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Reply to comment

Crowd dynamics and safety
Reply to comments on "Human behaviours in evacuation crowd dynamics: From modelling to "big data" toward crisis management"

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1. Introduction

The survey [13] presents an overview and critical analysis of the existing literature on the modeling of crowd dynamics related to crisis management toward the search of safety conditions. Out of this general review some rationale on research perspectives have been brought to the attention of the reader.

The content of this paper is also related to the authors' knowledge acquired in the EU project [50] which focuses on security problems during evacuation from complex venues. Crisis management should assure that the evacuation process occurs in a reasonably short time and that the local density of the people involved in the evacuation remains below a safety threshold.

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The whole content of [13] relies on the concept that a crowd is a living system. Hence, human behaviors have to be taken into account both in crowd modeling and in crisis management. The analysis has shown that an interdisciplinary approach is necessary to tackle the aforementioned security problems.

Since the readership is broad, the modeling sections of [13] have been organized into two parts to deal, respectively, with general theoretical concepts and formalized equations. Therefore, devoted mathematicians can intensively focus on Section 4 and related bibliography, while the reader interested in applications can skip over this section and go directly to the following sections.

Focusing on modeling topics it has been shown in [13] that the mesoscopic approach based on theoretical tools of the kinetic theory and of evolutionary stochastic games appeared to be more flexible as the approach can capture the complexity features of living systems and overcome, at least in part, the drawbacks of the modeling at the microscopic and macroscopic scales.

Focusing on crisis management, paper [13] has examined the existing literature, at the level of both scientific papers and technical reports, on databases repository of simulations and has proposed some guidelines toward the design of a predictive engine to support the decision making. A new science is recently developing on this topic [38]. Indeed, researchers strongly motivate the design of devices to support and optimize the process of decision making [58], where, according to the approach reviewed in our paper, interactions are modeled by theoretical tools of game theory.

The sequential steps along which the content of [13] has been developed can be summarized as follows:

1. *Analysis the main features of a human crowd viewed as a "social" hence complex, system;*
2. *Strategy by which mathematical sciences can contribute to understand the behavioral dynamics of crowds;*
3. *Development of computational methods to simulate the dynamics through complex venues;*
4. *Description of crowd behaviors in extreme situations such as stress induced by perception of danger;*
5. *Detailed analysis of what has been done and should be done to respond to crisis situations.*

The comments proposed by various authors have shown that the aims of paper [13] have been well understood. Some of them also include specific questions and suggestions of research perspectives. The overall set of comments represent a valuable contribution to future research plans in the challenging research field under consideration. As it is natural, some comments show a conceptual overlap of topics, while some of them refer to different topics. Therefore, our reply will focus on the following specific topics:

- Multiscale problems;
- Social and learning models in crowd dynamics;
- Modeling and computational problems toward crisis management;
- Predictive models toward crisis management.

These topics are treated in the next sections which are not limited to a reply to comments, but also suggest a variety of possible research perspectives.

2. Multiscale problems

The scaling problem involves several challenging issues such as: Derivation of macroscopic models from the underlying description delivered by the kinetic theory approach; Selection of the appropriate scaling, namely hyperbolic [8] rather than parabolic [9]; Modeling collective behaviors from the underlying individual dynamics; A unified approach to modeling at all scales.

This problem has been mentioned in various comments [34,66,69], where the authors have posed some conceptual issues on the derivation of macroscopic models of crowd dynamics at the macroscopic scale from the underlying description at the microscopic scale. This analytic derivation has been obtained in [6] for a crowd in unbounded domain, based on a previous study concerning vehicular traffic [10]. However, a complete analysis of derivation of macroscopic models in bounded domains is not yet available.

In more detail, comments [34] and [66] pose the same problem concerning the selection of the hyperbolic scale rather that parabolic. We do agree with this comment as propagation of perturbation in a crowd moves with finite speed rather than by diffusion. Still, the possible derivation of degenerate parabolic models should be investigated

similarly to what happens in multicellular systems [11]. However, we wish to stress that the problem is still open to the search of an exhaustive analytic treatment. In fact, only results in unbounded domains are available [6], while we know that the presence of walls and obstacles modifies the flow patterns. What is important is that the structure of hydrodynamic models is not postulated a priori as in a large number of models, e.g., [14,56].

In addition, comment [66] inquires on what is lost in descriptive ability of hydrodynamic models with respect to models developed at the mesoscale. Hydrodynamic models are certainly of interest from the computational standpoint as they present less expensive computational problems, but these models do not include specific features of complex systems such as heterogeneity, irrational behaviors, and various others. Still the question posed in [66] deserves attention to be viewed as an interesting research perspective.

An important topic, which has not yet treated exhaustively in the literature, is the modeling the links between individual behaviors and collective dynamics. The amount of information on this topic is not yet sufficient, although some interesting contributions have already been given to develop this challenging problem [63–65]. Therefore, it can definitely be considered an interesting research perspective, where the learning dynamics treated in the next section can play an important role.

Particularly interesting is comment [76] which introduces the concept of multiple scales. Namely not only microscopic and macroscopic, but also an underlying sub-microscopic scale. The author, due to his research activity, refers to multicellular systems, where this low scale corresponds to molecules related to DNA expression [15,33,80]. Crowd dynamics presents an analogous feature, where the low scale correspond to the psychological behavior of walkers. The content of the next section indicates how additional variables can be introduced to account for this specific feature.

Comment [68] brings some new ideas on the multiscale approach, where the dynamics at the microscopic scale is determined by some “rational” optimization of the available energy, see also [46]. In addition, some useful indications are given on available empirical data on this topic. The open problem, focusing on the specific aims of [13], consists in understanding how the psychology of a crowd is modified by stress in not safe conditions. This topic deserves further studies that can take advantage of the existing literature on safety problems, e.g., [36,58,73,79,81].

3. Physics, social and learning models in crowd dynamics

The introduction of models of social and learning dynamics in the modeling of human crowds is an important issue treated in [13]. The importance of this issue in evacuation dynamics is clearly stated in the already cited papers devoted to safety problems [36,58,73,79,81]. The critical analysis in these papers has shown that the present state of the art does not yet provide an exhaustive treatment of this topic, while the survey [13] indicates how the modeling approach at the mesoscopic scale [6,7] can take into account, at least in part, this specific issue.

This topic was introduced in paper [16] which suggests to introduce an additional microscopic variable, called *activity* to account for specific aspects of social behaviors. The model selected in [13] simplifies this approach by using a parameter β corresponding to *stress condition*, which is immediately shared by all walkers in the same zone. Indeed, we should not forget that this paper refers to evacuation dynamics, where the computational time must be equal or lower than the real time. Hence the simplification of [17] is imposed by the need of reducing the time required by computations.

If this requirement can be technically tackled by specific computational approach, such as parallel computing, the guidelines proposed in [16] can be followed to overcome the aforementioned simplification. Then, β is viewed as an internal variable which is modified by interactions and learning dynamics. However, even in the simplest case β is not a mechanical variable, rather a “social” variable which modifies the dynamics. Indeed, as reported in [13], when “stress” by evacuation increases, walkers increase their trend to follow the stream even if it is not optimal for their safety.

The need of using social dynamics is presented in [28], mainly focused on learning dynamics, while [39,57,66] refer to more general aspects of social dynamics. Comment [57] enlightens how stress conditions modify the evacuation dynamics. We do agree on these comments as well as with their indications of research perspectives. More specifically, future research directions are as follows:

- Mathematical models and related computational schemes should include the propagation, in time and space, of stress conditions that can have a localized onset and subsequently diffuse in the venue.

- A crowd can include, in certain circumstances, different typologies of individuals, such as leaders and followers or, in public demonstrations, individuals who behave correctly and rioters. Models should depict the transition from one group (functional subsystem) to another.
- The description of these dynamics should refer to systems approaches to social systems [2,23,40,41,49], while interactions that lead to the said dynamics should refer to the approaches to collective learning theory [29,30].

Although the present state of the art does not yet exhaustively treats these topics, some interesting preliminary results are available and, definitely, worth of future research activity. We observe that the kinetic theory methods to model crowd dynamics have been only recently initiated, and hopefully several developments will be proposed in the next years. Modeling social dynamics in crowds is one of the most interesting perspective. Some ideas toward this challenging objective have been already proposed in [13], see Subsection 4.3.

> *Social dynamics* in crowds refers to interaction of walkers that exchange their psychological attitude toward a consensus to a common walking strategy. The model takes into account this specific feature focusing on stressful conditions that might reduce safety conditions. An interesting topic, still to be developed, is the diffusion of other types of behaviors. An example is given by the presence of rioters in a democratic manifestation, when they attempt to obtain consensus from the other pacific demonstrators. A deep understanding of collective learning [29] can contribute to modeling social interchanges that can include violent acts [44] and transition into violence due to communications with rioters.

Comment [71] deserves special attention as it introduces a new aspect of the problem that has not been exhaustively treated in [13]. Indeed, it suggests to study crowd dynamics in the presence of fire. Let us first focus on two questions posed by the author:

> Given the practical applications of crowd evacuation models in fire safety engineering, an important follow up question arises from the review [13]: *How do current crowd evacuation models deal with the interactions between crowd behaviors and a physical threat in the environment?*

> An additional inquiry is the following:

> *The ability of evacuation models to qualitatively produce results which reflect the current knowledge on human behavior in fire.*

Both remarks are very important as they precisely focus on the need to adapt models to the specific safety situation that requires crisis management. This means that we cannot have a model valid in all possible situations, but we need a flexible model to be adapted to different possible situations.

We are very happy of this remark, which goes far beyond the traditional approach of a *rational crowd*, where walkers select optimal paths that minimize the energy which is spent. Therefore, it is worth stressing once more that the key problem consists in understanding human behaviors in the presence of fire, namely how the stress modifies walking behaviors and propagate in the crowd. The approach reviewed in [13] already provides the description of how stress conditions modify the walking strategy including reduction of velocity treated in [72]. However additional work is needed toward the modeling of dynamics in complex venues and propagation of stress conditions. A hint toward this topic is proposed in the last section.

Focusing again on fire situations, it is worth mentioning that modeling and simulations should tackle, in addition to various difficulties, the problem of the interaction of a crowd with the boundary of a domain which evolves in time due to fire propagation.

4. Modeling and computational problems toward crisis management

Modeling issues have been treated in the greatest part of comments, see [3,31,34,39,57,66,69,76]. As a matter of fact, this topic plays an important role in crisis management. Several papers have put in evidence that the existing literature is focused on models where the crowd exhibits rational behaviors, while real situations and stress conditions

induced by evacuation situations indicate that irrational behaviors appear thus generating crisis situations. This deficiency in the existing literature is properly described in papers that specifically deal with safety problems [51–53,73, 75,81].

An additional requirement is the need of real-time simulations as the crisis manager must be able to take rapid decisions during the evacuation. Monte Carlo particle methods are suggested in [13] as the appropriate computational approach to achieve the afore mentioned strategy. This method was first introduced by Bird [22] and subsequently developed by various authors by modifying the method to each specific system under consideration, see [4,67] and many others.

The influence of social dynamics on crowd behaviors has been already discussed in the previous section. Therefore, we will now simply focus on the general features of the crowd model selected for the simulation and safety analysis. Accordingly, we will summarizing its specific features referring to the comments as well as to the literature which have lead to the selection of the computational model reported in the survey [13]. In details:

- The complexity features of the crowd require a representation which accounts for the heterogeneous behavior of walkers as well as the difficulty of their deterministic identification. Therefore, the approach looks at the so-called kinetic theory for active particles precisely developed to model large systems of interacting entities [19].
- Walkers (pedestrians), namely the *micro-system*, are viewed as *active particles*, that have the ability of expressing a their own strategy, called *activity*. This ability can differ for different groups in the same crowd, as it is understood that the activity is heterogeneously distributed among walkers. The use of this variable has been already discussed in the preceding section.
- The overall system is subdivided into groups, called *functional subsystems*, of walkers who share common "mechanical" features, namely walking to the same direction (different for each group). This subdivision can also include *social* functional subsystems of walkers that behave differently from the others. As an example, this subdivision can include the presence of leaders who operate to drive the evacuation dynamics toward the most appropriate routes. The approach proposed in [16] satisfies this requirement.
- Interactions at the microscopic scale are modeled by theoretical tools of stochastic evolutionary game theory. These interactions are non-linearly additive and non-local. This is immediate to recognize as walkers modify their trajectory and speed according to the overall geometry of the system including exits, obstacles and walls.
- Particularly tricky is the treatment of boundary conditions as walkers feel the presence of walls at a distance and consider the option to modify the trajectory beside the trend to the exit and the search of less crowded areas. Also boundary conditions are treated in the framework of stochastic games, for instance the presence of walls introduces a trend to move along the wall, this trend decreases with the distance and it is only one of the various trends, this means that walkers do not proceed along the wall, but select their trajectories after having taken into account all coexisting trends.
- Models take into account the quality of the venue and of the environment which can determine different speed of walking as well as different observable dynamics, such as velocity and fundamental diagrams. Namely, these diagrams are not a universal property, but depend on the quality of the venue.
- Walkers can communicate and develop a *social dynamic*. Accordingly, they modify both strategy and dynamical rules followed in their dynamics. The output is a collective behavior which can be observed over the whole crowd.

Bearing all the above in mind, the answer to comments (and questions) on modeling topics can be given without naively claiming that all problems have been exhaustively treated. As a matter of fact, we believe that several challenging problems have been posed by the growing needs of safety requirements and that a lot of intellectual energies will be involved in the next years to deal with them.

Comment [3] indicates the importance of model validation. Indeed, it is an important aspect of the overall problem, which has been treated in Section 3, where it has been indicated that the validation process should take into account, at least, the following abilities:

(i) Capture the complexity features of a crowd;
(ii) Reproduction of the velocity and fundamental diagrams;
(iii) Qualitatively description of emerging behaviors including, in evacuation dynamics, severe changes in the dynamics of individual interactions and, hence, in the overall crowd behavior;

(iv) Modeling the role of environmental conditions over the observable dynamics.

Most of these issues have been treated in [17], however the search of appropriate empirical data is still going on although various interesting contribution, such as [36,42,74], have to be acknowledged.

Comment [61] brings the attention of the reader the pioneer paper [54], which has the merit of having introduced, for the first time, the concept of social force. Subsequently the authors indicate an interesting analysis of the physics of crowds [59,60,62]. This comment deserves attention in view of further developments of individual based models, at the microscopic scale. Indeed, it is worth looking for a unified approach of crowd modeling, where all scales contribute to a deeper understanding of the complexity of crowd dynamics.

As enlightened in [76], particularly important is the link between the scale below that of individuals and the microscopic scale. This concept is well understood in biology, where the low scale is that of molecules and their expression [5], while it needs still to be clarified at the level of a crowd. Therefore, it is not surprising that two comments [43,76] propose to study the analogies between walkers and cell dynamics. We do agree that it is a challenging perspective, where biologists can learn from experts in crowd dynamics and vice versa. The same reasoning can be applied to the analogy between crowds and swarms [21].

More in general, it is important mentioning that the approach to crowd modeling needs further improvements such as a development of the perspective ideas proposed in [16]. In addition, attention toward future research perspectives is deserved by the ideas of developing hydrodynamic models suitable to include some, at least, complexity features of living systems, as suggested in [66]. Additional suggestions [69] are focused on the introduction of a long range interaction potential not only for mechanics, but also for social behaviors, as and on the modeling of clustering and fragmentation phenomena in crowds, as suggested in [31].

The variety of possible improvements of models of crowd dynamics can be more vast than what one can figure out. However, the specific aims of [13] cannot skip over the fact that the scientific and technological community is waiting for developments suitable to support safety conditions. Waiting for these improvements, we wish stressing that a necessary condition for a successful approach is that the three scale problem is carefully treated and that computational codes satisfy the requirements of a computational time of the same order, at least, of the real time of the crowd moving in each venue.

Comments on computational methods have been proposed in [37] and [66]. In more detail, [37] focuses on the need of real time computations and provides some interesting bibliographic indications by which it is enlightened how mixed macroscopic and mesoscopic computing can be properly integrated. It is not an easy task, but it is worth developing future activity on this matter, where the main difficulty consists in implementing conservation equations by dynamical systems modeling particle dynamics.

Comment [66] inquires how far this method is necessary also considering that previous studies used deterministic methods [1,7]. Our reply accounts that the simulations proposed in [1,7] have been referred to very simple venues, while the interactions implemented in the model were somewhat simpler that those effectively needed by real applications. However, we do not feel like proposing a drastic decision and leave it to experts in numerical analysis, but we need stressing that safety requirements indicate the need of even more sophisticated models. Hence the design of codes should follow, in parallel, the derivation of models according to the need of real applications. The aid of parallel computing may be necessary to reduce the computational burden. In this respect, the possibility of exploiting the massively parallel architecture of modern Graphics Processing Units would be certainly of interest [48].

5. Predictive models toward crisis management

The survey [13] is not proposed, as already mentioned, on general topics of crowd dynamics, but it is specifically related to evacuation dynamics and safety problems. Therefore, once a model, or a class of models, has been selected among those available in the literature, models and scientific computations have to be used to support the decision process of crisis managers. This topic has been treated in Section 6 of the paper concluding with the proposal of the rationale to support the design of a *predictive engine*, where decisions can be extracted from a database repository of a large number of simulations to be properly related to possible real situations.

This topic has been object of two comments. In detail, comment [43], after having discussed modeling aspects and the need of reliable models, indicates the perspective of developing control theory methods to contribute practically to crisis management. Comment [39] enlightens the need of models with the ability of depicting social dynamics and

inquires about the possible use of *predictive engines* as tool to support decision making in situations where safety is at risk. Namely both comments refer to the key problem indicated in [13]: "what has been done and should be done to respond effectively to crisis situations".

Our idea is that the design of databases should go beyond the technical problem of *compression of data* and look for engines that have the ability of selecting data useful for crisis management. This idea is now shared by the scientific community of statisticians and experts in data mining. The key issue is already expressed in Section 6 of [13] and consists in the assessment, for the class of systems under consideration, of the set of variables which appear most appropriate to define the state of the system under consideration and, subsequently to define the most appropriate metrics to estimate how two different situations are closed each other. Finally, the selection of the actions suitable to induce safety needs the design of rules to score the validity of specific actions, so that the crisis manager can select the best action among those in the database [2].

These concepts are also well expressed in [39]:

> In fact, comparisons between different simulations and real situations cannot be restricted to the geometry of the venue and to the mechanical behavior of the crowd. Indeed, different social situations should be taken into account so that effectively useful simulations can contribute to decision making that, as it is known, have often to be taken in a very short time. This comment specifically refers to the design of predictive engine, where both social dynamics and its influence on the mechanical dynamics should be taken into account.

Transferring this rationale to a proper theory valid for applications is not an easy task. However, several intellectual energies have already been addressed to this objective and hopefully useful results will appear soon.

Some comments [26,43,68] have motivated the need of introducing the study of control problems for sparse systems and, in particular for crowd dynamics. Indeed, control actions can be properly addressed to improve safety conditions by addressing the decision process of walkers toward a rational way of selecting walking path. This objective can be achieved, as an example, by the presence of leaders [68].

Comment [26] provides a brief, however efficiently communicative, description of the possible mathematical approaches to this challenging problem. Indeed, researchers have perceived that the study of control problems in crowd dynamics can effectively contribute to manage dangerous situations.

The first step consists in developing a control theory for sparse systems. This interest is documented in several interesting papers, as examples [27,32,82]. The second step should look more precisely at crowd dynamics, for instance to control problems by leaders.

6. Research perspectives

The preceding sections have discussed the various comments which have been proposed on [13]. These comments and the related answers have generated further speculations on possible research perspectives. This section summarizes a number of possible perspectives selected, according to the authors' bias, among several conceivable ones. The indication of these perspectives is followed by some very preliminary reasonings on their approach. Pragmatically, only one topic has been selected for each of the preceding sections. Hopefully, interested readers can take them as a first step to support their own perspective ideas.

- *Derivation of models at the macroscopic scale from the underlying "kinetic theory" description at the microscopic scale for a crowd in a domain with boundaries and obstacles*: The derivation approach of [6] can be followed. However, the presence of walls and obstacles, namely Σ with the notations of [13], induces challenging difficulties. Further, if the model includes a "social" variable, such as "stress" in evacuation dynamics, the influence of this variable (or parameter in the simplified approach reviewed in [13]) should be studied to investigate how this feature influences the structure of equations at the macroscopic scale.
- *Modeling the interaction between social and mechanical dynamics in crowds*: Technical operators on safety problems are well aware on the importance that social dynamics can have on a crowd [73,75,81]. Due to this motivations the concept of social crowd has been introduced in [16]. The survey [2] reports on the existing literature and research perspectives on systems approach to model large social systems. A possible approach would consist in combining the two dynamics, namely by modeling how social behaviors have an influence on the me-

chanics of walkers and vice versa. An additional difficulty, to be taken into account, is that a crowd can include different types of walkers, for instance the presence of leaders, as well as the interplay of different types of social dynamics. Previous studies [18,40,41] have shown that this feature can have an important influence on social behaviors.

- *Development of the three scale approach outlined in [76] to implement the modeling of interactions between walkers focusing on the input of psychological status to individual dynamics*: The literature reviewed in [13] has shown that the four stimuli accounted for in the games, namely avoiding overcrowded areas, attraction from the stream, aim to reach the exit doors, need of avoiding walls and obstacles, generates well defined and observable flow patterns. In addition models derived within such framework have the ability to reproduce the fundamental diagrams as well as some emerging behaviors observed in reality [17]. It is a good point to start but now theoreticians are waiting for empirical data to be used for model tuning. Empirical data, such as those mentioned in [68], can provide a useful contribution to this objective.
- *Design of predictive engines to support crisis management*: As we have seen, the structure of the database and the design of the predictive engine march together. The challenging problem is that the overall design needs a common characterization of the social systems approach, the modeling of the venues, the modeling of the crowd dynamics, and development of a learning theory for crowds. The state of the art does not provides such common characterization, which means use of variables and parameters that can be related among themselves for all four components. Hence, research perspectives should pursue this specific objective. The development of control problems, proposed in [26] can constitute an important contribution to enrich the ability of predictive engines, as well as their use for training decision makers.

All these topics should not be developed for models in simple geometries such as square or circular rooms, but should refer to complex geometries such as crowd over lively footbridges [77,78], complex networks [24,25,45,47,55], venues with variable geometry due to possible incidents [17]. This means that the present state of the art, as it is reported in collection of papers, surveys, and books [12,20,35] needs further improvements and, if possible, also new ideas.

Bearing all above in mind, let us return, once more, to [71] and enlighten a challenging perspective that, although tangentially treated in the comment, clearly appears in the bibliography. Namely, the role that modeling can have in the design of venues during evacuation induced by possible terrorist attack [70]. Our interpretation of the letter to the journal *"Nature"* is that one has to look for highly sophisticated models suitable to link social dynamics and mechanics. Hopefully, a new systems approach might link [2] and [16] to support decision making toward safety problems for crowds.

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