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Situational awareness and decision-making in a crisis situation: a crisis management cell in virtual reality

Short title: Crisis management in virtual reality

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Abstract

In a constantly evolving and hyper-connected world, the crises we are facing are changing, exceeding borders, and impacting every sector of activity. More data can be gathered from the crisis site, arriving in a large flow of various types from multiple sources such as sensors, open data, or social media. This huge amount of data coming continuously from the crisis site leads to an ever-changing situational awareness that must be built and understood as quickly as it is evolving to ensure a relevant and effective crisis response. To build a shared situational awareness, decision-makers can gather in a room where they can share and compare the information they receive from the crisis site to build a common operational picture that they can use to make decisions and implement them: this is a crisis management cell. However, the tools in traditional crisis management cells may not be able to keep up with the new requirements induced by these changes: we need modular and dynamic tools able to adapt to the crisis and the needs of the crisis managers while ensuring collaboration and information sharing not only between the stakeholders but also with remote experts that might be needed to understand the situation. We need to start conceiving the future crisis management cell that would meet the new exigencies of crisis management. This paper proposes our version of that future crisis management cell, using virtual reality to provide a dynamic and modular crisis management cell linked to artificial intelligence and decision-support systems.

Keywords: Crisis Management, Situational Awareness, Decision-support, Virtual Reality

1 - Introduction

During a crisis, precise and accurate knowledge of the situation, as well as information sharing, is crucial for decision-makers to be able to make enlightened and relevant decisions to solve the crisis. A crisis can be defined as *a disruption within the state of a system revealing discontinuity and instability and requiring treatment to deal with the consequences of the disruption and reach a new acceptable state of the system* (Benaben et al. 2016). The notion of crisis management can design the means, process, and techniques allowing an organization to deal with a crisis before, during, and after its occurrence. Crisis management can be divided into four phases (Kruchten et al. 2008): the **prevention phase** (measures and means to avoid the crisis), the **preparation phase** (measures and means to ensure that the resources needed to deal with the crisis are ready, should the crisis occur), the **response phase** (deployment, as the crisis occurs, of

the resources and measures prepared during the preparation phase), and the **recovery phase** (measures to return to a stable situation). This paper focuses on the response phase, where crisis responders aim to regain control of the situation and reduce the consequences of the crisis.

To provide the most efficient response to a crisis, it is essential for responders from multiple organizations to be able to communicate and share information to achieve situational awareness. Situational awareness is defined as *the perception of the elements of an environment within a certain time and space, the comprehension of what they mean, and the projection in the near future of their status* (Endsley 1995). This communication and information sharing is complicated by the fact that each organization involved in crisis management has its own procedures, jargon, and chain of command and that they might need specific information at a specific moment (Bharosa et al. 2010; Netten and Someren 2011). To overcome these limitations and achieve situational awareness, common operational pictures (COP) are built. A COP is *a display of relevant information that is shared by the different organizations involved in the crisis response. Its objective is to facilitate collaboration and planning and to achieve situational awareness* (Staff 2001). Most of the time, COP are represented through geographic information systems (GIS), which present several limitations. Data analysis can be difficult, particularly in large-scale crises where a huge amount of information is gathered. Non-geolocated data such as available resources, decision consequences, or anticipated developments must also be available to decision-makers but are left out by GIS COP (Copeland 2008).

Besides, in a world that is constantly changing, the crises that we are facing are evolving as well: their scope has increased, they cross borders and impact all sectors of activity, and they can even combine to create cascading effects. The hyper-connected aspect of the world leads to an increase in available data coming from various sensors, open data, or even social media. Crisis managers must deal with a large flow of extremely varied data continuously coming from multiple sources. Depending on the source, that data can be more or less reliable or relevant, so it must be checked and distributed to the correct actors. This continuous flow of data leads to an ever-changing situational awareness, more fragile and volatile. The increased scope of crises combined with the volatility of situational awareness results in new exigencies, such as the need to involve experts from remote locations. Crisis managers must be able to understand the situation as quickly as it is evolving to be able to respond to it.

When a crisis occurs, decision-makers can gather in a crisis management cell, which refers to their gathering in a room where they can share and compare the information they get from their teams on the crisis site, build a common operational picture, and use it to make decisions, implement them, and pilot

the response (Inoguchi and Hayashi 2012). The tools that are currently available in crisis management cells are no longer sufficient to deal with that evolution of crises. We could imagine 2D maps connected to artificial intelligence to help analyze and display the huge amount of data coming from the crisis site, but this is not enough. We need a modular and interactive crisis management cell that could be adapted to the crisis and needs of the crisis managers. We need to imagine a future crisis management cell that would be able to provide more efficient and dynamic tools for situational awareness and decision-making, all the while keeping the interaction, collaboration, and information sharing between the stakeholders.

To sum up, there is a need for modular and dynamic tools dedicated to situational awareness and decision-making that would present several features: (i) a clear and relevant representation of voluminous data shared and understood by the different organizations involved in crisis management, (ii) a display of data, both geolocated and not, as well as more abstract information such as the consequences of decisions or projections in the future, and (iii) a real-time updating of all the data.

Virtual reality (VR) presents several features that make it an interesting tool for improving situational awareness and decision-making. Its ability to reproduce reality offers the possibility to faithfully reproduce the crisis and thus build situational awareness. VR can be fed by different kinds of sensors gathering data from the crisis site, such as drones, heat or presence sensors, or even social media. Thanks to an analysis of this information, it is possible to build a model of the situation. Besides, VR is assembling as it allows people to join in the same virtual environment and interact with each other even though they are not physically in the same place. VR can overcome the limits of the physical world. A user in VR can free himself of the law of gravity or the scale limitations, which offers several opportunities to visualize information in a new way and through different points of view and to interact with the data. VR is a great tool to help users understand and interact with artificial intelligence, and it can also bring new tools, such as immersive analytics, to help with decision-making. **This leads us to the following research question: how can VR improve crisis response?**

This paper presents the advantages of VR for crisis response, particularly in improving situational awareness and decision-making through the conception of a VR crisis management cell dedicated to crisis managers. We first present the limitations of current COP as well as the advantages of VR for situational awareness and decision-making. Then, we describe our proposal for a VR crisis management cell supported by a decision-support system, presenting the specifications and the implementation of a first prototype. This VR crisis management cell aims at proposing new visualization tools for complex data and facilitating

interactions between the practitioners and the artificial intelligence treating that data. Finally, we talk about the perspectives of this work.

2 – State of the art

During a crisis, COP are implemented to achieve situational awareness. They are essential for crisis responders from multiple organizations to achieve communication and action coordination (Comfort 2007), as they allow on-scene and off-scene actors to access and understand the same information (Wolbers and Boersma 2013). COP are mostly represented through geographic information systems (GIS), *spatial data processing systems, which are composed of a spatial database, analytical functionalities, and visualization capabilities* (Huang et al. 2001). Each of the crisis management organizations usually builds and maintains its own GIS COP (Steen-Tveit et al. 2020), which does not facilitate collaboration and communication. Data analysis and representation can be difficult on GIS, even more so in a large-scale crisis with a huge amount of data. COP must not only represent what is currently going on, but also logistics, resources available now or in the future, and every information needed to achieve situational awareness. All that information, which must always be up-to-date and available at any time, represents a huge amount of data that can lead to information overload (Fertier et al., 2018).

2.1 – Using VR to visualize and understand data

In most of the traditional crisis management cells, COP are built through heterogeneous and not interoperable paper maps or 2D GIS. They can be updated through phone calls, using board and post-its, which are not optimal tools to share and visualize critical and complex information. Using VR to replace these tools would offer new possibilities to visualize data, providing more engaging and embodied ways to support data understanding, collaboration, and the process of decision-making, notably thanks to immersive analytics (Dwyer et al. 2018). VR can offer users the possibility to immerse in data and extend their stimulated senses, space awareness, and depth perception, thus allowing them to viscerally understand the data. Interacting with the data is also more intuitive, prompted by immersion, which induces an easier understanding of data with complex geometry (Isaacs et al. 2011; El Beheiry et al. 2019). The increased dimensionality offered by VR induces multiple points of view, which is valuable for data analysis and offers more natural ways to explore and understand voluminous data (Millais et al., 2018). This immersion in data offered by VR has been proven to lead to a more successful understanding of data than 2D exploration (Andersen et al. 2019), mostly thanks to the possibility of physically interacting with them and to the 360° aspect of VR. Gestures-controlled interactions are more intuitive and efficient than mouse and keyboard interactions. They also offer more natural interfaces to interact with the data,

matching the movements of the user. VE offers the possibility to use spatial metaphors such as front or back to help understand complex data, for instance, placing more important data in front of the user and less important data behind (McCormack et al. 2018). Immersion into data offers better perception and relationship retention, in addition to a more intuitive understanding (Donalek et al. 2014). Another advantage of VR is the possibility for multiple users from different physical locations to join in the same virtual environment and thus explore and interact with the data together in VR (McCormack et al. 2018). They can thus work together on the same dataset, which can enhance collaboration between multiple organizations. This is particularly interesting in the crisis context where multi-organizational collaboration is crucial for the crisis response.

2.2 – Using VR for Common Operational Pictures

These advantages of VR for data visualization and understanding can be used to improve COP. The concepts of VR GIS and VR COP can be considered as VR representations of GIS and COP, facilitating the comprehension of the data on the GIS and allowing better interaction and comprehension of the data presented in the COP. VR GIS can be used to achieve a VR COP, but there is also the need to represent non-spatial information. There are few examples of VR COP outside of fiction, we found some examples that are presented later in the paper. However, the advances and new technological development will probably make it easier to achieve and use. COP, such as the ones that can be seen in science fiction movies (Avatar or Iron Man, for instance), might still be a bit too futuristic for the current time, but the arrival of the 5G or the metaverses, which can be defined as perpetual and persistent connected multiplayer environments merging physical and virtual reality (Mystakidis 2022), will probably accelerate the arrival of VR in several areas, and COP could be among them. VR GIS are a bit more common than VR COP, for instance, in urban and environmental planning, scientific visualization, military simulation, or education (Huang et al. 2001). They offer several advantages: better ways of visualizing geographical data and interacting with them, new interaction possibilities with GIS databases, and better decision-making (Germs et al. 1999). A 3D map in VR can be observed from several points of view, exo or ego-centered, and on different scales. This can help the users to better understand their environment. Associated with relevant information treatment and visualization, this could greatly improve situational awareness and decision-making in a crisis context. Besides, VR enables the building of collaborative GIS and facilitates the sharing of information between the crisis stakeholders and their understanding of the situation (Ball et al. 2007).

We found some examples of the use of VR for COP thanks to the request “Virtual reality + common operational pictures” on the Web of Science. This request returned 16 articles, one of them being one of ours, presenting the concept we are detailing in this paper. From the other papers, we excluded papers

that were not presenting a tool to visualize or build a COP. Three papers presented the same tool under different approaches. Finally, three examples of using VR to enhance COP can be presented, as well as two examples of using augmented reality, which also hold some interesting aspects. First, the project virtual reality devices in ground forces tactical command and control systems (Hodicky and Frantis 2009), accepted by the Defense Department of the Czech Republic, aims at using 3D visualization and VR to improve the commanders' situational awareness at a tactical and operational level. As shown in Figure 1, the 2D map presenting battlefield data is replaced with a 3D map, accessible in VR through head-mounted devices. This induces better visualization and understanding of the situation, where the commanders can support their decision-making with the exploration of the crisis in 3D and from the inside. They get an internal point of view while remaining safe, which is interesting in a crisis.

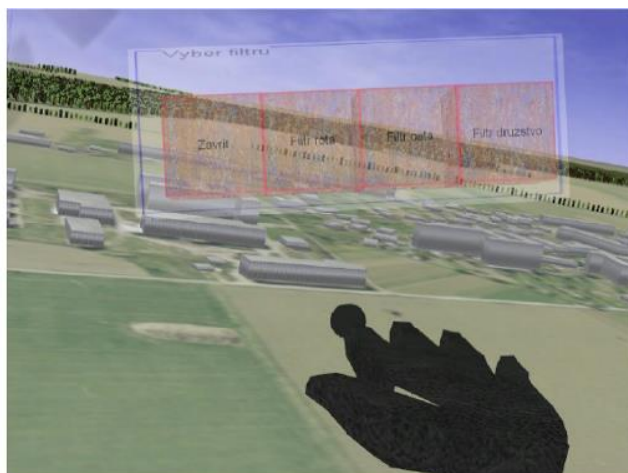


Figure 1: View of the VR COP presented in (Hodicky and Frantis 2009)

Another example can be found outside of the military domain: a VR COP in cybersecurity. Despite the development of solutions such as immersive analytics, cybersecurity systems are still mainly relying on classical graphical representation to analyze data (Kabil et al. 2018). Kabil et al. propose a 3D VR environment dedicated to collaborative cybersecurity investigations and reporting practices, illustrated in Figure 2. The users can perform specific actions depending on their roles. These roles also enable them to show only the most relevant data to them, thus avoiding information overload. They can also get multiple points of view to better understand the data. The objective of this VR cybersecurity COP is to use immersive analytics visualization as well as learning approaches to increase the users' cybersecurity situational awareness.

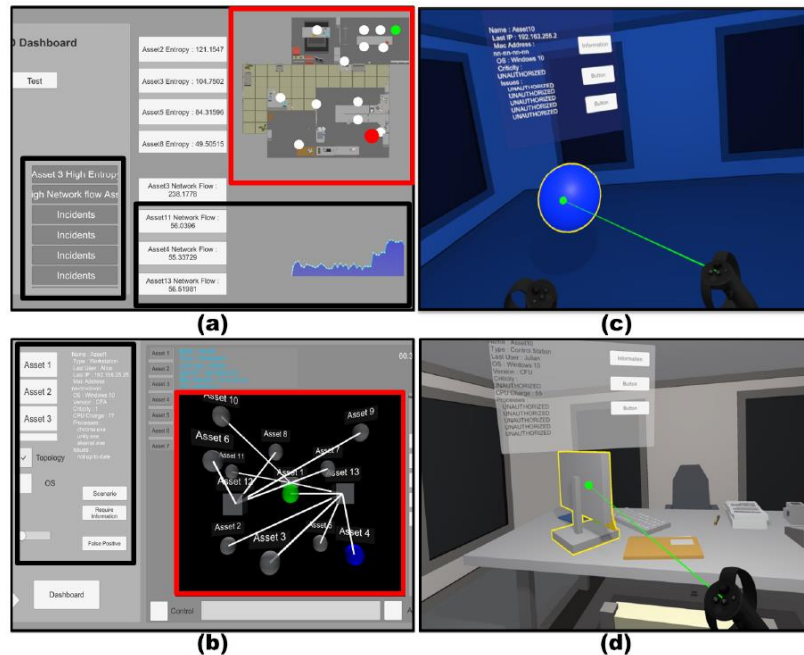


Figure 2: Views of the 3D cybercop prototype from (Kabil et al. 2018)

More recently, van de Camp et al. (2020) propose a mixed reality environment to provide intuitive analysis and understanding of the situation and collaboration between the users, regardless of their physical location. The system is based on software called DigTL which provides 2D and 3D maps on which the situation is displayed to the users. These maps can be visualized on cellphones or computer screens, on virtual tables, and in a VR environment. This VR environment is accessible to several users that are represented by avatars, which enable communication not only orally but also through body gestures (hand and head movements, for instance). The tool includes a feature called “pedestrian mode,” which allows the users to walk and stand inside the map to get a realistic idea of the surroundings.

Some authors present COP in augmented reality (AR), which is also interesting as it can offer the possibility to combine some physical parts of the crisis management cell with the AR COP. Besides, as mentioned in (Dennison et al. 2020), augmented reality does not induce a complete visual occlusion as is the case in VR, which can be easier to accept by the users. Mao and Chen (2021) study the combination of AR technology with COP to enhance battlefield situational awareness. Their system is used to train the Taiwanese Army Academy students and has been proven to improve their understanding of the situation. However, it is not used in an actual military operation. Zocco and De Paolis (2015) propose an augmented environment for the military, representing a 3D map of the mission area and displaying mission scenarios. One interesting point of this system is the possibility to represent the margin of error, for instance, in the

direction of arrival of enemies, thanks to pyramids with vertex. Collaboration between the users is also a strong point of this environment which aims at reducing information overload and allowing several users to visualize the situation at the same time. It is also worth noting that this system is able to recognize hands movements, which means that it can be used without controllers. This is interesting as it might also help reduce the reluctance of the users to actually use the tool.

2.3 – Conclusion of the state of the art section

VR proposes several advantages that can improve situational awareness and the decision-making process. These advantages are summarized in Table 1.

Table 1: advantages of using VR to improve situational awareness and decision-making

| ADVANTAGES | DETAILS |
|---|--|
| Immersion | <ul style="list-style-type: none"> - The users can be immersed in the data and surrounded by them. - Possibility to use spatial metaphors (front, back...). - A visceral understanding of the data and the relationship between them. |
| Interaction | <ul style="list-style-type: none"> - Direct interaction with the data through intuitive gestures. - Possibility to handle the data to observe it from different angles. - Facilitated understanding of the links between the data. |
| Multiplayer aspect | <ul style="list-style-type: none"> - Possibility for multiple users to gather in the same virtual environment, regardless of their physical location. - Enhanced collaboration through the possibility of working conjointly on the same data. |
| Multiple points of view and scalability | <ul style="list-style-type: none"> - Possibility to observe the data from different points of view. - Possibility to change the scale of what one's observing. |
| Multidimensions | <ul style="list-style-type: none"> - Possibility to represent data in multidimensional environments, which can help visualize and understand more complex data. |
| Virtuality | <ul style="list-style-type: none"> - Possibility to make mistakes without fearing their consequences. - Possibility to test new tools or new processes before implementing them. |



To the best of our knowledge, there is no VR COP actually used in crisis responses and emergency management, and we only found a handful of examples of VR COP for crisis management in research, even

though VR offers several advantages to overcome COP current limits and improve situational awareness and decision-making. **This paper proposes a vision of a crisis management cell in VR linked with a decision-support system that takes advantage of the technology to improve data visualization and, thus, situational awareness and decision-making.** The next section details our proposal.

3 – Our proposal

Traditional crisis management cells often are set up in simple rooms or tents equipped with computer screens and paper maps. Communication with the crisis site is generally achieved through phone calls or via walkie-talkies or radios. Collaboration and information sharing between the different stakeholders are limited and difficult to achieve within these crisis management cells (Bharosa et al. 2010; Netten and Someren 2011). To overcome these limits, we propose to take advantage of VR. Linked with a decision-support system, this technology allows us to propose an immersive virtual crisis management cell dedicated to crisis response, aiming at improving situational awareness and decision-making. This section first proposes specifications for a crisis management cell in VR. Then, we present a prototype of this VR crisis management cell, linked with a decision-support system to facilitate the analysis of the gathered data: R-IO Suite, detailed later. Please note that we did not conduct any tests to validate the concept yet. However, as part of several research projects, the prototype was presented to several crisis management actors such as firemen, the préfet du Tarn, or the Ministère de la Transition Écologique. R-IO Suite is mainly used at the operational level of crisis management. By presenting our prototype to the aforementioned actors, we cover the different kinds of actors involved in this level: operational staff and decision-makers from the firefighters as well as administrative decision-makers. They provided very interesting and promising feedback, as summed up in Table 2.

Table 2: Summary of the users' feedback

| |  |  |
|------------------------|--|---|
| Ergonomy | <ul style="list-style-type: none"> - Great immersion. - New ways to interact with the data. | <ul style="list-style-type: none"> - Cut off from the physical world. - Motion sickness and discomfort. |
| Functionalities | <ul style="list-style-type: none"> - Possibility to imagine new functionalities thanks to the VR. | <ul style="list-style-type: none"> - Lack of new functionalities implemented so far. |
| Practicality | <ul style="list-style-type: none"> - Adaptative topology of the crisis management cell, which can be easily rearranged and modified according to needs. - Accessible from anywhere. - Great variety of integrable users (distant users, remote experts, on-site responders...). | <ul style="list-style-type: none"> - Need of specific, potentially expensive equipment. - Need of internet connection. - Need time and practice to master the VR and the tool. |
| Acceptance | <ul style="list-style-type: none"> - Improved learning curve for R-IO Suite connected to the prototype due to an easier interaction and more intuitive nature. | <ul style="list-style-type: none"> - Technophobia. - Resistance to change. |

As shown by the feedback presented in the table above, the prototype presented in this paper provides new ways to interact with artificial intelligence and complex data, notably by providing a new interface with decision-support systems such as R-IO Suite. Despite some limits, it offers the possibility to improve both the utilization of existing complex tools as well as to improve the tools themselves by allowing the creation of new functionalities.

3.1 – A VR crisis management cell: specifications

Endsley proposes three dimensions to situational awareness: **perception** (gathering the data from the ongoing situation), **comprehension** (understanding that data), and **projection** (projecting the current situation to determine its future state) (Endsley 1995). To achieve situational awareness, a VR crisis management cell must faithfully reproduce the situation. This can be achieved, for instance, through the gathering of data via on-site sensors, for instance, reports from the actors on-site, social media analyses, or drone captures. This data must be analyzed to be transformed into information and knowledge to achieve the comprehension described by Endsley. Finally, the VR crisis management cell must also offer

the possibility to determine the future state of the situation to ensure projection. VR can help with these aspects, notably thanks to the immersion and interaction it enables. To achieve situational awareness in a crisis context and to help with the decision-making process, the VR crisis management cell presented in this paper will be linked to the decision-support system presented in (Benaben et al. 2017). R-IO Suite presents five main functionalities: (i) **interpretation** of the data to build a model of the situation, (ii) **deduction** of a collaborative response process based on this model, and (iii) **orchestration** of the response to the crisis following the deduced process, (iv) **monitoring** of the situation to detect any divergence between the expected situation (based on the response process) and the actual situation on the crisis site), and (v) **anticipation** of the situation model based on projections, prediction models and the response process. Figure 3 links the functionalities of R-IO Suite and the dimensions of situational awareness (Endsley 1995) and decision support (Simon 1957). The VR crisis management cell will first transpose these functionalities in VR and then take advantage of the possibility offered by this technology to complete and improve them.

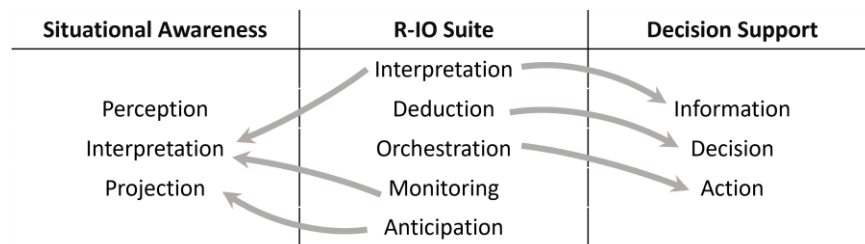


Figure 3: Links between situational awareness and decision support and R-IO Suite functionalities

We identified several functionalities for the crisis management cell that can be connected to the functionalities of digital twins. A digital twin can be defined as a virtual representation of a physical system along with its environment updated through information exchanges between the physical system and the virtual system (VanDerHorn and Mahadevan 2021). The notion of digital twins can be specified into digital models or digital shadows, depending on the level of data exchange (Kritzinger et al. 2018): a **digital model** refers to a representation of a physical system without any automated data exchanges between the physical system and the digital system, while a **digital shadow** refers to a representation of physical systems where data is exchanged from the physical system to the digital system. The notion of digital twins adds data exchange from the digital system to the physical system to the digital shadow's exchanges. The VR crisis management cell should function as a digital model of the crisis thanks to the possibility of establishing a COP, as a digital shadow since it receives and interprets data from the crisis site, and as a digital twin (at least partially) since it allows the users to orchestrate the response on-site (for instance by

sending tasks and information to the crisis site). Thus, the functionalities of R-IO Suite, situational awareness, and decision support must be transposed into the VR crisis management cell. Figure 4 illustrates the relations between the functionalities of the VR crisis management cell and the notions of digital models, shadows, and twins.

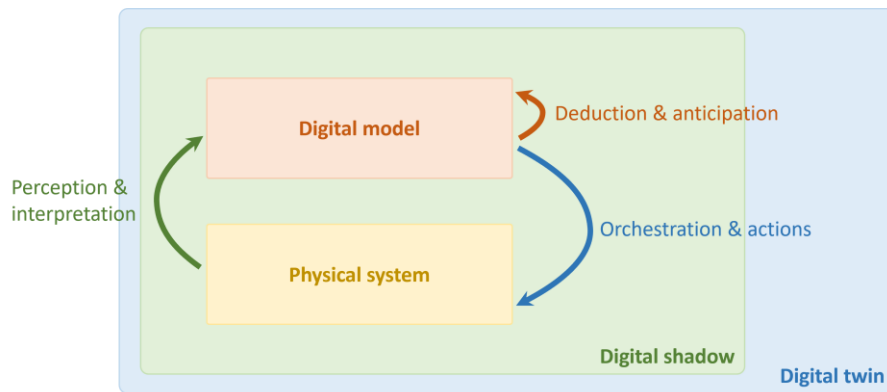


Figure 4: Links between digital model, shadow, and twin and the functionalities of the VR crisis management cell

We identified eleven functionalities for the VR crisis management cell: from data gathering and representation in a clear and understandable way to facilitate the decision-making process to the deduction and orchestration of a response process, the VR crisis management cell must enable the users to get a precise situation awareness, to make decisions more easily and effectively, and to follow the situation in real-time. These eleven functionalities are presented below.

F1 – Representation of the situation:

The VR crisis management cell must provide a faithful and accurate representation of the crisis, updated in real-time. Geolocated data can be represented on an interactive 3D map, as illustrated in Figure 5. Users must be able to zoom in and out on that map, to displace or rotate it to observe other places and different points of view. The idea is to be able to observe the crisis progress from above as it is replicated on the 3D map, thus enjoying a god's eye view allowing users to take in the situation in its globality. Crisis concepts such as the available actors and resources must be displayed in the VR crisis management cell, as well as useful information such as weather or traffic forecasts.



Figure 5: Interactive map in the VR crisis management cell

F2 – Gathering and treating the data:

The VR crisis management cell must be connected to the crisis site through sensors to be able to update the crisis representation. Several kinds of sensors can be used to gather data from the crisis site, such as heat or presence sensors, AI-assisted drones, cameras, or even social media. The idea is to be able to gather any kind of data that will help decision-makers to assess the situation and make decisions. This can be, for instance, the number of civilians on-site, the positions of the first responders, the perimeter of a risk or a danger, the potential victims that have been or remain to be evacuated, or the available resources. All the data that is gathered by these sensors must be analyzed, treated, and sorted to be correctly added to the representation of the situation, as illustrated in Figure 6.



Figure 6: Model of the situation on the interactive 3D map

F3 – Walking through the data:

The VR crisis management cell must provide new ways to experience data, such as immersive analytics, to allow the solicitation of the users' senses that are not usually solicited. The idea is to immerse the users inside the data, as shown in Figure 7, so that they can viscerally understand them. The sense of hearing or touch, depth perception, or space awareness can be used to convey information more intuitively. The connections and links between the different pieces of data are easier to comprehend in VR, where the users are in the middle of them and able to interact with them and handle them. For instance, the most important data can be placed closest to the users, who will then naturally consider them first.

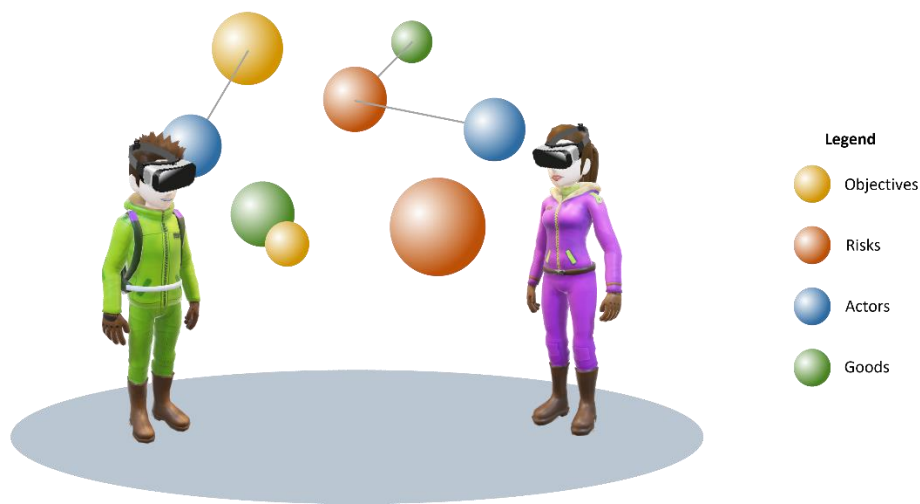


Figure 7: Walking through the data

F4 – Multidimensional aspect:

The VR crisis management cell offers the possibility to represent multidimensional data more easily. The addition of tactile, auditory, or even olfactory stimuli can convey more detailed information to the user. The time can be represented, for instance, through the vertical axis. The present would be represented on the 3D map of the VR crisis management cell, the future being above it and the past under it, as illustrated in Figure 8.



Figure 8: Future and past situations displayed above and below the map

F5 – Multiplayer aspect:

The VR crisis management cell is intended to be used by several users from different physical locations. They must be able to join in the VR crisis management cell and share the representation of the situation, see each other, talk to each other, and conjointly act upon the items of the VR crisis management cell. Roles must be attributed to them depending on their function in crisis management. These roles can be linked with a filtering system that will ensure that the users get the information that they need and avoid information overload. The VR crisis management cell could provide three different modes for the multiplayer aspect. The first mode is the *solo mode*, where each player has his own view of the 3D map and can interact with the map and the crisis concept on its own. In this mode, changes made by one user are not shared with the others. The second mode is the *shared mode*, which corresponds to the idea of sharing one's screen in an online meeting. In this mode, a player can choose to share his vision with the other players. All the users will then see the same things, but only the sharing user will be able to interact with the map or the concepts. The last mode is the *group mode*, where all the users can see the same map and interact with the same crisis concepts. They can thus work together on a shared map. This mode is the closest to what happens in traditional crisis management cells. The users would be able to switch from one mode to another depending on their needs.

F6 – First-person experience and God's eye view

The VR crisis management cell must provide the possibility for the user to adopt several points of view on the crisis. This is one of the advantages offered by VR. While the 3D map provides a god's eye view from above, it can also be interesting for the users to be able to observe the crisis from the inside. The VR crisis management cell could thus provide a model of the crisis site inside which the users would be able to walk with a first-person point of view, thus being able to get as close as possible to the crisis without taking any risks. Users would be able to switch from one mode to the other depending on their needs. The multiplication of the points of view offered by the VR crisis management cell would help the users with comprehension of the situation and thus help them make efficient decisions.

F7 – Deduction of a collaborative response process:

Through R-IO Suite, the VR crisis management cell must propose a collaborative response process adapted to the crisis. Based on the model of the situation and depending on the crisis objectives prioritized by the users, the idea is to provide a list of tasks attributed to certain actors in a certain order that will allow the resolution of the situation. The process can be modified by the users until it perfectly suits them, in which case they can validate it. This means that the users keep control of the decision-making process and make the final decisions. The validated process can be displayed above the interactive 3D map, as shown in Figure 9, the time represented by the vertical axis. The tasks closest to the map are those that must be completed first. If a user touches a task, a beam appears to show the concerned area of the crisis site and the concerned actors.



Figure 9: Deduction of a collaborative response process

F8 – Orchestration:

Thanks to R-IO Suite, the VR crisis management cell must provide the possibility to follow the advance of the crisis resolution. Each task of the validated process is sent to the concerned actor at the right time. Once the task is completed, the actor sends a notification to R-IO Suite, and the process is updated accordingly. The VR crisis management cell must display this orchestration, as illustrated in Figure 10: once a task is accepted by an actor, it turns yellow above the map. A completed task goes green before disappearing to avoid cluttering the model.

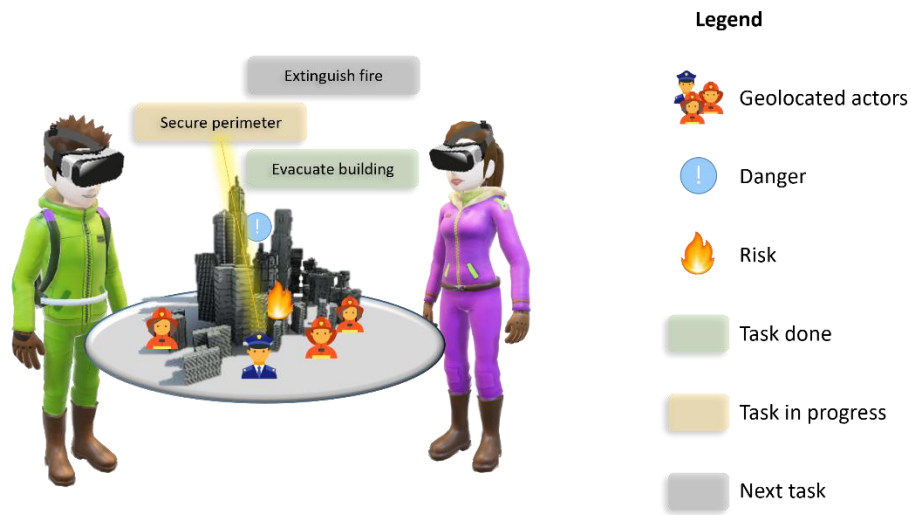


Figure 10: Orchestration of the process

F9 – Adaptation:

Based on the functionalities of R-IO Suite, the VR crisis management cell must be able to monitor the situation. It will supervise the orchestration, comparing potential updates with the advancement of the process. These updates can be made manually or induced by the analysis of the data gathered continuously from the sensors, social media, or any other data sources. The idea is to follow the theoretical progress of the process (defined by the theoretical duration of the tasks) and compare it with the actual advancement (described through the tasks updates and the data gathered from the crisis site). Differences might be highlighted: they are called divergencies and must be displayed on the VR crisis management cell, for instance, turning the concerned task red, as shown in Figure 11. Three kinds of divergencies can be identified: (i) a change in the situation, such as a new event or a previously unknown element coming up, (ii) a change in the resources, such as a new resource coming up or an unavailable resource, and (iii) a

task that did not perform as expected. The users can then decide to stop the current process and cancel it and then order the deduction of a new one taking the updated situation into account.



Figure 11: Detection of a divergency

F10 – Anticipation:

The VR crisis management cell must provide an anticipation feature. Based on prediction models and projections such as weather forecasts, traffic forecasts, water level projections, or theoretical evacuation durations, users must have access to anticipated situation models describing the situation in X hours. The idea is to be able to compare the projected evolution of the response (according to the deduced process) with the evolution of the environment (according to the forecasts), detect potential incoherencies, and take action accordingly. Anticipated models of the situation can be displayed above the map on translucent maps to avoid cluttering the environment, as shown in Figure 12. This functionality can also allow the users to anticipate the consequences of potential actions and thus make decisions that would not only take into account the current and past situation but also the expected future evolution of the situation.



Figure 12: Anticipated models of the situation

F11 – Recording the crisis response:

The virtual aspect of the VR crisis management cell can enable the users to record the crisis response and watch it later. The idea is to be able to observe and analyze past situations to gather feedback, see what worked and what did not, and learn from it. It could be linked to dashboards and systems to analyze the gathered KPIs. This functionality would allow the improvement of the crisis response.

Table 3 illustrates how the functionalities of the VR crisis management cell cover the functionalities of R-IO Suite, situational awareness, and decision support.

Table 3: Transposition of the functionalities of R-IO Suite, situational awareness, and decision-support in the VR crisis management cell

| VR crisis management cell | R-IO Suite | Situational awareness | Decision-support |
|---------------------------|----------------|-----------------------|------------------|
| F1 – Representation | / | Perception | / |
| F2 – Treating data | Interpretation | Interpretation | Information |
| F7 – Deduction | Deduction | / | Decision |
| F8 – Orchestration | Orchestration | / | Action |
| F9 – Adaptation | Monitoring | / | / |
| F10 – Anticipation | Anticipation | Projection | / |

3.2 – Implementation of a prototype of the VR crisis management cell

Preliminary note: screenshots from different scenarios were used to illustrate this section. All of them show the same tool, the VR crisis management cell. However, the crisis scenario represented can be either a flooding scenario, a fire in a cathedral scenario, or a terrorist attack scenario. This is due to the fact that we wanted to use scenarios that best demonstrated each functionality. Still, all functionalities are usable with every scenario.

Our lab developed a prototype for the VR crisis management cell linked with the decision-support system R-IO Suite (Benaben et al. 2017), hence the name of the prototype: R-IO VR. It was developed between May 2021 and March 2022, using Unity© in its 2021.1.20f1 version, and deployed through Open XR¹. The interaction with the VR crisis management cell is achieved through HTC Vive Pro headset and controllers. A video presenting the prototype is accessible on YouTube². The VR crisis management cell has been developed following a DevOps approach driven by the interactions with R-IO Suite. This means that the VR crisis management cell is intended as a VR interface for R-IO Suite, dedicated to helping the users understand and interact with artificial intelligence. We did not involve the end users in the developing process because we did not want the solution to be limited by what they knew or were able to imagine; we wanted to propose a disruptive innovation. According to Benaben and Benaben (2020), there are two ways to answer a need: the innovation-pushed paradigm corresponds to the case where researchers or industries propose an innovation that will then be adopted by the community to answer a particular need, and the need-pulled paradigm corresponds to the case where a need already exists, and researchers or industries propose an innovation to answer it. In this case, the innovation-pushed paradigm was used: we propose a prototype that is then to be presented to practitioners to see if it can meet some of their needs. An interactive circular 3D map representing the location of the crisis is displayed in the center of a neutral room. This map is created based on Open Street Map data with a post-treatment in Blender to make them appear in 3D. Users can interact with the map: they can zoom in and out, turn it or move it so that it displays other locations. They can also move around the map or in the virtual room. Thanks to Photon Unity Network©, a multiplayer aspect was achieved: multiple users from several locations can join in the VR crisis management cell and collaborate, as illustrated in Figure 13. They can thus see and talk to each other, interact with the same map, and see what each other is doing. At this point, the multiplayer is implemented as the *group mode* presented for functionality F5 above; the two other modes will be developed in a later version of the prototype.

¹ https://www.khronos.org/api/index_2017/openxr

² https://www.youtube.com/watch?v=TIcu_CCa7Kc last access 05th September 2023.

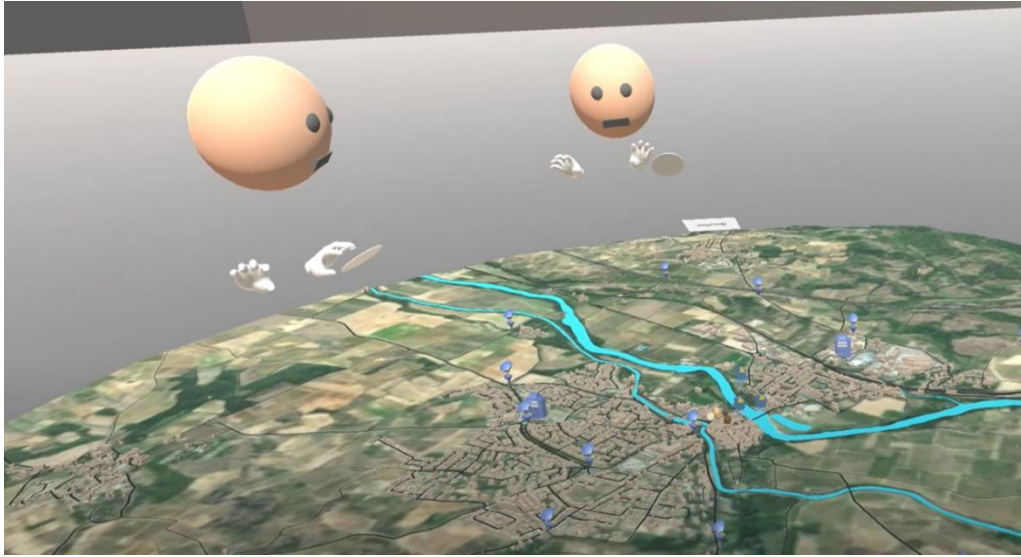


Figure 13: Avatars of two decision-makers around the map in R-IO VR

The VR crisis management cell is connected to R-IO Suite via its API. A C# driver was developed to translate the request from Unity to the database of R-IO Suite and retrieve the needed information. This enables R-IO VR to display the model of the situation on the 3D map: crisis concepts are represented by 3D objects and placed at their right location on the map, as shown in Figure 14. Pointing to a concept makes a popup appear with further information, as illustrated in Figure 15.

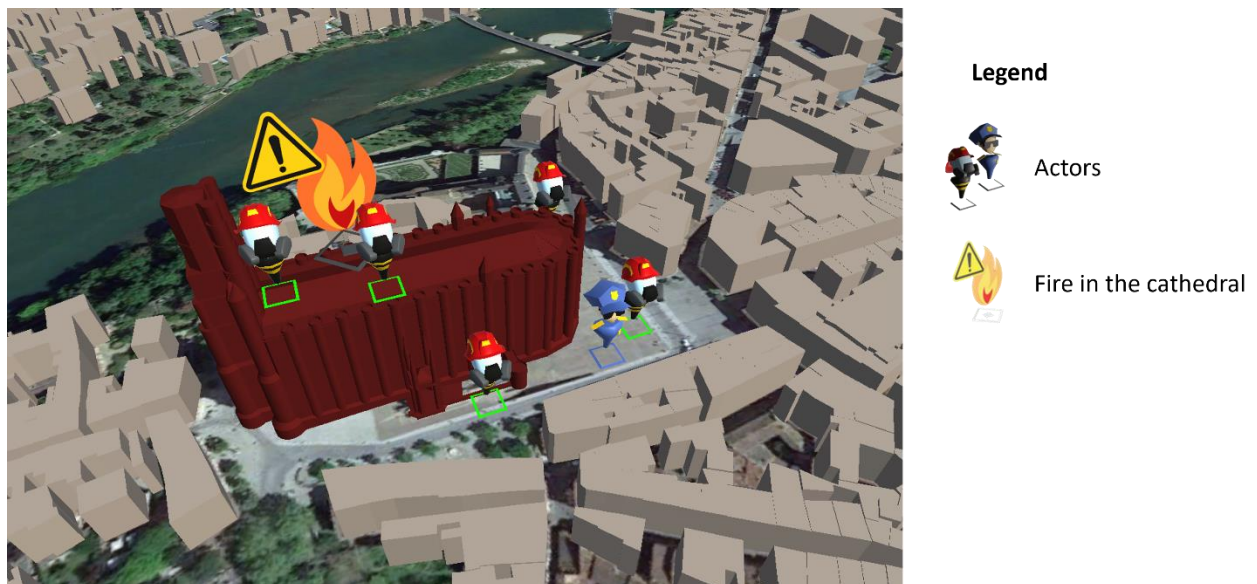


Figure 14: Crisis concepts on the map of R-IO VR

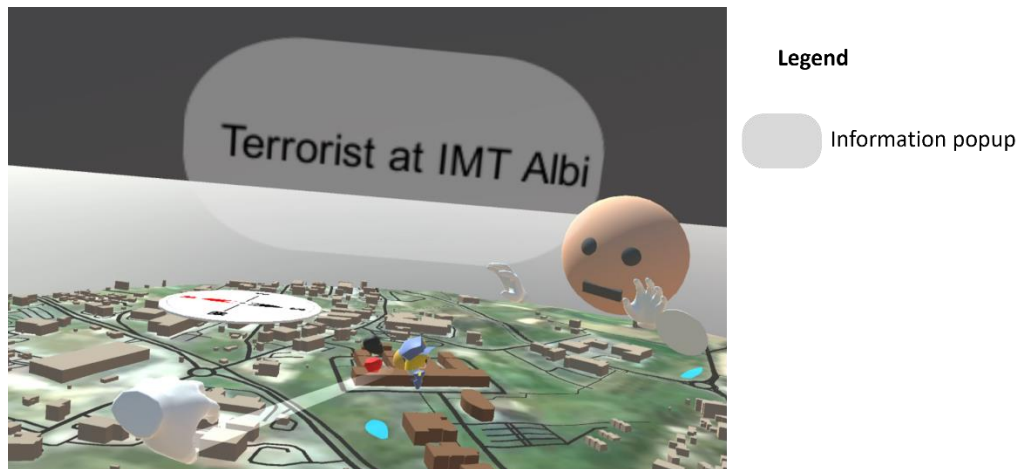


Figure 15: Popup giving more information on a concept

Several objectives are available, depending on the crisis. They refer to what must be addressed to deal with the situation, such as damages, victims, or risks. They can be prioritized by the users before the deduction of the process. Based on that prioritization and the crisis context and partners, R-IO Suite can deduce a collaborative response process adapted to the situation and corresponding to the process response, composed of several tasks assigned to the different organizations and which must be performed in a particular order. This process is displayed above the map of R-IO VR, as shown in Figure 16. Pointing on a task of this process displays a beam pointing to the area and actor concerned by the task. Once it has been accepted by the users, the process can be deployed and orchestrated thanks to a workflow engine. The orchestration presents two features: (i) sending the tasks to the relevant actors on-site and (ii) receiving updated status of the tasks (accepted, done, refused...). Once a task is completed, it turns green on R-IO VR and disappears. Should R-IO Suite detect a divergence between the expected evolution of the situation and the actual progress on-site, the corresponding tasks would turn red on R-IO VR, and the users will then have the possibility to cancel the current process and deduce a new one. Please note that R-IO Suite is a support system, by which we mean that humans will always have the last words. R-IO Suite is a flexible tool that proposes a response process and tasks to the users but does not prevent them from deciding not to follow the tasks or to improvise.

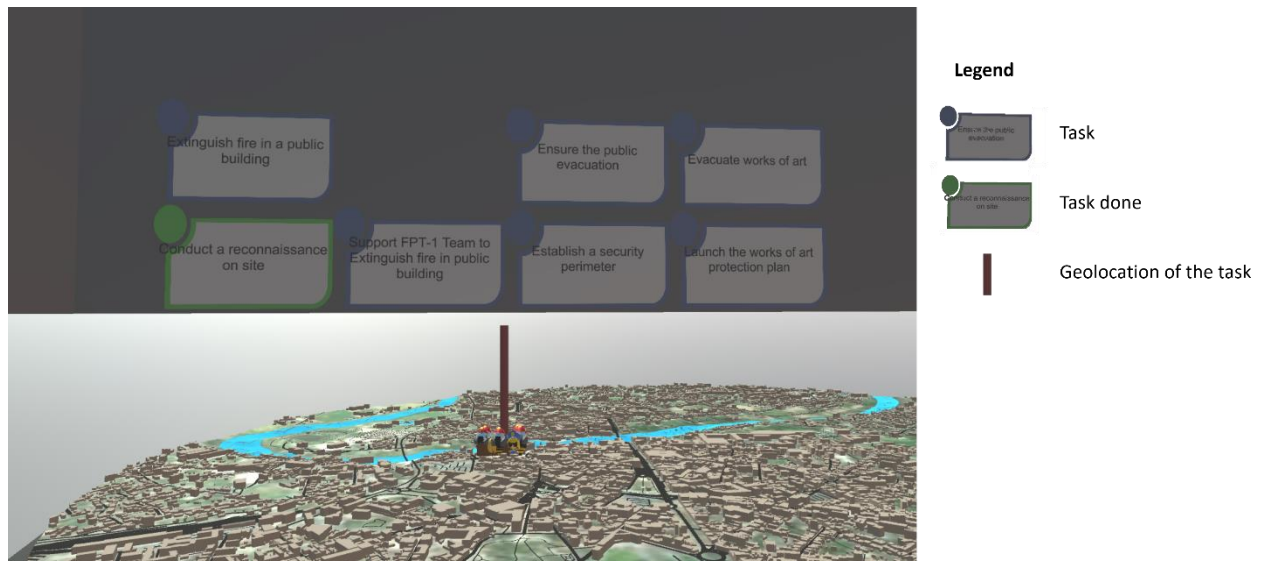


Figure 16: Collaborative response process displayed in R-IO VR

The prototype presented in this paper is still at an early stage of development. However, it has potential. Imagine decision-makers united around a digital shadow of the crisis, able to observe in real-time its progress and the set-up response from different points of view, to know at one glance the status of the resources and actors, and to anticipate the future situation. Collaboration and discussions between the different organizations would be enhanced through the multiplayer aspects and the interactive map and crisis concepts, which would help them achieve a common situational awareness. The addition of artificial intelligence through the link with the decision-support system would prevent information overload and help actors get the right information at the right time to make efficient decisions.

In the next steps of the development, we intend to work on the missing functionalities, such as anticipation. Visualization modes will also be added, such as the possibility for the users to zoom in on the crisis model until they can enter the crisis site and observe it from a first-person point of view. Immersive analytics will also be added to provide more intuitive ways for the users to visualize and understand the data coming from the crisis site, especially the not geolocated one.

4 – Perspectives and conclusion

To answer the research question “how can VR improve crisis response?” this paper proposes a concrete use of VR to improve crisis response, particularly situational awareness and decision-making. **The paper presents a vision of a VR crisis management cell featuring actors’ distribution, data visualization through visual and spatial metaphors, and interaction with artificial intelligence and a decision-support system.**

There are several limits to using VR in crisis management, such as the social and physiological difficulties

for the practitioners to accept such a tool (motion sickness, headaches, mistrust of an “unreliable” and novel technology...) (Van Krevelen and Poelman 2010; Berndt and Herczeg 2019; Cook et al. 2019). Just as it seemed impossible to spend several hours a day in front of a computer when they first appeared, it seems unthinkable to use virtual reality for more than a few minutes, especially in a field as critical as crisis management, where human lives are at stake. Some technological limits of the VR crisis management cell can also be mentioned: we present a tool that is still at a very early stage of development. We are presenting a proof of concept, which means that more work is necessary to ensure that the tool is completely functional, that it can work even in conditions where the internet might be slow or unreliable, and that there are degraded modes to keep the tool functional even in bad conditions. There is also the problem of the realism of the representation of the crisis, which must be addressed: a certain level of realism is necessary for the users to be able to work efficiently and effectively. However, we must be careful not to fall into the uncanny valley. Nevertheless, VR brings visualization and interaction possibilities that help make more enlightened decisions in an emergency context.

VR can faithfully and accurately reproduce reality. This ability, coupled with a connection with on-site sensors, drones and cameras, or even social media, allows the crisis management cell to provide a situation model that can be displayed on a fully interactive map. VR provides new ways to interact and visualize the data treated with artificial intelligence and decision-support systems, making it more intuitively understandable. Users’ roles and filtering systems will prevent information overload and allow decision-makers to access the right information at the time when they need it. VR offers the opportunity for the decision-makers to adopt multiple points of view, from a global vision from above to a closer first-person point of view. The connection with the crisis site can be envisioned both ways: data coming from the crisis site continuously and in real-time ensure a strong situational awareness, but decision-makers could also transmit information or orders to the on-site actors. For instance, moving the icon of a firefighter on the 3D map of R-IO VR could send the corresponding on-site actor a notification, indicating that he is needed elsewhere. This new functionality would bring the virtual crisis management cell closer to a digital twin of the crisis. Meanwhile, VR keeps the collaborative aspect of the current crisis management cell, allowing stakeholders to join in the same environment, interact with each other, and share information.

VR can not only reproduce reality, but it can also free itself from it to go beyond. It offers the possibility to take advantage of intuitive notions such as depth awareness or relation to items in space to provide new visualization tools. Multiple dimensionalities can thus be represented without losing clarity or endangering the user’s comprehension. Complex data sets can be made easier to understand and analyze, notably

thanks to immersive analytics (Dwyer et al. 2018). VR also offers the possibility for users from different physical locations to join in the same virtual environment and collaborate easily (Heinrichs et al. 2008). Different multiplayer modes can allow the users to work conjointly or separately and to try solutions before sharing them with others. The virtual aspect of this new technology also offers several advantages: solutions, tools, or processes can be tested before being implemented to check their relevance and efficiency with no risk. Past crisis responses can be recorded to be analyzed later, and future situations can be anticipated and visualized to help with the decision-making process.

The evolution of the world induces a change in the type of crises that we have to face, with, for instance, a huge increase in the quantity of available data coming from various sources (Bastin et al., 2013). It becomes important to be able to analyze and understand that data better and faster. VR is then a powerful and promising tool to improve situational awareness and decision-making in the context of crises. The virtual aspect of the VR crisis management cell makes it an extremely dynamic and modular tool that can be adapted to the crisis needs as well as to the crisis managers' needs. If the reluctance and resistance to change of crisis responders are limiting, we believe that technological advances will make the technology easier to use and accept, thus giving it a bright future in the crisis management domain. The arrival of metaverses will bring further possibilities and opportunities to the VR crisis management cell. It is already possible to envision a sentient crisis management cell featuring a faithful real-time representation of the crisis as well as powerful tools to analyze and treat voluminous and complex data. We can then imagine a symbiotic association between VR and artificial intelligence (AI), VR making AI easier to use, providing visualization and understanding possibilities to the user, and AI making VR more powerful, granting it data interpretation and analysis means.

It is, however, vital to be able to test this kind of tool to ensure its effectiveness and relevance. Crisis management is a domain in which changes must be carefully done as human lives are at stake, so it is of the greatest importance to make sure that any new tool is actually effective and functional. This means that one of the next steps of our work will have to be to conduct tests and trials to evaluate the impact of a VR and sentient crisis management cell on crisis management, using, for instance, the Trial Guidance Methodology (Widera et al. 2020). For instance, it would be interesting to compare crisis management with and without this tool, to be able to quantify the potential benefits of the tool in terms of time gained, the additional percentage of information perceived and understood, or the number of victims avoided. We will notably work with French and US practitioners to gather feedback on the VR crisis management cell. Then, exercises would have to be conducted as well so that practitioners can train and be ready to use this kind of tool in an actual crisis. Another perspective of this work will be to focus on the crisis

management aspect, which is so far covered by R-IO Suite. Using VR brings new considerations that can result in new functionalities to improve crisis management, such as the possibility to switch from a god's eye view to a first-person experience or to use immersive analytics. Thus, one of our next steps will be to study these new possibilities and add new functionalities to R-IO Suite to further improve crisis management. We will, for instance, work on the possibility of changing the topography of the crisis management cell: VR could allow the users to create separate rooms or working groups to compartmentalize crisis management.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: