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On current crowd management practices and the need for increased situation awareness, prediction, and intervention

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ABSTRACT

Recent accidents (News, 2006, 2010, 2013, 2015) show that crowded events can quickly turn into tragedies. The goal of crowd management is to avoid such accidents through careful planning and implementation. Crowd management practices are collaborative efforts between the different actors of the crowd management team and the crowd that depend on effective handling, sharing, and communication of information. Safety and comfort of a crowd depend on the success of such efforts. We have studied current practices and the role of technology through interviews to crowd managers. Our findings show that event planning and monitoring can be complex and sophisticated, but are operated with little support from technology. Crowd managers intend to increase their use of technology, but they have been so far dissatisfied by existing solutions. We provide recommendations for a bigger role of technology in crowd management.

1. Introduction

Crowd management is essentially a set of collaborative practices between a number of different actors, e.g. event planners and managers, emergency services, local authorities, transport authorities, stewards, and the crowd itself (W. Challenger et al., 2009; Wijermans et al., 2016). These practices start months ahead of an event. In fact, as we discuss in this paper, preparations take about 90% of the efforts. Usually a multi-agency approach is followed, incorporating all relevant parties, to enable a wide range of knowledge and expertise to be drawn upon. Preparation activities include detailed risk analyses to identify and prioritize potential risks, use and development of comprehensive "what-if" scenarios to consider management strategies and contingency plans, establishment of a control point to coordinate all activities and personnel. The remaining 10% consists of implementing the plan, comprising monitoring crowd activity to identify potential problems, and intervention, that in extreme conditions can result in crowd control. It must be noted that the focus of crowd management is facilitating crowd activities, hence proactively preventing, or quickly resolving, problems. The correct and effective execution of such practices is crucial to the success of an event, with the most important outcome being the safety and comfort of the crowd (Abbott and Geddie, 2000; Earl et al., 2004).

It has been argued that a more systematic approach to crowd management could have avoided recent accidents in large crowded events (Dickie, 1995; Challenger and Clegg, 2011). We postulate that new developments in technology, including mobile sensors, decision-support systems, and novel communication and interaction paradigms, can support crowd management operations during the planning and implementation of an event. However, as also supported by our results, currently the success of operations is still mainly dependent on the personal experience and skills of the crowd management team, with little or no aid from technology.

Towards a better understanding of the limitations and requirements of current crowd management practices, in particular regarding the role of technology, we present the perspective of crowd managers. We interviewed 10 crowd managers daily involved with managing large crowds, including a stadium hosting tens of thousands of visitors, a large train station, a multi-day music festival, a yearly celebration involving more than a million people. A main result emerging from our interviews is that crowd managers feel the need for instruments offering an increased situation awareness, a more reliable and timely monitoring of the state of the crowd, and the ability to predict and steer the behavior of the crowd without use of force.

In this paper, we make the following contributions. First, we present background and supporting literature, including crowd

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behavior modeling and prediction, mobile sensing, and decision-support systems. Second, we present current crowd management practices, as they emerged during our interviews. In particular, we focus on the role of technology and its limitations. Third, we present crowd managers' requirements for future technology to support their operations. Finally, we discuss opportunities and recommendations within the framework of a techno-social system.

2. Background

A generally accepted definition of a crowd is that it is a large gathering of diverse people at the same physical location, at the same time, not necessarily sharing the same goal or interest (Wijermans, 2011). Understanding the behavior of crowds, and how to manage them effectively, is still a scattered effort that involves different fields including theoretical physics, sociology, psychology, computational science, and artificial intelligence. Recently, studies have been published with overviews of common crowd management practices (W. Challenger et al., 2009; Health and Executive, 2014), but more work is required. The literature about crowds and crowd behavior focuses on theoretical modeling of the psychology of crowd behavior (Sime, 1995; Reicher, 2001), predicting crowd behavior through physics-inspired models, recognizing behavior through various kinds of sensors and analysis.

An approach to studying crowd behavior is by synthesizing it through crowd behavior prediction models. Crowd behavior prediction models are also used for a priori planning of events through simulation (Still, 2000; Zarboutis and Marmaras, 2007; Al Bosta, 2011; Siddiqui and Gwynne, 2012). A popular example of a crowd behavior model is the social-force model (Helbing and Molnar, 1995). The models usually target so-called crowd dynamics, referring to patterns of crowd movement, and more precisely to "the coordinated movement of a large number of individuals to which a semantically relevant meaning can be attributed, depending on the respective application" (Roggen et al., 2011). Examples include a queue of people, the formation of uni-directional "lanes" in bi-directional pedestrian flows, the intersection of these lanes, or a group of people at a specific location. Approaches to crowd modeling and simulation have been extensively surveyed (Venuti et al., 2007; Bellomo and Dogbe, 2011; Duives et al., 2013).

A different approach is to investigate how to detect and recognize crowd behavior. Traditionally, computer-vision techniques have been employed to characterize and automatically detect anomalies in a crowd (Zhan et al., 2008; Yaseen et al., 2013). The diffusion of pervasive and ubiquitous technologies such as smart phones and smart watches, has enabled the monitoring of social behavior through a wide range of sensing modalities, from temperature, to movement, to spatial proximity (Vinciarelli et al., 2009; Atallah and Yang, 2009). For example, smart phones have been used to detect crowd dynamics such as pedestrian flows and bottlenecks, and social groups (Wirz et al., 2009, 2012, 2013b). In particular, crowd dynamics such as pedestrian lanes and clogging have a strong spatio-temporal nature that can be captured as so-called crowd textures using proximity sensors (Martella et al., 2014). Accelerometers can be used to characterize queues, and activities such as running and walking (Kwapisz et al., 2011). Finally, microphones can be used to measure the mood of a crowd (Cinimodstudio, 2011) or recognize locations and places (Lane et al., 2010).[1] Some of these approaches are grouped also under the term Ambient Intelligence (AmI), referring to "electronic systems that are sensitive and responsive to the presence of people" including context and social-aware miniaturized pervasive computing devices and sensors, which can be envisioned to enhance and support, for example, crowd monitoring and evacuation (Mitleton-Kelly et al., 2013).

While synthesizing and recognizing crowd behavior has been addressed in the literature, less attention has been dedicated to how such data can help crowd managers make effective decisions in the control room, for example, during an event. Existing works either tend to focus on managing disasters and emergencies (Bui and Sankaran, 2001; Perry, 2003; Lorincz et al., 2004; Reddy et al., 2009; Asimakopoulou and Bessis, 2011; Illiyas et al., 2013), or on very specific cases such as air traffic control (Bentley et al., 1992; Mackay et al., 1998) and underground stations (Suchman, 1997; Luff and Heath, 2000), overlooking how technology can be used to support decisions *before* accidents happen during an event, or to support planning and debriefs.

Theories on socio-technical systems recommend new systems to be designed and operated with a holistic approach that optimizes both technical and social factors (Cherns, 1976, 1987; Clegg, 2000; Clegg and Shepherd, 2007). This body of work is crucial to the design of system that make use of technology to support the work of crowd managers. While these principles have been applied to the domain of technology and work design over the last decades, a broader and braver approach is necessary to extend their reach, for example, to crowd management (Davis et al., 2014). In this paper, we take a technological stand within this attempt, by studying how technology currently helps (or fails to help) crowd managers in their practices, and how existing and new research can serve the work of crowd managers in organizing and managing safer and more secure crowds.

3. Method

In this section we present our participants and the methods used to conduct the interviews and analyse the collected data.

3.1. Participants

We carried out 10 individual interviews with 10 crowd experts. We selected and approached 10 organizations in The Netherlands known for hosting and managing among the largest crowds in the country. From each organization, we interviewed a senior professional with experience in dealing with large crowds. Type of event, location, visitors profiles, time of year, among others, define different scenarios of crowd behavior and the different strategies to manage them. For this reason, we chose organizations that allowed us to cover the widest range of events and crowds, from those emerging at peak hours in train stations to those in multi-day outdoor music festivals. Note that also within the same type of location, e.g. a train station, experts manage diverse scenarios. For example, train stations must deal with both week-day peak-hours crowds and day-long special celebration events, with hundreds of thousands of people coming in from all over the country. We summarize the participants and their domain of expertise in Table 1. We also included an expert from the Research & Development department of an organization specialized in designing and building barriers for large events, such as music festivals and parades. As such, he presented a different perspective of the requirements and the use cases of the crowd managers. Finally, the organization we dubbed "Security Company" differs from the other organizations due to their consultancy-oriented business model, that includes the delivery of crowd management trainings and workshops, as well as consulting on events organization and man-

[1] Note that these techniques differ from the emerging field of Mobile Crowd Sensing (MCS) (Ganti et al., 2011). MCS uses mobile devices to collect information from individuals dislocated and distributed in wide areas, and defines a crowd as a large number of individuals that may be distributed geographically in *different locations* (and even different countries), or that visit the same location at *different times*.

Table 1
Description of the experts interviewed.

Crowd expert	Description	Crowd size	Crowd duration
P1 Indoor Music Festival	Chief organizer of an annual indoor music festival, coordinating the preparation, registration, staff training, communication during the festival	2000	6 h
P2 Indoor Conference	Chief organizer of an annual large indoor conference, coordinating the registration, communication, transportation, parking, catering, etc.	1000	12 h
P3 Central Train Station	Crowd manager of a central train station in a capital city, managing the crowds in daily situations and in large events	250,000	4 h
P4 Police	Crowd manager involved with large crowds e.g. on a national festival	700,000	8 h
P5 Security Company	Head of a security company, consulting on organization and management of various crowd events	1000–100,000	Hours to days
P6 Barrier Company	Head of a barrier company designing and building custom barriers for various types of crowd events as well as managing their layout	1000-100,000	Hours to days
P7 Outdoor Music Festival	Manager of an annual outdoor music festival, coordinating the site construction, ticketing, crowd flow control, transportation, parking, catering, etc.	60,000–100,000	3 days
P8 Stadium	Crowd manager of a stadium, managing the crowds for various events, such as concerts and football matches	55,000	4–5 h
P9 Theme Park	Manager of a theme park, focusing on managing the daily crowd flows, queues and large crowds (e.g., crowds watching a music fountain) during holidays	40,000–60,000	12 h
P10 Train Station Flow	Crowd manager of a central train station, monitoring real-time crowd flows via video cameras, Bluetooth and Wi-Fi signals	180,000	12 h

agement. While diverse, the profile of the crowds managed by the participants matches our definition of a crowd provided above, that is of a large number of individuals gathering at the same location at the same time (Wijermans, 2011) (see Fig. 1).

3.2. Interview process

We chose to conduct semi-structured interviews because they guarantee consistency in the topics that were addressed, but also freedom for the participants to diverge and provide their unique and personal perspective when necessary. The approach prevented interviews falling into a strict question-response pattern and encouraged the raise of theme-related new questions that can adequately elicit the issues to compose a more comprehensive report. Each interview was scheduled around 1–1.5 h at the work place of the participant, and it was recorded with a voice recorder. All the artefacts accessed in the interviews, for example, sketches, booklets, photos and maps, were collected at the end. We began the interviews by posing questions about three themes: (i) daily operations, (ii) crowds characterization, and (iii) use of technology. Then, we triggered the participants to develop further each theme by talking about concrete stories, rather than about general and abstract concepts.

3.3. Data analysis

We analyzed the data following a creative on-the-wall method (Sanders and Stappers, 2012) consisting of four steps: (i) transcription, (ii) interpretation, (iii) categorization, and (iv) presentation.

We started by transcribing and timestamping the interviews. The artefacts were used to aid the process and were included in the corpus. After the transcriptions, a team of three researchers coded the text of each interview as follows. First, each researcher independently selected relevant paragraphs. Then, the team collaboratively grouped overlapping choices into statements cards. If no consensus could be found, the researchers would either decide to discard the paragraphs, or to do another pass on the transcriptions. A statement card consisted of a statement and a group of selected quotes cut out directly from the printed transcripts.

At the end of the process, the three researchers generated 241 statement cards in total. For the following session, a fourth researcher joined the team. To categorize the statements cards, the four researchers followed a process resembling a bottom-up clustering process. Statement cards were grouped inductively into categories, and so were the resulting categories themselves, when possible, until no more categories could be generated or grouped. Fig. 2 presents the first two levels of the hierarchy of categories, which we use to present our results in Section 4. The clustering was not directed by any pre-defined hypothesis, and each category name emerged during the process. The session was carried out in a room with walls covered by magnetic white boards. A dozen of A1 white paper sheets were fixed on the wall with magnets. The statement cards with relevant information were put together on the same A1 sheet.

The findings were presented in the form of a poster.[2] As we discuss in the next session, time is an important dimension in the management of crowds. For this reason, the visualization is constructed around a timeline. The poster visualizes the categories together with the most important statements. Interesting quotes are printed with larger font sizes to guide the attention towards the more detailed summaries. We present a detailed analysis of the results in the next section.

4. Findings

In this section we present our findings, organized following the hierarchy of categories pictured in Fig. 2, emerged from the data analysis presented in Section 3.

4.1. Overview: on the definition of crowd management

All experts strongly emphasized two main distinctions during the interviews. The first distinction related to the difference between *crowd management* and other practices like *crowd control* and *riot control*. The second distinction related to the two phases that constitute the crowd management practices, namely what happens *before* the event and what happens *during* the event. We organize our findings around these distinctions.

Crowd management is usually defined as the set of measures taken in the normal process of facilitating the movement and enjoyment of people (Berlonghi, 1995), for instance measures to control the distribution of people over a certain area. This definition fits that of the interviewees. From their responses, crowd management is taken to refer mostly to the preparations for a given event and it involves predicting what is going to happen

[2] The poster can be downloaded from https://goo.gl/O38B9F.

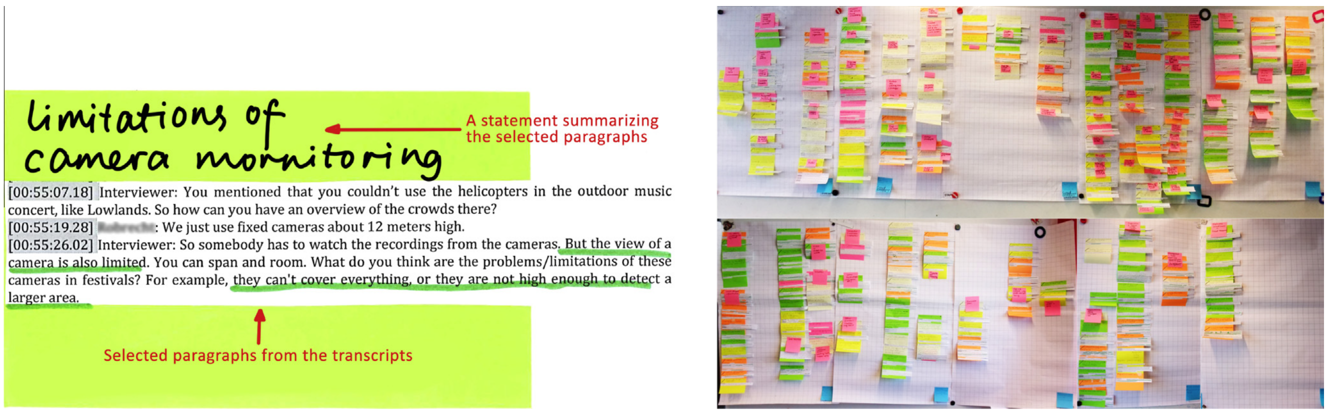

Fig. 1. (Left) An example of statement card with a quote. (Right) The magnetic wall with the categorized statements.

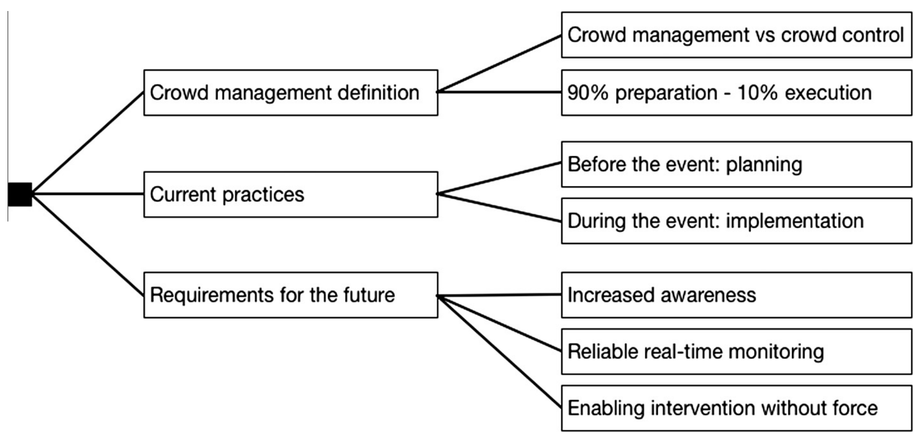

Fig. 2. The hierarchy of categories generated by the bottom-up clustering of the statements. Each category further contains common themes emerged during the interviews.

and preparing for it, i.e. designing for the desired behavior of the crowd. The preparations involve all aspects, namely getting people into the site, people participating to the event, and getting people out of the site. These preparations usually start much ahead of the event, e.g. six months or more. The resulting plan or design for a given event concerns the technical infrastructure and operational measures needed for the safety, well-being and enjoyment of the crowd. The effort to produce the plan was estimated by the interviewees to be about 90% of the total effort for the event's crowd management. The remaining 10% refers to the (mostly) operational measures, including potentially emergencies during the event itself, which implement and support the plan for the event.

Crowd management was distinguished from crowd control. The latter includes all measures taken once crowds are beginning to or have gone out of control. In other words, crowd management is proactive while crowd control is reactive (Berlonghi, 1995). This distinction is reflected both by the uneven allocation of resources towards preparation, and by an emphasis of monitoring, predicting, and steering behavior during the event to avoid the need for crowd control. In this paper we focus in particular on current practices, limitations and requirements of crowd management.

4.2. Current practices

We start by presenting current practices. Where not specified, crowd managers did not mention use of technology, or explicitly reported none. Fig. 3 summarizes the elements that comprise the current practices, including both planning and execution of the event.

4.2.1. Before the event: planning

The type of knowledge required to produce a plan in crowd management includes (i) expert knowledge based on experience, (ii) guidelines learnt from past events data, (iii) trial and error, (iv) common-sense knowledge, as well as (v) computer simulations of the crowds in the event. Planning is typically done within a management team, in which each member has his or her responsibilities and disciplines. They input their knowledge, expertise and experience on past events to the management process. Typical roles and responsibilities include (i) the transportation to the event, which can start far away from the event location, (ii) the security, sometimes taken care by or in collaboration with the police, (iii) the barriers built on the location to contain or steer the crowd, (iv) the event manager, taking care of the event plan and representing the various stakeholders.

There is no general recipe to produce the plan, and a number of factors need to be taken into account, including (i) visitor profiles, (ii) location, (iii) client, (iv) institutions, (v) personnel, (vi) event type and (vii) weather. We now proceed with a description of the content of the crowd management plan, and later in this section we describe the aforementioned factors in detail.

The planning starts with a definition of the desired behavior the crowd management team wants to obtain from the crowd. The content of the plan is the outcome of all the decisions that should eventually steer the crowd towards that desired behavior during the event. Such plan is generally composed of two parts.

The first part is a *logistical plan* that concerns decisions about, for example, the number of tickets sold, the mobility plan and the resulting layout of the event site including the position of

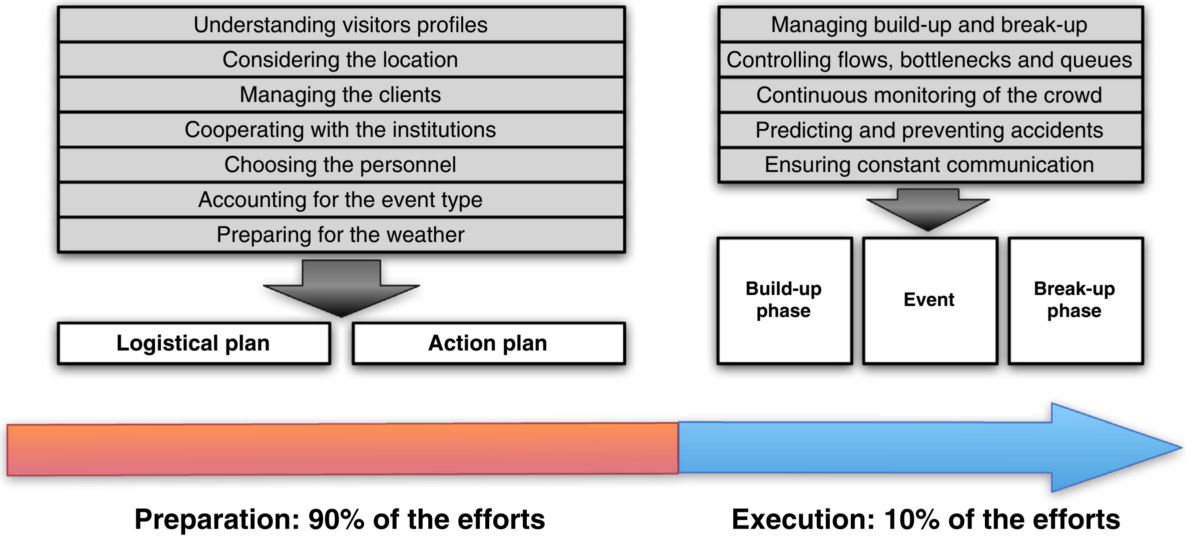

Fig. 3. Crowd management can be divided in two parts: the planning of the event, that takes up to around 90% of the efforts, and the execution of the plan during the event, taking about the remaining 10% of the efforts. Multiple elements must be take into account when generating the scenarios and the plans. During the event most efforts concentrate on managing the different phases of the event predicting and avoiding certain behaviors, more than securing the crowd once these happen.

barriers, entrances, exits, toilettes, bars, the transportation systems, the provisioning of food and beverages. The main goal of these decisions is to allow the crowd to move freely and safely, but at the same time avoid certain dangerous or unpleasant situations caused, for example, by uneven distribution of the crowd, obstructions, bottlenecks, and dissatisfaction. Communication with the crowd is also taken into account. Hence, the plan includes decisions, for example, about signs, screens, event program, and maps. Additionally, the plan contains information about the number of individuals in the personnel and their profiles, including their protocols and briefings.

The second part resembles an *action plan* which consists of a number of what-if scenarios and strategies regarding how to respond to each given situation. This includes the preparation of scenarios for several alternative normal situations, depending on weather, type of public, locations, most likely crowded areas, peak hours, as well as for dealing with emergencies, including evacuation plans and crowd control. Scenarios are typically constructed with the help of expert knowledge and computer simulations, and the planning also indicates the courses of action that may be taken in the given situation. Critical scenarios in events involving large crowds are the arrival and departure of the people at and from the site, so especial attention must be paid for the preparations for these moments.

Understanding the visitors is the first step in event planning. All the planning for an event has to be adapted to its visitor profiles. The age and gender of the visitors are of great importance. It is easy to imagine that young, aggressive and male adults in football stadiums are more difficult to manage than less active and well-behaved older adults. The visitors familiarity or former experience of an event also plays an influential role. For example, it is common to see loyal visitors to some annual events, and this influences their behavior.

When the visitors mainly consist of groups of friends or family members, e.g. a theme park, strategies for keeping them together should be considered in the planning with particular importance. The transportation of the visitors should also be taken into account, making sure there are enough parking places or clear paths connecting the public transportation to the event field. This again may depend on the visitor profile, as more mature visitors may visit the event through their car, while an event attended by teenagers may require better planning of public transportation.

The location is evaluated next. Event locations can have various, sometimes very specific characteristics. An indoor event must follow stricter rules than the outdoor ones. For example, the amount of visitors allowed to an indoor event is limited by the amount of emergency exits. On the other hand, outdoor environments tend to have fewer regulations, as present fewer physical constraints that can limit the behavior of the visitors in case of emergencies, such as, for example, walls, gates, and stairs.

Besides whether the event takes place indoor or outdoor, a location-related aspect that requires particular attention is the level of mobility, namely whether the crowd is seated, standing, or continuously walking. Some events may include multiple levels of mobility. For example, in a conference, people are mostly sitting during the presentations, walking around during breaks and standing to listen to a scholar explaining his/her posters. Several managers pointed out that managing the seated crowds, e.g. in a stadium, is much easier than dealing with the randomly moving crowds, e.g. in a train stations hall or when people are approaching the event location from multiple points.

Is the location built on grass or concrete? This is the third consideration related to location. If the event is on an outdoor grass field, more attention will be paid to the weather resistant measures. For example, by preparing the sawdust for soaking up the water in case of rain. The fourth consideration is whether the event is in city center, in a neighborhood, or in a tourist attraction. Organizing the event in the limited area of the city center is less regulated than an event in a neighborhood, because a city center is designed for social activities while a residential neighborhood is less tolerant for noise.

An important part of running a safe event is *managing the clients*. The client of an event includes artists that perform and organizations that promote a festival. Sometimes, crowd management reasons can influence the choice of clients and/or the design of schedules. For example, for a multi-stage music festival, inviting a very dominant and famous band to perform may produce dangerous skewed distributions of visitors across stages. For this reason big bands are often scheduled at the same time on different stages. So, planning may also need to consider the behavior of certain clients or the behavior they may cause. Some clients may behave in unplanned or expected way, creating dangerous situations in the crowd by, for example, attracting many individuals or creating excitement in areas not designed to handle such conditions.

Part of managing a crowd is *cooperating with the institutions*. Various institutions can be promoters or owners of an event, like the government. However, often governmental institutions are not experts in crowd management. They promulgate regulations and give permits to event organizers, or fine the organizers due to noise, damages to the locations, and so on. They work mainly as a partner or stakeholders in crowd management, who can provide support or help coordinate in an event. For example, the manager of the security company, the manager of a central train station and the manager of a stadium, all believed that the police partly belongs to the government, whose responsibilities are different from those of security personnel in the event. Hence, institutions can act as resources, but also as constraints in the collaborative work of creating a crowd management plan.

Choosing the personnel by hiring the right amount of people with the right set of skills is a significant part of the preparation. Certain personnel works well for one event, but may not adapt to another. For example, personnel you need to manage the audience of a television show is different from the people needed in a football game. In a football game, crowds can be very large, and sometimes aggressive. Plus, one needs more personnel for ticket sales on the location. Part of the personnel are the security stewards and the first-aid staff, focusing on safety issues. The catering professionals take charge of the food and beverage that is considered as a big element contributing to visitors happiness. The critical role that skills and communication play in the choice, instruction, and management of the personnel, shows once again the importance of the collaborative nature of the work.

Many *attributes of an event* have impact on planning. How do you control the crowd size in a ticket-less event? What are the different strategies in a heavy-metal concert and in an classical concert? What is the duration of the event? All these questions raise the concerns on the internal attributes of an event. The goal of an event sometimes includes making profits. Finding a balance between maximizing profits while keeping the crowd safe is one of the biggest challenges. For example, if an event is free for all the visitors, how many visitors will come may be unknown in advance. A free party is planned differently from a paid party. For this reason, when possible, free events are still organized with tickets to control the size of the crowd.

Finally, *preparing for the weather* is very important as it can change the conditions of the event very quickly. The weather mainly affects outdoor events. Some events plan also for bad weather, and need to guarantee that the temporary architectures, such as tents and decorations, resist also to bad weather conditions. Weather can also largely influence transportation. A storm may drive a large crowd of visitors of an outdoor carnival to the train station in a very short time, potentially paralyzing the train station.

4.2.2. During the event: implementing the plan

During the event, the role of the crowd management team is to assess the condition of the crowd, evaluate the active scenarios, predict future scenarios developments, and execute the related actions according to the plan. Given the limited range of actions a crowd management team can execute during the event without resulting in crowd control, many of the strategies implemented by crowd managers concentrate on avoiding density reaching critical levels, more than actually reacting to it. For this reason, many of these strategies focus on particular moments and areas of the event, e.g. the entrances and exits, the locations where queues can form, e.g. shops and toilettes. In this section we present important lessons stressed by the experts.

Managing the build-up and break-up phases of the event, such as the few hours preceding and following the event, often involves different strategies and considerations. As a general strategy, the management of the crowd begins as far as possible from the site, guiding the gathering in a safe and comfortable condition. Although not always possible, guiding the crowd as early as possible provides managers with a wider time window to predict future developments, and allows for proactive actions. For example, depending on the size, the type of event, the location, and the actors involved, the management of the crowd can start from the public transport stations, the neighboring towns, up to the extra-regional areas.

When possible, multiple routes and entrances should be made available to the crowd. This often depends on the location. For example, modern stadiums and urban areas can have routes that start already from dedicated motorway exits. When such infrastructure is not in place, use of barriers, turnstiles, and signs should help the formation of these routes. The type of event has a relevant impact on this phase. For example, a long lasting event without a fixed main attraction, such as a festival or a national celebration, will present a fairly more diluted and continuous flow of individuals over the event duration, compared to a football game or a concert.

Central to the management of the safe movement of the crowd is *controlling of pedestrian flows, bottlenecks, and queues*. Ensuring the emergence of safe pedestrian flows and queues that do not develop into bottlenecks and clogging behavior is rated among the highest priorities of both phases of crowd management. Many factors affect the movement and flows of pedestrians, and their characterization is central to their understanding and control to ensure the safety of the crowd (Stanton and Wanless, 1995; Smith, 1995). Crowd and pedestrian dynamics do not only play a role in the build-up and break-up phases, when the crowd arrive at and leave the site, but also throughout the whole duration of the event. For example, flows and queues can generate also from state to stage between concerts, or between platforms in a train station.

In general, three main strategic guidelines are applicable to the scenarios of flows, queues, and bottlenecks: (1) keep the flow moving, (2) avoid long intervals of times where the individuals are forced to wait still (it is generally accepted that waiting for longer than 8 min may affect the mood of the individuals in a queue), (3) keep the individuals informed of waiting times, the causes of the block, and the condition of the crowd in front of them. The strategies to obtain a continuous and safe flow of pedestrians range from a good combination of capacity planning and human resources, to communication (including signs), and site design (i.e. with the aid of barriers). For example, a simple yet practical strategy is the avoidance of money exchange at the food stands, in favor of particular coins or prepaid cards to be bought in advance that minimize transaction times. At a theme park, a queue can be entertained by the surrounding attractions.

Barriers can be used to divide the crowd in smaller and more manageable groups, to guide people towards exits and entrances, to support queuing, to create routes and detours, to avoid the stagnation of individuals in certain areas, such as gates or corridors. While barriers can be positioned to "mold" the crowd in specific areas, it is sometimes necessary also to temporarily remove them, for example, in train stations when very large crowds are expected for special events. In those occasions, when the site is close to the maximum capacity, barriers can turn into dangerous obstacles.

Communication is of utmost importance, as it is used to keep the crowd informed about the decisions made by the managers, and to support independent decisions by the individuals. Communication is also used within the management team to exchange information about monitored areas, to brief agents/stewards about plan changes or actions to be taken. To a certain extent, communication is one of the few and most powerful means the managers have to influence and steer the behavior of a crowd without use of force.

As far as communication to the crowd is concerned, the content of the communication can range from the densities in the different areas, early information about public transport, time schedules, different path options, and changes to the schedule or weather conditions. Within the constraints of crowd management, the role of communication is to discourage the crowd to move towards certain areas of the site, and persuade them to take different routes, sometimes also representing longer d-tours that allow the mass to spread more evenly. Communication can be supported by physical infrastructure such as screens, barriers, and signs. It is recommended to spread them evenly across the site to reach the largest audience, and position them in places that can host potentially large groups to avoid bottlenecks. For example, screens with train schedules can sometimes be installed already outside of the train station. When the event allows it, information about paths and routes can be spread already in neighboring urban centers through flyers, radio and television broadcasts, Internet sites and social media. These means of communication can complement more traditional ones, such as loud speaking and megaphones.

On the other hand, communication within the team has different goals. First, it allows to share information about the state of the crowd, such as the distribution of people in different areas, the formation of flows, warnings about anomalies, or more logistical information such as the need for specific resources. This type of information generally travels from the agents in the field to the control room, where it is processed and used for decision making. Moreover, communication is needed to provide agents and stewards in the field with actions to execute as a result of the decisions made in the control room. Finally, communication is used to coordinate actions on the field, among agents and stewards. Communication within the team occurs through different channels and technologies, depending on the endpoints, the density, and the distance to cover. For example, for short ad hoc communications between two people in a sparse area, telephones can be sufficient. However, cellular mobile phones have problems functioning in high-density situations. Also, the C2000[3] can be used when actors working for different institutions are involved, and in particular for the management of emergencies. Walkie-talkie and other radio-based communication tools can be used to broadcast information from one point to multiples at the same time. These instruments often support multiple channels, so that communication endpoints can be multiplexed and information overload can be avoided.

Monitoring of the state of a crowd is currently human-centric. Information about the state of the crowd is collected by stewards and agents in the crowd, through heuristics and visual estimations. When technologies like video cameras are used, they are monitored by humans in the control room. In other words, they allow for centralization of information, but the information is still processed by humans. UAVs (Unmanned Aerial Vehicles) can be equipped with cameras: they can fly over areas, used to monitor in detail queues, spot riots, and detect abnormal situations. These remotely controlled systems provide valuable information, but they are often not legally permitted due to the risk imposed on the crowd, in case of malfunctioning. Automatic processing of video streams is still not wide-spread among crowd management practitioners, and still present low accuracy at high densities.

Automatic monitoring of a crowd, turnstiles can count the amount of people that entered the event site, and their speed can be contained from the control room to control flows. Also, barriers can incorporate pressure sensors to monitor the state of the crowd in critical points e.g. in front of a stage. Nonetheless, this information is usually used to validate and design the barriers layout for future events.

Recently, social media, such as Twitter and Facebook, have been used to monitor the use of certain keywords to detect emergencies and feedback from the crowd. Moreover, mobile phones provide a good source of information as they can be used to approximate counts of individuals. This can be usually achieved either by counting the number of telephones registered to a cell, or, for example, by counting the number of telephones with active Bluetooth connectivity. However, these types of radio-based systems operate poorly in highly dense scenarios.

An important aspect of crowd monitoring is timely information exchange and integration between the different actors. Often, different agencies such as the police, the municipality, the national railways, collect information about the crowd that can be useful for the other actors. For example, data collected from the police about flows directed towards the train station can be of great value for those managing the crowd at the station. Exchange of information is currently performed on a face-to-face basis in the control room or through the phone. Finally, also external factors should be monitored as part of the process, as they have an impact on the crowd and the event. Weather conditions, for example, can influence highly the schedule of the event, forcing people to leave the event in advance, or even representing a danger in itself in the most extreme cases.

4.3. Limitations of current practices and crowd managers' requirements for the future

In this section we discuss the challenges and limitations of current practices, and the requirements for the future as they were identified and outlined by the crowd managers. In Table 2 we summarize the requirements for the future together with the current limitations of crowd management practices.

4.3.1. Increasing situation awareness and decision-making support

For what concerns the planning phase, most crowd managers acknowledged that predicting all possible and relevant situations that may develop is an essential component of crowd management, yet far from trivial. In the scenario planning performed during the preparations for an event, for instance, biases towards specific scenarios (for example too optimistic or too pessimistic scenarios) often exist, even amongst experienced crowd experts. Moreover, it may be difficult to take into account situations that the experts have never experienced before. In addition, computer simulations of crowd behavior, sometimes used in these predictions, do not fully capture all essential mechanisms that are relevant in a given setting. Hence, crowd managers require more support for the generation of sound and comprehensive plans.

Regarding the implementation of the plan, crowd managers emphasized the need for increased situation awareness. That is, crowd managers require to be informed in advance about how a certain situation is developing, to help them act accordingly and as early as possible. For instance, they would like to have an estimate of how soon an area will get overcrowded and how early to give feedback to the crowd and scouts to handle the situation. Essential parts of situation awareness are perception, comprehension, and prediction (Endsley, 1995). To increase the former, most crowd managers expressed the need to have a spatial overview of the crowd, including information such as density, movement and flows in real-time. Density in particular can affect the flow and

[3] The C2000 is a private radio-based encrypted communication infrastructure used by dutch emergency services for public safety.

Table 2
Current practices' limitations and requirements for the future.

Requirement	Current limitations
Increased situation awareness and decision-making support	• limited, biased, and over-simplified what-if scenarios • inability to generate unforeseen conditions • unvalidated and unrealistic computer simulations • inaccurate estimation of crowd future states • poor overview of the crowd (density, movement, flows) • limited support of decision-making support systems
Reliable real-time monitoring and communication	• human-dependent and limited monitoring (e.g., on-the field stewards) • surveillance cameras are not ubiquitous and mostly human-operated • data is collected not in real-time • coarse-grained and unreliable data with high densities • communication happens verbally and through few shared channels • little sharing of collected data between actors
Enabling intervention without use of force	• few non-pervasive means to communicate with the crowd • inability to provide timely preventive feedback to the crowd • only fixed screens and loudspeakers are available • infrastructure such as barriers and gates are passive with little control

speed of movement of the crowd (Fang et al., 2003) and can hence convey relevant information to the crowd managers about the current and future state of the crowd. Such a dynamic "map" of a crowd could provide situation awareness to crowd managers and should be available at three different levels, namely (i) specific areas of interest, e.g. bottleneck areas that may get overcrowded such as entrances/exits, corridors, and stairs, (ii) the whole area where the crowd is present, for instance the whole area of a football stadium that is used by the crowd, (iii) areas around/outside the total area of interest, for instance the parking areas around/leading to the football stadium. Ideally, the map would include additional information about the crowd, such as the profiles of the people, their mood, the placement of exists, stewards and other infrastructure. To increase prediction, the information in the map needs to include trends in crowd behavior and dynamics, and how they develop over time.

4.3.2. Reliable real-time monitoring and communication

Crowd managers expressed the need for reliable means to measure the state of the crowd, that can operate particularly in critical conditions. Current "instruments" to survey large crowds are the stewards on the ground inside the crowd and surveillance cameras watching over the crowd. These approaches are limited as they may lead to personnel missing relevant information. Feeds from the surveillance cameras are monitored by personnel who cannot watch all screens at all times. Current automatic approaches, like computer-vision image analysis of video streams or automatic counting from mobile phones traces, do not operate at high density and large-scale. Finally, crowd managers desired to collect and integrate information currently stored in "silos" from different sources. For example, smart turnstiles and barriers are used to collect information about the crowd for future planning. Crowd managers emphasized the importance of obtaining and using this information in real-time during the event.

Similarly, crowd managers expressed need for reliable communication within the team as well as with the crowd in critical conditions. Current approaches present limitations similar to those regarding monitoring, that is they are mostly human-dependant and manually operated, causing information loss or overload. For what concerns communication to the crowd, managers stressed the need for effective means to communicate beyond current loud-speakers and screens.

4.3.3. Enabling interventions without usage of force

Concerning the actions that must be taken to manage the crowds, crowd managers expressed the need for mechanisms to effectively control the movements of the crowd. In particular, a mechanism was sought which would allow the coordination of the movements of groups of people in a crowd. Conceptually, a "traffic light", in the own terms of one of the managers, that would control which groups of people could move, where and when. Moreover, crowd managers expressed the need for means to evenly distribute the crowd in a given space, e.g. a train platform or a concert area, as well as to evenly distribute the crowds in time, for example, to prevent that large numbers of people arrive to and depart from an event all at the same time. Solutions for queue management in large crowds were also mentioned as important requirements, which could support flexible queuing, for example, allowing people to leave and re-join a queue, or even queue-less events and help the speeding up of queues.

While some of these interventions could be implemented through new physical and mechanical infrastructure, crowd managers acknowledged that in order to take actions towards the crowd, communication with the crowd is of utmost importance. Therefore crowd managers expressed the need to communicate well with the crowds. Mechanisms are thus needed which can very clearly and effectively provide the crowds with information such as: (i) overview of the crowd situation (ii) reasons for any troubles and delays, (iii) predictions, waiting times, (iv) advices, alternatives, orders.

5. Recommendations: the anatomy of a techno-social system for crowd management

In this section we provide a systematic discussion on how technology may improve the support of crowd management practices. We frame our recommendations around a *techno-social system* comprising of two feedback control loops. If we consider the interaction between the crowd management team and the crowd as a social system, then we can define a techno-social system for crowd management as a system where technology supports and augments such interaction. We envision a system implementing data-driven practices common to other industries. Examples of such practices are (i) collection, processing and sharing of large streams of heterogeneous data coming from mobile and fixed sensors, (ii) support for analysis and sense-making of crowd data, for example, by means of tools for exploration and visualization of large datasets, and (iii) recommendation and implementation of intervention strategies executed for example through actuators, such as turnstiles and barriers, and communication. At the same time, we envision empowered individuals in the crowd taking autonomous decisions based on feedback provided by the system.

Table 3
Overview of the impact of the envisioned techno-social system on the crowd management operations emphasized by the crowd managers as requiring aid from technology.

Operations	Current	Future
Crowd monitoring and communication	Data about the crowd is estimated by the agents on the field and behind the surveillance cameras screens, and it is communicated verbally to the control room. Data is managed and shared manually by the different actors operating in the control room	Data from fixed and mobile sensors, such as video cameras, smart phones, and e-bracelets is collected, shared, and processed automatically to estimate in real-time densities, flows, congestions, crowd mood, and further supports automatic decision-making support systems and prediction models
Planning and decision-making support	What-if scenarios, and logistical and action plans are generated by the managers based on personal skills and know-how, and sometimes simulated with synthetic models. During the event, decisions are made based on the information communicated by the agents on the field, by matching the static what-if scenarios with the current state	Historical data collected from sensors and other events is used to support the generation of what-if scenarios and plans, and to simulate different conditions. The models are validated with past data. During the event, the data collected in real-time is used not only to match the current what-if scenario, but also to enhance the overview of the crowd managers about the current state of the crowd and the predictions about future outcomes
Intervention without use of force	Information is communicated verbally from the control room to the agent on the field who operate with the crowd and provide feedback either verbally, aided by loudspeakers, or through screens. Gates and barriers are operated manually in response to the different orders given by the control room	Feedback is computed automatically and transmitted to the devices of both the agents and the members of crowd, as well as to the fixed screens. The decisions of the crowd managers result in actuations by the smart turnstiles, gates and barriers, which help the agents steer the crowd

A number of different technologies and state-of-the-art techniques can fit into such framework, and could aid tackling the limitations and drawbacks presented in Table 2. In Table 3 we provide some hypothetical concrete examples of how the implementation of our model would impact on the operations outlined by the crowd managers (note how the operations in Table 3 match the requirement in Table 2). We go in the details in the following sections.

5.1. Crowd management as two feedback control loops

In a nutshell, a feedback control loop comprises three phases: (i) *measurement* of input, (ii) *control* of input, and (iii) actuation through *feedback*. Crowd management can be seen as two of such loops. One that happens during the event, and one that takes place between events. Looking at crowd management practices as feedback control loops allows us to reason about how technology can help, in all three phases, the group work of crowd managers towards a more effective and data-driven approach (see Fig. 4).

5.1.1. The loop within each event

The first feedback control loop takes place during the event, and comprises all the operations to (i) collect information about the state of the crowd, (ii) assess and predict the state of the crowd within the planned scenarios, (iii) intervene, if necessary, to prevent uncomfortable and dangerous situations. The loops should be operated at short intervals (e.g., seconds or few minutes), to ensure real-time monitoring and quick response.

The measurement phase is perhaps the phase that has received most recent attention in the literature. Existing pervasive and ubiquitous sensing infrastructure have been proposed and investigated as a means to measure the movement of flows of people, the areas affected by undesired crowd mood, but also the capacity of parking lots and the development of weather conditions. This infrastructure includes mobile sensors such as smart phones and RFID-enabled bracelets used as festival tickets, as well as, for example, fixed sensors like video cameras and weather stations. However, crowd managers expressed a need for real-time measurement of crowd behavior, and a dissatisfaction with the unreliability of current solutions at high densities. Recent work on decentralized protocols, for example, to detect density (Cattani et al., 2014), hold the promise of providing reliability at large scale.

Once a continuous stream of data coming from these sensors would be established, it can be shared among agencies, and processed automatically to help sense-making about the behavior of the crowd. This is the control phase of the loop. Crowd managers have expressed a desire for instruments that can increase situation awareness and support decision making. Unfortunately, most current prediction models about crowd behavior, while numerous, still lack evaluation with real data (R. Challenger et al., 2009). As also reported by one of our interviewees, they are still too inaccurate to be useful. Increase in collection of crowd data can be an opportunity for improvement in validation of current models, and aid the design of novel and more comprehensive models (Gwynne et al., 1999; Bellomo and Dogbe, 2011). Adaptive and interactive applications can help crowd managers identifying current active "what-if" scenarios by recognizing and highlighting relevant pieces of crowd state, and recommending related interventions (Conrado and de Oude, 2014). Four interviewees reported the need to visualize the flows of people within the location on a map, and the predicted densities for the near future. Visualization can be a powerful tool to facilitate computer-supported cooperative work (Isenberg et al., 2011). Current work on visualization of mobility traces within urban areas and large scale festivals provide examples of such interfaces (Martino et al., 2010; Wirz et al., 2013a).

Regarding the feedback phase, again smart phones and other wearable devices are an opportunity for crowd managers to communicate with crowd members, and platforms to support autonomous decisions by the individuals in the crowd. For example, apps running on smart phones can allow fine-grained location-aware communication targeted to specific zones of the event location with personalized information (Wirz et al., 2010). While current music festival apps allow to share and visualize the location of friends on a map, they do not display, for example, the flows of people between stages, or the densities around the different spots. Such information, automatically provided by the system, could allow individuals to make informed decision, and avoid unpleasant situations (Blanke et al., 2014). With respect to fixed infrastructure, barriers are also opportunities to communicate information about the state of the crowd, for example, through a displays showing densities at the front of a queue or near an exit, or by indicating alternative routes through lights.

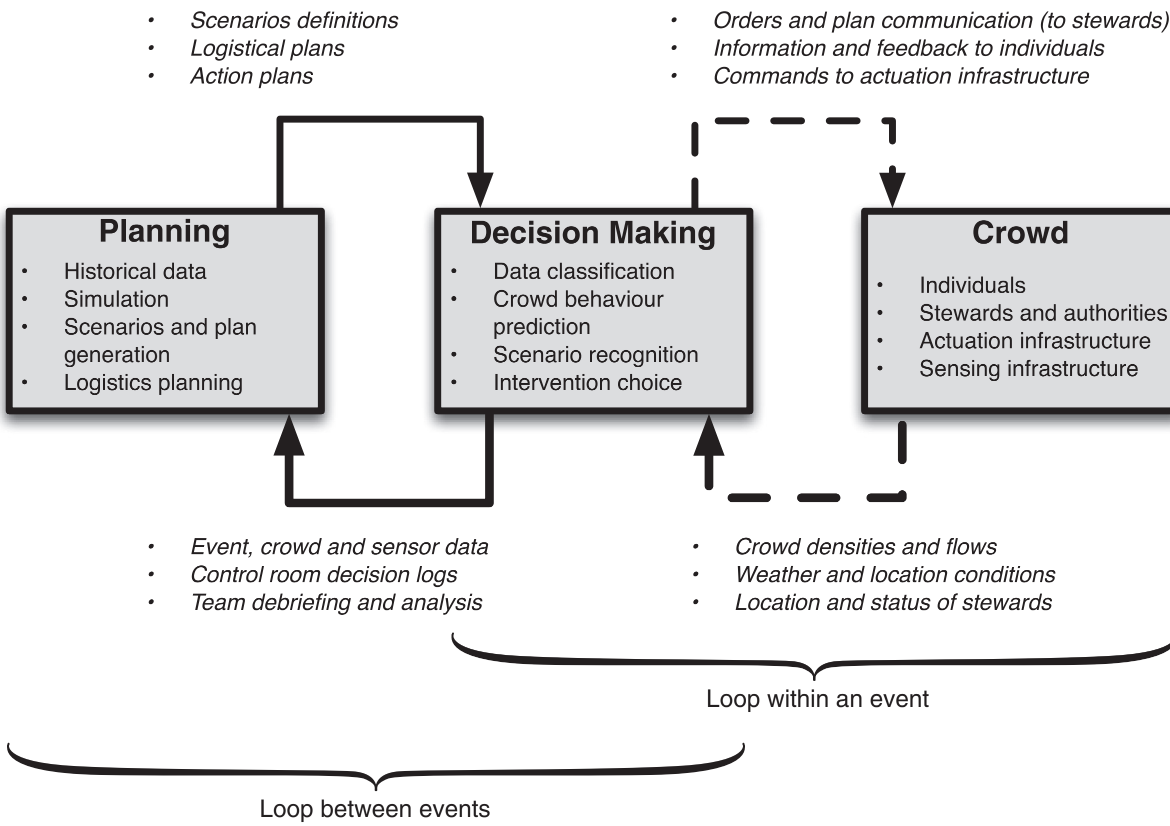

Fig. 4. Crowd management can be seen as two feedback loops. The first loop happens within an event and it is characterized by (i) data collection from personnel and sensors (ii) decision making in the control room and on the field based on the data, the scenarios prepared and the plans, (iii) feedback in the form of information, orders, and commands to the infrastructure. This loop is executed at high frequency to ensure quick response time to changing conditions and emergencies. The second loop happens between the events and it allows the planning of the following events to be adapted based on the lessons learnt during the previous (i.e., based on collected data during the event, debriefs, expert analysis, and decision support systems).

5.1.2. The loop between events

The second feedback control loop consists of the process of crowd management itself, and includes (i) debriefing outcomes of a previous event, (ii) analyzing possible flaws in the plan or in the decision making process, and (iii) updating of the planning processes to accommodate new lessons.

The utility of the information collected during an event does not finish at the end of the event. The databases of sensed data, together with the log of decisions made by the management team during the event, provide a solid base for a systematic reasoning about the outcome of the event (Leveson, 2011). Interviewees underlined the generation of the what-if scenarios as being at risk of bias, lack of coverage and depth. A more data-driven approach can reduce errors and bias, as well as allow experts to recognize new scenario that happened during th event. Scenarios can be recommended to the crowd managers based on the data collected over time, during previous events. Moreover, such scenarios can be automatically characterized by estimates based on historical data. Also, data can facilitate the reviewing procedures at the end of the event (Health and Executive, 2014). Finally, sensed data can be fed into crowd behavior simulators, to overcome the aforementioned limitations related to absence of rich scenarios and validation (Gwynne et al., 1999; FTRE, 1999), or fed into computational models to support operational research techniques for task force deployment (Drechsel and Kimms, 2008). The result is a live process, where data-driven approaches support collaboration within the crowd management team from the phase of planning to the phase of implementation, during and between events.

5.2. Implications

In this section we discuss implications and constraints that need to be considered when introducing more technology within such a techno-social system.

5.2.1. Keeping the human in the loop

While we advocate a bigger role of technology in crowd management, we emphasize that such transition shall happen with the human, both as a member of the crowd management team and of the crowd, in the center. When designing crowd applications, one should take into account explicit and implicit motivational factors. For instance, users in the crowd may require incentives to share their data and, for example, utilize an energy-consuming application on their phone. Providing a platform to help locate friends could be an example of an incentive to share with the system current locations and social ties. Moreover, individuals have different psychological needs when it comes to well-being (Li et al., 2013). Crowd members seek for fulfilling higher level of psychological needs, i.e. staying autonomous, connected, competent and respected in normal crowd conditions, while their focus will immediately change to low level needs, i.e. safety and security issues, when unexpected things happen.

For what concerns crowd managers, it is important to support their planning and collaborative decision-making, in particular in emergency situations (Kapucu and Garayev, 2011). Interviewees pointed out that current technological solutions often lack comprehensiveness or accuracy, which resulted in rejection of the system. Perceived usefulness of an instrument is known to be strongly influencing the intentions of the user, even more than perceived ease (Davis et al., 1989). Importantly, the goal of decision-support system should be to aid the expert decision of a crowd manager, and not substitute it (Schubert and Suzic, 2007).

5.2.2. Guaranteeing privacy to the crowd

While not directly mentioned by the interviewees, ensuring privacy and trust are critical adoption barriers of such a system. For example, detection of flows and bottlenecks as well as mood, require constant probing for sensitive information such as location and emotions. Moreover, privacy is user specific, that is each individual has a different perception of privacy. Various techniques have been proposed to solve the issue of privacy in sensing, and they include anonymization (Sweeney, 2002), cryptographic techniques (Yao, 1982; Erkin et al., 2014), and data obfuscation (Agrawal and Srikant, 2000; Ganti et al., 2008). Crowd data, in particular with respect to crowd dynamics, lends itself to these techniques. For example, the characterization of pedestrian flows and their volumes, does not require knowledge about the identity of the comprising users.

5.2.3. Minimizing the need for new infrastructure

Introducing technology can often imply new and expensive investments. Two distinctions are necessary in this case. First, there are gatherings that take place in fixed locations, designed for the purpose of hosting crowds. Examples are train stations, music halls, stadiums, and theatres. These locations already employ substantial infrastructure, starting from barriers, video cameras, turnstiles, sometimes Bluetooth and Wifi scanners. In these scenarios, the interviewees reported being open to the installation of new infrastructure, given a reliable functioning in critical conditions.

Second, there are events that take place in locations that are not designed to host large crowds. For example, periodic parades and celebrations taking place in city centers and neighborhoods. In these occasions, it is difficult and expensive to temporarily deploy new infrastructures pervasively across town. As reported by the interviewees, smart phones are widely adopted and minimize the need for additional infrastructure. Moreover, event planners often cooperate with telecom companies to obtain cellular data about densities. Finally, additional cellular towers can sometimes be installed to alleviate the problems of congestion.

6. Discussion

We interviewed 10 crowd managers to gain an understanding of the current role of technology in their current practices, including limitations and requirements. We have formulated our recommendations within a techno-social system framework. Despite the fact that the 10 volunteers agreed on many of the fundamental definitions about their practices and needs, regardless of their diverse domains of work, it is likely that our results are influenced by different biases, for example, cultural, organizational, and geographical, as all the managers operate in The Netherlands. To be able to generalize the results of the interviews more work needs to be done in different geographical, cultural and economical contexts. Nonetheless, the consistency of our results with the other work (W. Challenger et al., 2009; Health and Executive, 2014; Berlonghi, 1995) suggests that our results can be generalizable at least to similar contexts to those in The Netherlands.

While the volunteers are indeed experts with decades of experience, we should not treat the data completely as “ground truth”. To validate some of the statements and assumptions, further on-ground and observational work should complement the insights extracted from the interviews. We suggest this work to be conducted both in the control room and on the field, during the different phases of the planning and implementation of an event.

It is unclear whether many of the technological problems and limitations we described in this paper are specific to crowd management, and how much of the related research should be adapted to in the context of crowd management specifically. For example, radio-based communication is known to operate poorly at high densities and hence it does not represent a crowd-specific problem. Yet, crowds are not characterized solely by high densities but also by movement patterns that are innate and hence exploited, for example, by so-called epidemic protocols used by wireless sensors to disseminate data and communicate at large. At the same time, the bodies of individuals influence communication in a much different way than metallic objects as, for example, cars, making some of the related work on transportation systems not directly applicable to crowds.

The vast majority of existing literature on crowd and pedestrian behavior focuses on modeling and predicting behavior. More recent work has focused on how to devise sensing infrastructure to collect real-time data about the behavior of a crowd, and support sense-making. Less attention has been dedicated to how to support crowd management specific decision making and even less to how to intervene and steer crowd behavior to ensure the safety of the individuals. Tackling these challenges requires multi-disciplinary work that comprises investigating how to influence the behavior of a crowd, how to choose the right action to obtain a certain reaction from the crowd, what information to communicate to the crowd and with which medium and feedback. Answers to these questions are far from trivial and, to this date, mostly unknown.

7. Conclusions

We have presented crowd management as a set of collaborative practices. The successful management of an event depends on the cooperation and communication between these actors, and the crowd. Our findings show that crowd managers do already look at technology to solve some of their problems, and see it as an opportunity for future developments. As technology plays a bigger role in crowd management, a number of technical and technological challenges need to be tackled, from different fields and practices. We have addressed these challenges within the framework of a techno-social system. This work shows that there is space for more support from technology at different stages of the planning and implementation of an event, and it motivates and suggests new directions for research to support the safe management of crowds.

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