13th International Defense and Homeland Security Simulation Workshop
20th International Multidisciplinary Modeling & Simulation Multiconference

2724-0363 © 2023 The Authors.
doi: /10.46354/i3m.2023.dhss.008

Strategic Engineering for Decision Making during Urban Crises

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Abstract

Analyzing the dispersion of hazardous agents is a critical component in crisis management. The complexity of this task amplifies when considering the intricate geometry of the environment in question, ever-evolving boundary conditions, and the presence of individuals. Notably, many of the prevailing models for agent diffusion primarily concentrate on the physical aspects, often sidelining the challenge of assessing the impact on people present in the scenario. To bridge this gap, the authors introduce a comprehensive simulation model designed not only to forecast the movement of substances in multifaceted urban settings but also to factor in the attributes and activities of individuals within these spaces. This paper concludes with a detailed case study, shedding light on the practical implications and results of the proposed model.

Keywords: Modeling & Simulation, CBRN, Decision Making Support

1. Introduction

One of critical elements in crisis management and in particular of situations involving diffusion of dangerous substances in the urban environment, is the prediction of behavior of the substance as well as of produced damages. In some cases, a general idea regarding possible outcomes could be obtained by traditional procedures of risk analysis (Braglia et al., 2003). However, to better address this problem, diffusion models for pollutants must be employed; furthermore, in order to take care of complex and important environments such as urbanized areas, these models need to take care also of complex geometry caused by presence of buildings and transportation networks. Such models are necessary to simulate the dispersion and transport of agents emitted from various sources within the urban environment. These models need to take into account the complex geometry of the city, including the presence of buildings and the road network, which is expected to significantly affect the dispersion patterns of the agents. Considering this, even to create a sufficiently precise geometrical model of the environment it is necessary to have such data as Digital Elevation Model (DEM) or Digital Terrain Model (DTM) of the area of interest, information about soil types and land register, at least approximate data regarding shape, type and location of buildings; furthermore, the resolution of data must be sufficiently high in order to cover properly areas even in medieval city centers, characterized by very narrow roads, which otherwise might be not represented, making whole area be erroneously considered as one single building.

Very important aspect of this kind of models is related to the presence of population in interested areas. Indeed, the situation becomes much more complex in case of presence of individuals, which may act unpredictably and require assistance (Bruzzone et al., 2018b). Finally, the situation becomes even more critical in case when there is a CBRN (Chemical, Biological, Radiological and

Nuclear) incident (Maciejewski et al., 2022).

Complexity of such models is caused by necessity to take into account numerous factors, initial and boundary conditions, as well as their evolution in time. For example, in order to produce reliable result, such model needs not only to have information regarding the properties of the diffused substance, but also geometry of the area of interest and accurate meteorological data, including wind speed, wind direction, temperature, and atmospheric stability. Finally, in order to be of use for decision makers, the model need to take care about population in the involved area, including human behavior, as this information is crucial for planning of remediation activities (Bruzzone et al., 2022a; Vairo et al., 2017).

In the past, there were various accidents involving release of dangerous substances, with the most catastrophic being Bhopal disaster, which happened in 1984 in India and caused thousands of casualties (Yang et al., 2015). In particular, due to unsafe and poor operations, approximately 42 tons of methyl isocyanate (MIC) leaked from the chemical process facility and covered significant area of nearby city, leading to massive casualties and contamination of significant part of adjacent urban area.

Another important accident occurred in 1976 near Seveso, Italy, caused by release of 2,3,7,8 Tetrachlorodibenzodioxin (TCDD) (Fabiano et al., 2017). Fortunately, there were no known casualties and the impact was limited to death of animals and several hundreds of people being displaced and intoxicated. This accident had such significant impact, that it lead to creation of European Union Law, named after it, the "Seveso Directive", which regulates safety in sites containing high quantities of dangerous substances.

Fortunately, cases of this scale are rare and since then a lot of new norms, regulations and controls were introduced to reduce risk of future events. However, it is necessary consider non-zero probability of their occurrence as well as possibility that such situation could be caused by deliberate actions.

For example, one of most known events of this kind is the terrorist attack conducted in Tokyo subway, Japan, in 1995 (Okumura et al., 2005). In that case, sarin gas was purposely released in the subway by several persons in different moving trains, in a way that higher number of persons came in contact with the substance. Indeed, while the number of casualties is relatively low, about one thousands of people between passengers and personnel became intoxicated.

Provided examples illustrate completely different scenarios from point of view of released substance, conditions and causes. However, in all these case a simulation could be used in order to help with identification of potential risks as well as with evaluation of possible outcomes.

2. State of the art

In the past, the authors created several models of crisis management, which address problem of dispersion of dangerous agents in industrial facilities (Bruzzone et al., 2020; 2018a). Indeed, in the past years there is growing interest to the problems related to dispersion of agents in environments with complex geometry and not only of industrial nature, such as towns and urban areas; often, it is done by simplification of the geometry. While in some cases, it could be possible to use idealized representation of cities, with simple and regular geometries, which however is poorly applicable in some real-life cases (Carpentieri et al., 2018). For instance, one approach to obtain more reliable results is to represent urban area as graph, with building and their groups represented as boxes and surrounding open areas (e.g. roads) as segments and nodes (Salem et al., 2015). However, in order to obtain results that are applicable to various types of city patterns (e.g. to both rectilinear grid of Manhattan and narrow winding streets of medieval city centers), the urban area need to be represented as a complex network (Fellini et al., 2021; 2019).

Another important framework in which study of diffusion of dangerous substances is very important are seaports and their adjacent areas. Indeed, these critical infrastructures are used to transport variety of goods including dangerous substances, while presence of bulky equipment significantly increases probability of collision. At the same time, there are present numerous factors which increase difficulty of evaluation of risks as well as leading to necessity to tempest reaction. Indeed, proximity of open water bodies with typically strong winds, presence of large objects, which affect wind and limit visibility (e.g. ships, container blocks, port structures), and often nearness of populated cities and towns, requires from the decision makers capability to react swiftly to any emerging threat. In the past, the authors developed various models related to handling of emergencies in seaports and in their proximity (Bruzzone et al., 2022c).

As anticipated, another important aspect is related to prediction of reaction of involved persons. Indeed, human behavior modeling is a complex interdisciplinary topic, as actions of single individuals and especially of groups and crowds could be very difficult forecast. To address such issue, a common approach could be utilization of advanced Intelligent Agents (IA), which in such scenario could be capable to reproduce behavior of single individuals and of social groups (Bruzzone et al., 2014; Massei & Tremori, 2014).

Nowadays, simulation plays very important role in crisis management, starting from preparation of emergency plans and training of personnel and up to forecasting of outcomes of actions during remediation (Bruzzone et al., 2009). Similar approach is used for many years in industrial framework, in which probability of undesired spills and releases of dangerous materials is higher (Longo et al., 2019). At the same time, the material diffusion in urban areas was addressed by similar yet different studies related to forecasting of atmospheric pollution, e.g. by Nitrogen oxides NOX (Kim et al., 2018). Finally, diffusion of dangerous agents is of particular interest of defense, as such events involving CBRN threats may occur due to an accident or even to deliberate attack (Bruzzone et al., 2015).

In the contemporary world, the evolution of threats and challenges to national security and defense has significantly expanded. The spectrum of risks spans from traditional concerns of Chemical, Biological, Radiological, and Nuclear (CBRN) threats to the multifaceted domain of cognitive warfare. Each of these domains requires specialized tools, strategies, and crisis management techniques. In an era dominated by information and technology, mass media plays a pivotal role in crisis management. Effective communication can prevent panic, provide accurate information, and guide the public during emergencies. During the 2009 H1N1 influenza pandemic, media outlets worldwide played an essential role in disseminating information about the virus's spread and educating the public on preventive measures (Vasterman, 2005). This aspects have led to the Cognitive warfare which is an evolving domain that targets the mental framework of adversaries (Backes, 2019). It aims to distort perceptions, spread disinformation, and influence decision-making processes. The objective is not just to win the battle but also to win hearts and minds. Russia's annexation of Crimea in 2014 exemplified cognitive warfare in action (Giles, 2016)

Another important aspect is related to necessity to provide to the model updated and relevant data. From one side, often, the data banks are incomplete or poorly maintained, which introduces errors in initial conditions of the problem. From another side, even during the crisis, it is necessary to perform constant monitoring of the situation, in order to have clear understanding regarding differences between simulated and observed behavior, to correct the model. Considering this, it is necessary to consider possibility to feed new data to the model, e.g. obtained by sensor network installed on autonomous systems (Bruzzone et al., 2022b), meteorological stations (Soulhac et al., 2017) and satellites (Magrì et al., 2021).

3. Proposed Solution

Analysis of literature as well as of available commercial products shown that in most of the cases, the models address only one of single aspects, relevant to the simulation of diffusion of dangerous substance in a city. Indeed, such solutions usually aim to solve one specific problem, such as wind and mass transfer in complex environment, contamination of soil or evacuation of people from affected area. Obviously, in order to have a clear picture of possible outcome, it is necessary to employ all these models together, synchronize them and make them affect one another. However, many of these available solutions are not conceived with interoperability in mind and only part of them have their source code available to make necessary modifications.

Considering this, the authors propose an innovative simulation solution capable to forecast outcomes of releases of dangerous materials in complex urban environment, addressing factors related to wind in urban environments, gas dynamics, chemical reactions, human physiology and behavior. Indeed, in order to create a comprehensive model, an interdisciplinary approach is required; for instance, a model, which takes care only of gas transportation, may produce wrong results in a case when Chlorine release is studied, as in reality this gas may be photolysed by the sunlight before dangerous concentration achieves critical areas, e.g. residential buildings.

The Conceptual Model considers gas transportation on a three-dimensional grid, discretizing an open area in smaller elements with different properties. The mesh is built first considering terrain morphology, thus identifying plain zones and gorges; buildings are then added in the system considering shapes, occlusions and typology. Each element of the grid corresponds to an area with different characteristics, thus properties of mesh's elements are dynamically updated. In this way, it is possible to have elements representing open zones or occupied by a building. Flows of gas are therefore affected by obstruction, while terrain's gradient analysis enables to recreate preferential directions in which the wind can flow. As double effect, it is possible to determine which area is more likely to material stagnation.

Each element bounds a volume, which is connected to surrounding elements of the grid. However, material flows through neighbors consider nature of terrain if available, or is inhibited if not allowed. Mass balance during time in each single element is then computed as sum of incoming and outcoming mass. For each volume, flows can then be defined considering different contributions which d affected by many factors, but which can be summarized in following equation (3.1).

$$\frac{dM}{dt} = \frac{dM_{weath}}{dt} + \frac{dM_{diff}}{dt} + \frac{dM_{fl}}{dt} + \frac{dM_{wind}}{dt} \qquad (3.1)$$

In above equation, M represents the mass of gas contained by a single element. This equation is computed over time. The different contributions in eq.(3.1) are:

- M_{weath}, mass flowing due weathering effects. This includes mass that is lost by chemical reactions and fallout.
- M_{diff}, mass flowing due diffusion effects. Diffusion is mainly caused by density gradients between different areas.
- M_{fl} , mass flowing due buoyancy effects. Gas flow can rise or go down, according to buoyancy law.
- M_{wind}, mass moved by wind speed.

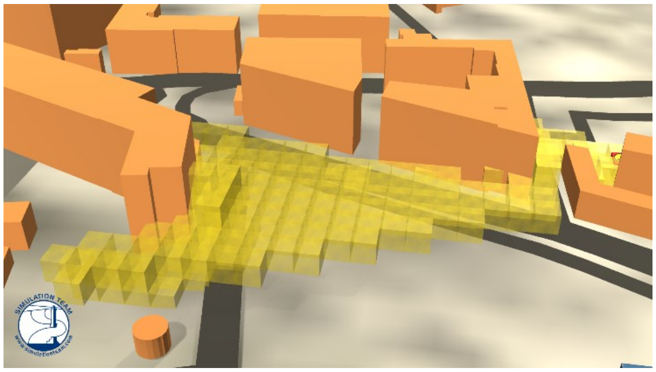


Figure 1. Simulator view

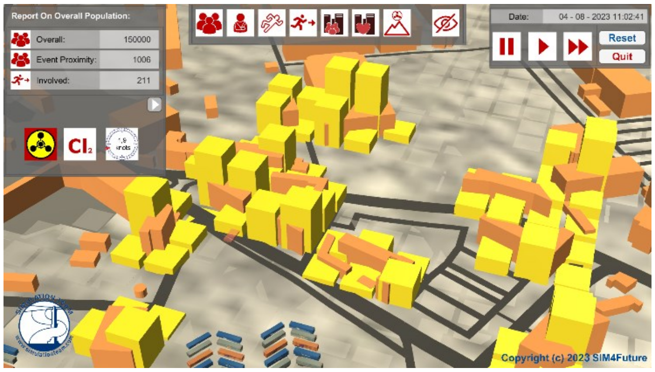
Thus, during the simulation the gas is allowed to move inside the grid, until it escapes from interested area. Population is distributed inside the targeted area, virtually occupying elements inside the grid. The initial distribution of population can be estimated considering characteristics of buildings, such as dimensions and intended use. Assuming that gas starts to spread at the beginning of the simulation, persons become directly involved when concentration of gas in their zone rises. Health of each person can be determined, increasing the number of persons in danger and injuries.

In order to evaluate the simulator, the authors created a hypothetical scenario, which involves diffusion of chlorine in urban environment.

4. Experimentation and Results

In order to provide reliable results, the system uses following principal data sources: terrain model obtained from open data, 3D models of buildings, obtained dynamically from a geographic database as well as demographic data related to the area of interest. Once the data is pre-processed, the model creates a 3D representation of the target area, analyzes surfaces of buildings, splits resulting environment in finite element mesh and calculates terrain gradient in elements.

At the start of the simulation, the user is enabled to choose type of dangerous substance, indicate position and type of release as well as to adjust meteorological situation according to desired values. Once the initialization is complete, the model starts to simulate propagation and diffusion of the agent in the area, its precipitation and neutralization, effects on population. Indeed, the simulator takes care of parameters of various agents, which allow for instance to neutralize some substances in case of direct exposure to the sunlight. During the whole simulation, the decision maker has access to information about contamination of air and soil, estimation of number of involved persons as well as possible casualties.



Report On Overall Population:

Overall: 150000

Event Proximity: 1006

Involved: 211

Date: 04 - 08 - 2023 11:02:41

Figure 2. Involved persons

At each time step, the gas dynamic model calculate gas transfer between each element of the 3D mesh, taking into consideration diffusion, buoyancy force, wind phenomena in all direction, including the influence of terrain and buildings.

Considering that the mass transfer, at least in cases of interest, occurs much faster in horizontal rather than in vertical direction, its calculation in vertical direction is altered, in a way to guarantee high performance of the model while maintaining sufficient precision.

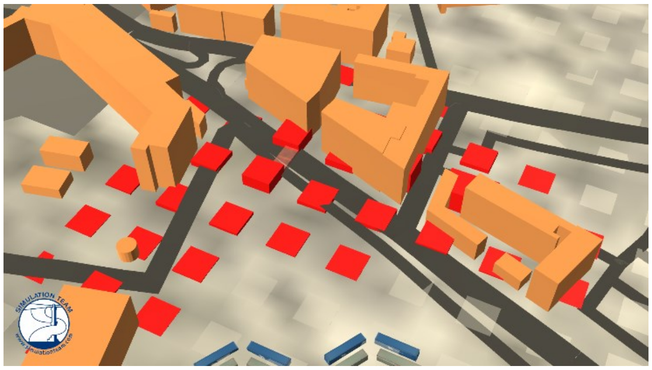


Figure 3. Soil contamination level at the end of simulation

The model operates in fast-time mode, which allows to the decision maker to have clear picture of situation in hours in the future by simulation in less than a minute. Hence, in order to achieve sufficient level of precision despite relatively big time steps, a Runge-Kutta integration technique is used. Hence, it becomes possible to obtain sufficiently precise results, at the same time, to perform analysis of numerous possible scenarios. The simulator was subjected to preliminary testing with subject matter experts, which confirmed correctness of the model.

5. Conclusions

Simulation of complex urban environments during crises is a difficult task, which requires combination of experience, interdisciplinary knowledge and capability to create advanced simulation models. In this paper, the authors propose an innovative solution, capable to address issues related to this crucial task. Indeed, presented model allows to simulate in fast and precise way the evolution of crisis related to release of dangerous agent in atmosphere in populated city center. Utilization of this model allows to the decision makers to perform much better evaluation of current situation as well as to predict future outcomes, perform "what-if?" analysis.

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