in Section IV, representing different scenarios of disasters. Finally, in Section V, we conclude the paper.

II. Factors Influencing the Human behaviors in the Particular Context of Disasters

In order to position our research about the state of the art in this domain, we will first precise the notion of human behaviors and the factors influencing these latters during a catastrophic event. This fast overview will permit to specify our choices both in terms of reactions to take into account and parameters to integrate in the modeling.

In 1936, K. Lewin (1936) formalized the human behavior (C) by a function of the form:

$C = f(P, E)$. This formalization indicates that the environment (E), in the broader sense of the term (i.e physical, social cultural, spatial, temporal environment), and the characteristic of individuals (P) (i.e. physical resistance, experience, memory of past events) are parameters conditioning the reactions of populations. Relatively to the field of disasters, these parameters are:

a) *Origin of the risk and anticipation of the beginning of the disaster (parameter E)*

Some disasters can be anticipated and announced by different information channels (newspapers, radio, televisions...). It is often the case of hurricanes, floods, volcanic eruption. However, other disasters arrive by surprise as earthquakes and nuclear explosions or, in another domain, terrorist actions. In the first case, we observe controlled behaviors (Baumann and Sims 1974; George and Gamond, 2011) since the authorities actions allow the population to be prepared in front of the risk (organised evacuation, consideration of the potential effects of the disaster) whereas in the second case, because of the effect of surprise and fear, reactions are more instinctive (Laborit, 1994), immediate and automatic (sideration, leak for example during non anticipated auto-evacuation) at least in the first time instants of a disaster (Provitolo et al., 2015).

b) Areas of the disaster (parameter E)

Human behaviors depend also on the area of the catastrophe in which the population is located (Crocq, 1994). The affected area is usually divided in four types of zoning: the impact zone, where the material destructions, the number of victims and the social and territorial disorganization are maximal; the destruction zone, where the material damages are very important but where the number of injured people is less and the social organisation is very perturbed; and finally the marginal and external zones which are generally less impacted by the disaster.

c) Specificities of the impacted zone (parameter E)

The human behaviors and the associated displacements are generally guided by the territory and the alternatives that it offers particularly for the evacuation or leak, the accessibility of temporary shelters. One can name some non exhaustive elements, that affect the behavioral reactions: the presence of open spaces or buildings permitting to ensure the security of populations, the number and the position of exits (Helbing et al., 2000; Henein and White, 2005), the identification of arrow evacuation exits, the morphology of networks and the state of the communication infrastructures (Nabaa et al., 2009).

d) Characteristics of individuals (parameter P) and density of population (parameter E)

The behaviors vary also with the physical factors of individuals (age, agility), their learnings and experiences (culture of risk), their knowledge about the place, the individual motivations (join or save his family members, to become an hero...) but also the local perception of the environment (Wijermans, 2007). Indeed, without any consideration of the risk, most of individuals are influenced by the density of population (E). This density, which increases when the crowd is being formed, makes the situation more dangerous (i.e. reduction of the choices for the individual displacements, increasing of interactions between individuals and their neighbours) and can lead, for example, to extreme situations of trampling and suffocation. The origin of the risk, the anticipation of the beginning of the catastrophe and the spatial zoning are factors that are taken into account in the construction of the mathematical model. At this stage of the modeling, we have decided to integrate general parameters, that is parameters not specific to an area or to social, economic or cultural characteristics as age, sex, cultural area, level of income or wealth. Indeed, the latter do not play key role during the catastrophe but rather before and after the catastrophe (Baumann and Sims, 1974).

III. CHOICES OF THE MODELED BEHAVIORS

Exceptional catastrophic events induce a complete break with daily behaviors (Noto et al., 1994). These behaviors can be varied in nature, they can be isolate or collective, they can change over time (succession of behaviors) and have a limited duration.

These particular behaviors come from an hostile pressure of the environment, often brutal and unpredictable (e.g. earthquake, local tsunami), sometimes continuous (e.g. drought), that impose new ways to act in state of stress.

Provitolo et al., 2015 have proposed a typology of human behaviors in impacted zones of catastrophic events, based, first, on the implicated cerebral zone in the behavioral answer, then, on temporal phases of the event and its alert.

In the impacted zone, two mains categories of behaviors have been noted, according to the region of the brain that acts:

- the reptilian zone of the brain, the center of our instincts and the basis of our emotions. It induces instinctive behaviors that handle with the impulsive and urged behaviors;
- the pre-fontal zone of the brain that leads to controlled behaviors. It adapts in a more reflexive way the reactions to an external perturbations.

The first category groups together the behaviors of instinctive escape and fight, the panic, but also the behaviors as sideration and automaton (Crocq, 1994). This mechanism allows people to react quickly either by running away as fast as possible or by being flabbergasted and being physically unable to move in space. The second category concerns calm and self-control behaviors.

In our mathematical model, we have decided to distinguish three different types of behaviors in the situation of a sudden disaster. Despite the diversity of reflex behaviors, we have decided to divide them just in two types. The first one consists in reflex behaviors except panic. Thus, for example, it groups together sideration and automate behaviors.

The second type concerns the panic reactions since they have a particular status in reflex behaviors. Indeed, this behavior is the most feared: it can provoke dangerous situations in a crowd, due to trampling and crushing and can cause deaths. Furthermore, this mechanism is difficult to stop once started since its extinction is more linked to internal dynamics than to the remoteness of the danger (Crocq, 2013). Notice that this behavior is not always adopted as, for example, during an earthquake in Japan, a country where the population is formed to react adequately in case of such disaster.

Finally, since the prefrontal cortex takes over the reptilian brain, the third type of considered behaviors includes all the controlled, intelligent and reasoned reactions. They can take different forms in a catastrophe, as, for example, evacuation, leak, containment, sheltering, research for help, looting, theft, etc... Despite their variety, we have decided to globalize, as for the first type, all these controlled behaviors.

The three previous behaviors do not all occur at the same time and respect a certain order. Indeed, the first behavior of an individual in the face of danger is a reflex one, followed, in a second step, by controlled or panic behavior (George and Gamond, 2011).

The dynamics of these behaviors can be represented as a complex system composed of different groups in interaction. Interactions can come from different mechanisms: the simple aggregation resulting of identical individual behaviors; the causality, taking into account the possible succession of behavioral reactions; the emotional contagion, a process resulting of imitation between individuals.

In the following section, the mathematical model is presented.

IV. Mathematical Model

Before presenting our model, we propose to describe the three meta-behaviors in the exceptional situation of a disaster through a graphical model.

a) Graphical model

The graphical model (Fig. 1) corresponds to the evolution of individual behaviors of a population at different times *t*.

Here, *Q* corresponds to the number of individuals in a daily behavior, *r* and *p* to uncontrolled behaviors, more precisely reflex and panic behaviors, c to controlled ones.

The population *Q* is composed of *N* individuals and is constituted of two sub populations.

- Q_1 (t) represents the number of individuals with routine behaviors before the disaster at the instant time *t*. Clearly, just before the catastrophic event occurs, all the population is in this state, therefore $Q_1(0)=N$.
- Q_2 (t) represents the number of individuals who come back to pseudo-normal lifestyle after the outbreak of the disaster at the instant time t. We expect that, at the end of the event, all the individuals will be in this state except the death individuals. We suppose that only those in a controlled behavior can go back to a normal lifestyle and this return is modeled through the function $\varphi(t)$. Once in Q_2, we suppose that individuals can not join again the system. This condition corresponds to immunized people in classical SIR-models.

Let us now describe the dynamic of the processes.

The exterior event, that is the disaster onset, is modeled by a forcing function γ whose form could vary according to the specificities of the event (event with a slow or fast kinetic, expected or not). During the disaster, the population, initially in Q_1, evolves during the time according to different modalities within the three sub-populations *r*, *p* et *c*. However, according to the effect of surprise, we suppose that all these individuals will be in a reflex behavior *r(t)*. This aspect has to be modulated if the catastrophe is announced (in that case, we can have as soon as the beginning of the catastrophe some controlled behaviors *c(t)* of type confinement).

Some transitions, recurrent in each disaster, set up between these sub-populations: causality processes (B_1, B_2, C_1, C_2) and imitation and contagion processes (α, δ, μ). Furthermore, some specific transitions are used to model domino effects (s_1 and s_2), these transitions slowing the individuals to a return in a pseudo-normal behavior in Q_2.

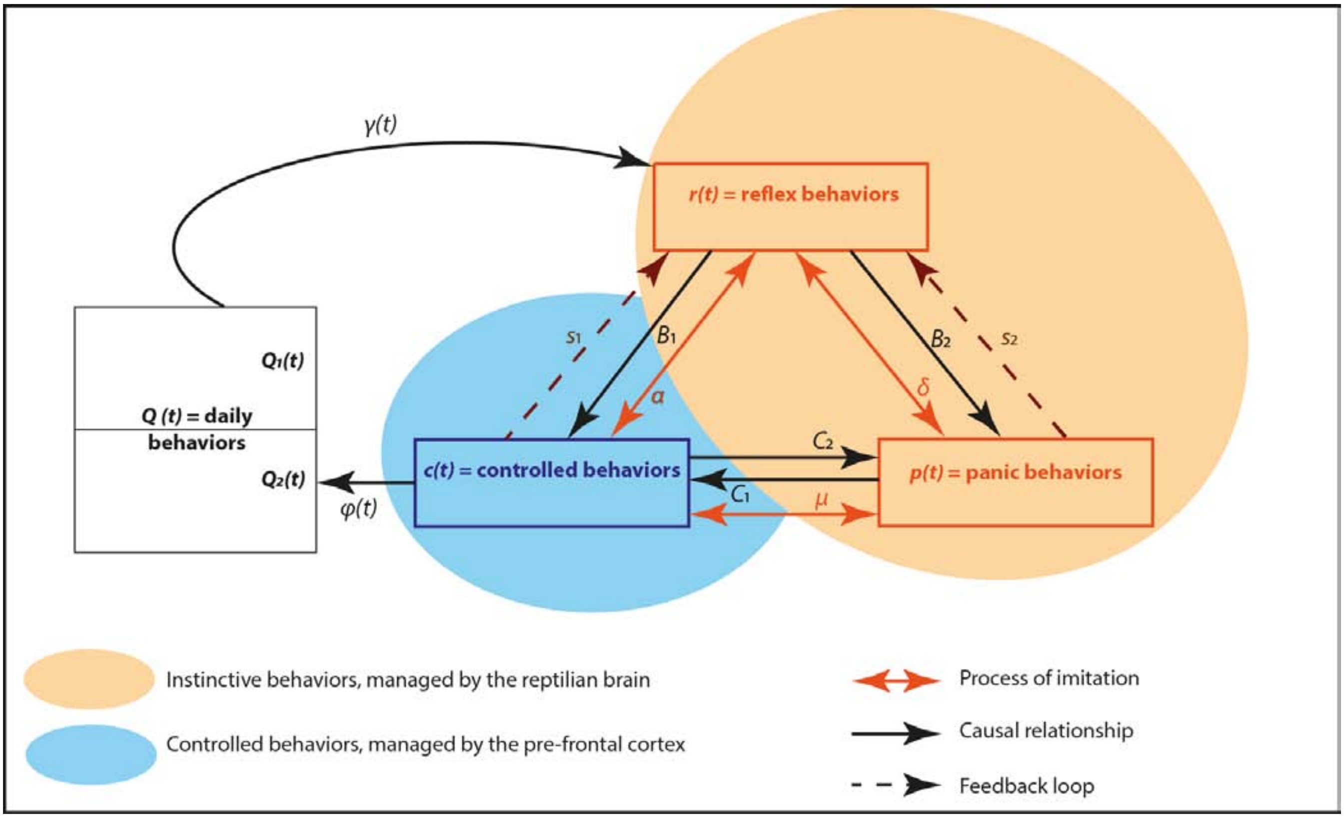

Fig. 1 : Graphical model of the three meta-behaviors (PCR: Panic, Reflex Controlled) in the exceptional situation of a disaster

b) Mathematical model

This graphical model has been mathematically formalized as follows:

$$\begin{cases} \dfrac{\mathrm{d}r}{\mathrm{d}t} = \gamma(t)Q_1\left(1-\dfrac{r}{r_m}\right) - (B_1+B_2)r + F(r,\ c)rc + G(r,\ p)rp + s_1c + s_2p - m_1(t)r \\ \dfrac{\mathrm{d}c}{\mathrm{d}t} = B_1r - F(r,\ c)rc + C_1p - s_1c - C_2c - \varphi(t)c(1-Q_2) + H(c,\ p)cp - m_2(t)c \\ \dfrac{\mathrm{d}p}{\mathrm{d}t} = B_2r - s_2p - G(r,\ p)rp - C_1p + C_2c - H(c,\ p)cp - m_3(t)p \\ \dfrac{\mathrm{d}Q_1}{\mathrm{d}t} = -\gamma(t)Q_1\left(1-\dfrac{r}{r_m}\right) \\ \dfrac{\mathrm{d}Q_2}{\mathrm{d}t} = \varphi(t)c(1-Q_2) \end{cases}$$

The following table together the variables and parameters involved in this model.

Table 1 : Variables and parameters of the model

State variables	**Qualification of variables and functions**
$Q_1(t)$	The number of individuals with routine behaviors at the start of simulation
$Q_2(t)$	The number of individuals who come back to a normal lifestyle after the outbreak of te disaster
$r(t)$	The number of "reflex" behaviors at a time t
$c(t)$	The number of "controlled" behaviors at a time t
$p(t)$	The number of "panic" behaviors at a time t
$m_1(t)$, $m_2(t)$, $m_3(t)$	The percentages of individuals in reflex, panic and controlled behaviors respectively who die during the disaster at a time t
Causal relationships and domino effect	
B_1	From reflex behaviors to controlled behaviors
B_2	From reflex behaviors to panic behaviors
C_1	From panic behaviors to controlled behaviors
C_2	From controlled behaviors to panic behaviors
s_1	From controlled behaviors to reflex behaviors
s_2	From panic behaviors to reflex behaviors
$\gamma(t)$	Forcing function to represent the type of hazard
$\varphi(t)$	From y(t) to $Q_2(t)$
Imitation and contagion processes	
α	Imitation and contagion processes between r et c
δ	Imitation and contagion processes between r et p
μ	Imitation and contagion processes between c et p

Let us analyze the first equation. The evolution of individuals in a reflex behavior depends on:

- the proportion of individuals in a daily behavior, the proportional term being function of the nature of the catastrophe modeled by the function γ;
- the decrease of the number of individuals due to causality processes, B_1 and B_2 being the

proportions of individuals adopting naturally a controlled behavior and a panic behavior respectively;

- the increase or decrease of the number of individuals in a reflex behavior adopting a controlled behavior due to imitation processes through the interaction term $F(r,c)rc$. The imitation process is proportional to the number of individuals in reflex behaviors and in controlled ones. The term $F(r,c)$ will depend on two functions each of them traducing one of the imitation (the imitation of reflex by controlled and vice versa) and according to the proportion of individuals in each behavior, its sign could be positive or negative allowing us to favour one sens or the other;
- the increase or decrease of the number of individuals in a reflex behavior adopting a panic behavior due to imitation processes through the term $G(r, p)\ rp$;
- the increase of the number of individuals in a reflex behavior due to a succession of catastrophes (s_1c+s_2p);
- finally, the decrease of the number of individuals in a reflex behavior due to mortality causes through the function m_1.
- The other equations are constructed in the same way.

Compared to (Verdière et al., 2014), the imitation terms have been modified and improved. Indeed, in their first version, their expressions did not well consider the interactions between the two populations and lead rapidly to non-sense negative solutions. In the model proposed in this paper, $F(r,c)$ takes into account the fact that the imitation can be in both directions. Indeed, it is reasonable to suppose that when the controlled population is more important than the reflex one, individuals in reflex behavior will adopt a controlled one. On the contrary, in case of preponderance of individuals with reflex behaviors, we will have a transition from controlled to reflex behaviors, these transitions not being in the same proportions.

c) *Calibration of the model*

Unfortunately, in the literature, the available data necessary to calibrate the model, are scarce. However, one can mainly distinguish two groups of quantitative data. The first one concerns the percentages of the population adopting during the event a certain type of behavior and the second one relates on the duration of such behaviors.

i. *Percentages of population adopting a certain type of behavior*

The different types of human behaviors described previously can manifest in variable proportions, in function of the considered catastrophic event, the suddenness of the threat, the composition of the group, the individual aptitudes for understanding the danger and the knowledge of the environment. Moreover, Boyd (1981) considers that in most of the disasters, "15% of individuals manifest obvious pathological reactions, 15% keep their cool and 70% manifest an apparently calm behavior but answer in fact to a certain degree of emotional sideration and lost of initiative which reports to a pathological register". These percentages have to be modulated according to the different parameters, which leads us to consider:

- 50 to 75% of the population was in a reflex behavior *r* during the event;
- 12 to 25% of the population was in a controlled behavior *c* during the event;
- 12 to 25% of the population was in a panic behavior *p* during the event.

At our knowledge, no data are available for quantifying transition mechanisms from one state to an other.

Notice that these percentages will be evaluated in computing areas in the numerical part.

ii. *Duration of the behavior*

These different reactions have different durations (Vermeiren, 2007).

- $r(t)$ = duration of reflex behavior varies from few minutes to one hour. Most of the time, it does not exceed 15 minutes, but it can be longer especially if it corresponds to a delay of evacuation in a disaster area. In this case, support and research behaviors for relatives and victims gradually appear.
- $p(t)$ = duration of panic behaviors varies from few minutes to one hour. Most of the time, it does not exceed 15 minutes and finishes spontaneously. Sometimes an outside energetic intervention allows to the panic population to recover a calm behavior, synonym of prostration, that is why this population can adopt an automate behavior $r(t)$ before adopting a controlled one $c(t)$.
- duration of the uncontrolled behavior $r(t)+p(t)$ does not last more than 1h30. In this model, we suppose that an individual cannot stay 1 hour in a reflex behavior and another hour in a panic state.
- $c(t)$ = duration of controlled behaviors. It varies from few minutes to several hours according to the intervention of institutional actors.

These data can be used as results towards which the solutions of our model have to converge, as explained in the numerical simulations section. This work can be done from the choice of the parameters of the model.

V. Numerical Simulations

For the numerical simulations, we have transformed the model in a dimensionless form, that is, population numbers correspond to fractions of the total population.

In the following subsection, the functions involved in the dimensionless model are specified.

a) Functions γ, φ, F, G, H, m

The construction of the functions γ and φ is based on the same function ψ defined by:

$$\psi(s, s_{min}, s_{max}, \psi_{min}, \psi_{max}) =$$
$$\begin{cases} \psi_{min} & \text{if } s < \psi_{min} \\ \psi_{max} & \text{if } s > \psi_{max}\ . \\ \frac{\psi_{min}-\psi_{max}}{2}\cos\left(\frac{s-s_{min}}{s_{max}-s_{min}}\pi\right) + \frac{\psi_{min}+\psi_{max}}{2} & \text{else} \end{cases}$$

We suppose to be in the case of a sudden catastrophe, so the population is rapidly informed, in our case after 1 minute and all the concerned population is informed in the three following minutes. Obviously, the return to the normality cannot be immediate, so we suppose that individuals begins to return to the pseudo-normal lifestyle after 5 minutes and this return is done very slowly. These considerations lead us to consider the following functions φ and γ.

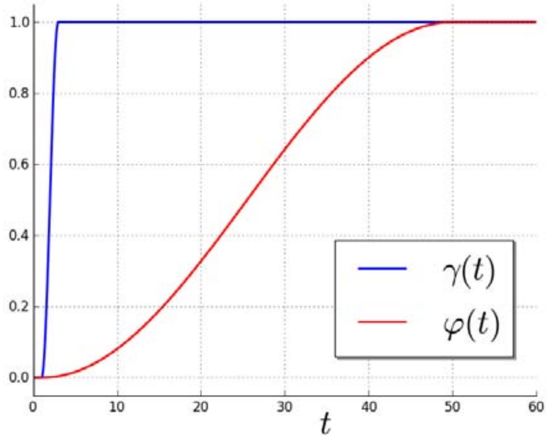

Fig. 2 : Functions φ and γ

As we have said before, the shape of the curves has to be modulated according to the type of disaster (depending if it is announced or not).

The imitation terms are modeled by the functions *F, G* and *H* that have the following form:

$$\begin{cases} F(r,c) & = \alpha_1 f_1\left(\dfrac{c}{r+\epsilon}\right) - \alpha_2 f_2\left(\dfrac{r}{c+\epsilon}\right) \\ G(r,p) & = \delta_1 g_1\left(\dfrac{p}{r+\epsilon}\right) - \delta_2 g_2\left(\dfrac{r}{p+\epsilon}\right) \\ H(c,p) & = \mu_1 h_1\left(\dfrac{c}{p+\epsilon}\right) - \mu_2 h_2\left(\dfrac{p}{c+\epsilon}\right) \end{cases}$$

where f_1, f_2, g_1, g_2 and h_1, h_2 are built in the same way. For example, f_1, f_2 are represented in Figure 3.

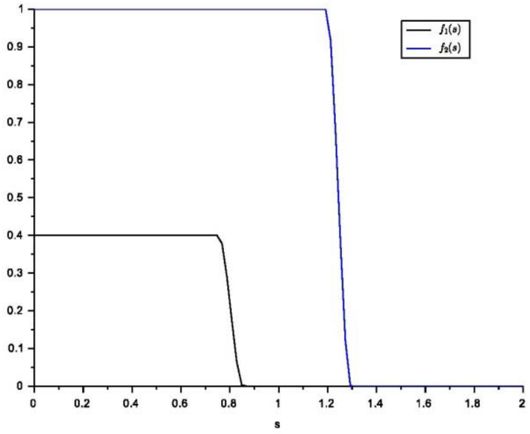

Fig. 3 : Functions f_1 and f_2

The imitation term *F(r,c)* depends on the proportion of reflex behaviors compared to controlled ones. The parameter ε is chosen to model the beginning of the interaction process, which occurs only over a certain value of the subpopulations *r* and *c*. The terms $f_2(c/(r+\varepsilon))$ and $f_2(r/(c+\varepsilon))$ are chosen so that, during the meeting of reflex and controlled behaviors, which is modeled by the product *rc*, there must be at least 55% of reflex behaviors so that 40% of the controlled individuals involved in the interaction adopt reflex behaviors. Under 55% of reflex behaviors, 100% of the individuals in a reflex behavior imitate the controlled behaviors. For the imitation of *p* and *c*, we build *G* so that the imitation is essentially in the sense *p* towards *c*.

The imitation functions have been modified and improved compared to those proposed in (Verdière et al., 2014). Indeed, they take easier into account the imitation in the two sens. In (Verdière et al., 2014), the imitation functions depended only on one variable contrary to here. For example, *F* depends on the two variables *r* and *c* and can describe the imitation process between individuals in a reflex behavior and in a controlled one, or vice versa. According to the sign of the imitation term, one of the sens is favoured compared to the other. Furthermore, with the imitation functions taken in (Verdière et al., 2014), it was difficult to play with their values because we obtain in lot of cases negative solutions.

In sudden and brutal disasters, death can be an important parameter. In our simulations, we suppose that the mortality is important just after the beginning of the disaster for the three behaviors *r*, *c* and *p*. This leads us to consider the following function m which will modelize the three mortality functions m_1, m_2, m_3.

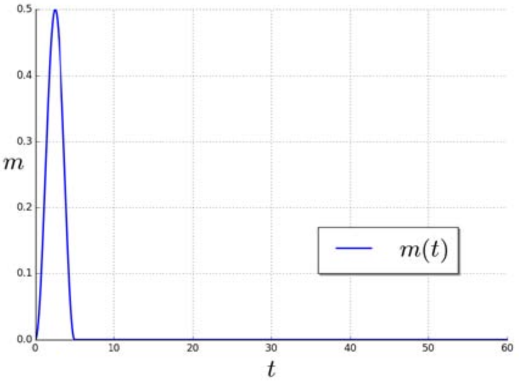

Fig. 4 : Function m

Another scenario will be to consider an event in which individuals in panic behavior are widely concerned by death, for example in the case of the rush during the pilgrimage at the Mecca in 2015.

In the following sections, we present simulations allowing us to validate our model.

b) Validation of the model

In this section, we test our model on two different extreme situations without any mortality (thus, $m(t)=0$ for all $t>0$). In these two simulations, we have verified that the percentages given in the calibration section are verified. For this purpose, we have computed the areas between each curve and the horizontal axis which give the global percentages of the corresponding population.

- *Scenario 1: An earthquake in Japan*

We propose simulations in order to find the characteristic behaviors in such an area when an earthquake happens. Since in Japan, the risk culture is well established, the population is formed to react quickly, the causality process from reflex to controlled is important with respect to the other processes, as the causality process from reflex to panic and the corresponding imitation processes. The parameters of our model are the following: $s_1 = s_2 = 0.01$, $B_1 = 0.7$, $B_2 = 0.1$, $C_1 = 0.4$, $C_2 = 0.1$, $\alpha_1 = 0.2$, $\alpha_2 = 0.01$, $\delta_1 = 0.01$, $\delta_2 = 0.01$, $\mu_1 = 0.5$, $\mu_2 = 0.1$ (see Fig. 5)

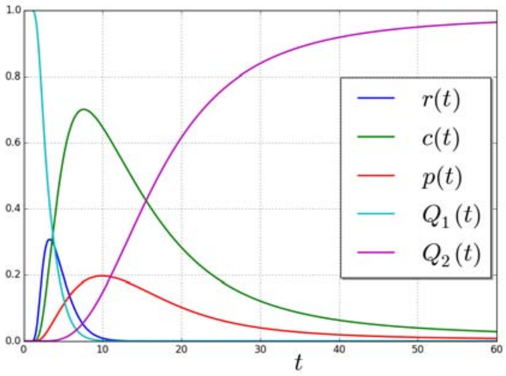

Fig. 5 : An earthquake in Japan

Figure 5 shows a domination of the controlled behaviors which perfectly matches with the geographers observations. Notice that population Q_2 increases until 1 since there is no mortality.

- *Scenario 2: An unexpected catastrophe on a non prepared population*

In 2010, an important earthquake place in Haiti. At the opposite of Japan population, the population was not prepared for such an event. In this case, the causal process from reflex to panic and the imitation of the panic control are dominant with respect to the other processes. The choice of the parameters is the following: $s_1 = s_2 = 0.01$, $B_1 = 0.1$, $B_2 = 0.4$, $C_1 = 0.1$, $C_2 = 0.1$, $\alpha_1 = 0.01$, $\alpha_2 = 0.01$, $\delta_1 = 0.4$, $\delta_2 = 0.01$, $\mu_1 = 0.1$, $\mu_2 = 0.8$. According to Figure 6, there is a high proportion of panic behavior during the event and a difficult return to daily behavior.

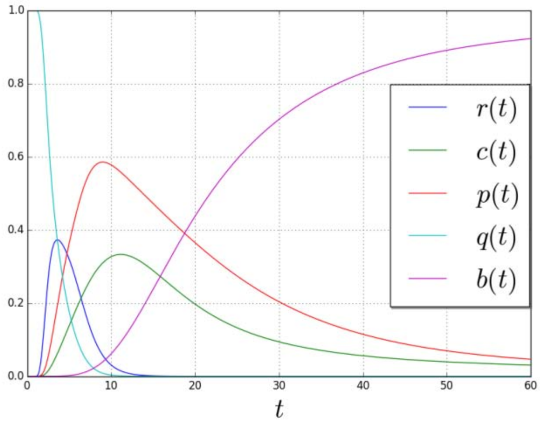

Fig. 6 : An unexpected catastrophe on a non prepared population

c) Succession of catastrophes

Frequently, the population is confronted to a succession of catastrophes. For example, earthquakes are very often followed by seismic events which lead the population to suffer again extreme behaviors. In our simulations, we suppose to be in presence of two successive catastrophes so that all individuals have not the time to come back to a daily behavior. To model this succession of two catastrophes, we consider that s_1 and s_2 are not equal to zero and depends on the time, so a second catastrophe is modeled in considering that individuals return in a reflex behavior. The functions s_1 and s_2 are as in Fig. 7.

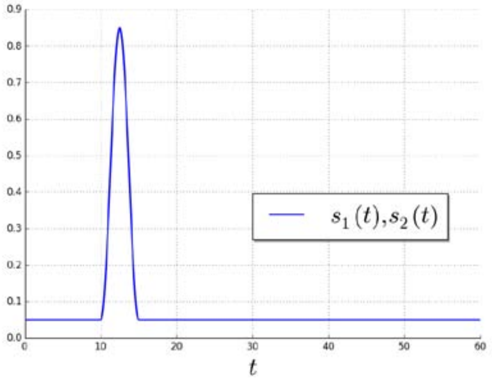

Fig. 7 : Functions s_1 and s_2

The curves represented at Fig. 8 show the impact of the second catastrophe.

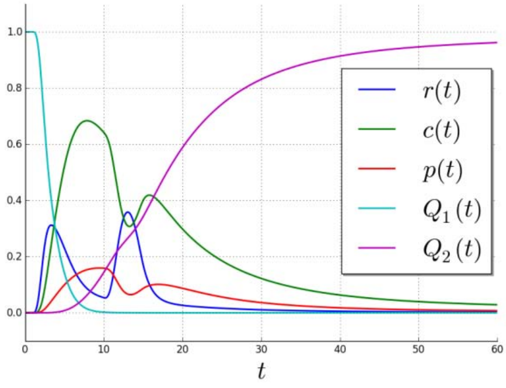

Fig. 8 : Succession of disasters

In Fig. 9, the three behaviors are represented in three dimensions.

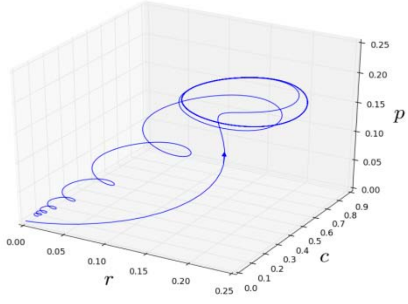

Fig. 9 : Succession of disasters (3D)

d) Simulation in case of mortality

The coefficients are the same as in the first simulation, that is $s_1 = s_2 = 0.01$, $B_1 = 0.7$, $B_2 = 0.1$, $C_1 = 0.4$, $C_2 = 0.1$, $\alpha_1 = 0.2$, $\alpha_2 = 0.01$, $\delta_1 = 0.01$, $\delta_2 = 0.01$, $\mu_1 = 0.5$, $\mu_2 = 0.1$ and the results are represented at Fig. 10.

Notice that population Q_2 does not increase until one and that the mortality impact significantly the behavioral dynamics essentially controlled behaviors.

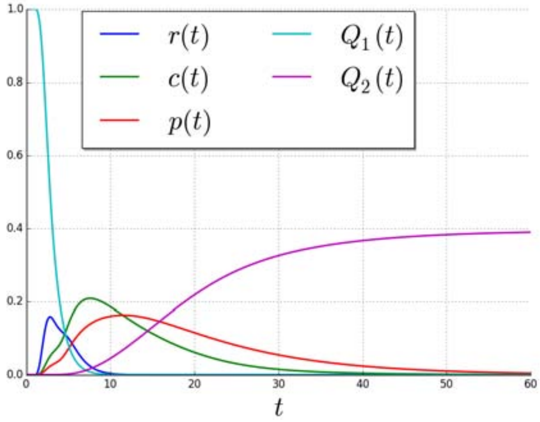

Fig. 10 : Model with mortality

VI. CONCLUSION

During a disaster, individuals adopt exceptional reactions completely distinct to daily ones as leaking under panic reactions, seeking victims under the rubble, fighting against the effects of a flood, evacuating at the request of authorities, etc... Unfortunately, these observations are not sufficient to understand clearly all the different concurrent behaviors and their sequence in such situation.

In order to deal with the limits of observation, we have formalized graphically and mathematically collective behaviors in the impact area and during a sudden event. These formalizations permit to consider the constraints of the situation and to analyze behaviors during the time evolution of the disaster. Furthermore, the actual model better integrates the imitation processes, the domino effects due to a new natural or technological disaster or corresponding to a closed door in situation of evacuation for example; mortality, all of these additions allowing to enrich the possible scenarios. Thus, this formalization permits to better understand and apprehend the apparition of behaviors spreading from individuals to a crowd and processes of interactions and imitation between individuals. This understanding and prevision of collective human behaviors represent a significant step forward the crisis management and specifically for the safeguard of civil populations. Indeed, during a disaster, the difficulty to prevent victims reactions increase the difficulty to master the situation for the institutional actors responsible of the crisis management. However, even if the proposed model has been improved compared to (Verdière et al., 2014), it does not consider all the human behaviors and have to be enriched in order to integrate more subtil behaviors, for example in distinguishing in controlled behaviors, altruist and selfish behaviors, to take into account geographical constraints.

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