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Bridging Resources and Agencies in Large-Scale Emergency Management

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Title:

Modelling of Structure

Editor(s):
Prof. Friedrich Steinhäusler

Approved by:
Andreas Zimmerman

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Abstract / Executive summary:

The objectives of this Deliverable are the development of tools for the generation of: (a) Computer-based 3D graphics model based on available information about affected critical infrastructure; (b) 3D simulation based on the scenario developed in WP02, using models of critical infrastructure.
Thereby the Deliverable contributes to the overall goal of this Work Package, i.e. the development of a library of 3D models in order to assist first responders in their training for improved crisis management, as well as assessing risks on scene in complex, large scale catastrophic incidents.The methodology applied adheres to *incident-based modelling*, i.e., actual catastrophic events of the past are used to provide a realistic input for the parameters to be modelled, and *science-based modelling* by detailing the underlying physics of blast effects on man and structures. Different software was used for modelling in order to reflect the future practical application of the models.

For the *preparatory phase in crisis management* (e.g., for training purposes and business continuity plans), a 3ds-MAX model of a virtual chemical facility CHEMCO was generated. The 3D CHEMCO model – a dynamic, movie-like sequence of scenes – enables the user to carry out a detailed camera-drive through the facility. Thereby, first responders and/or crisis managers can familiarize themselves with the facility in great detail prior to an incident and train for possible scenarios. For the *practical application on scene of an incident*, HEXDAM/VEXDAM software was used to develop generic models corresponding to the EU Critical Infrastructure (CI) components. Based on the analysis of examples of CI systems in Member States, generic 3D models were developed for typical structures in the CI categories *Power Plant*, *Financial Centre*, *LNG Terminal*, *Railway Station*, *Subway Station* and *Airport*.

The methods presented can be applied to model a natural-, technical-, *natech*- and *maltech* catastrophe. In some of these cases computer modelling is the only feasible way to prepare for events of such magnitude, since simulating them in an exercise may represent either an unacceptable risk to all participants, or result in unreasonably high environmental damages and/or cost.

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Contributing partners

PLUS
Hellbrunnerstr. 34
5020 Salzburg
Austria

Friedrich Steinhäusler (WP Leader)
Friedrich.Steinhaeusler@sbg.ac.at

Wilhelm Heidegger
Wilhelm.Heidegger@sbg.ac.at

Thomas Wilflinger
Thomas.Wilflinger@sbg.ac.at

Robert Richter
Robert.Richter@sbg.ac.at

Dietmar Carl
Dietmar.Carl@sbg.ac.at

Lyudmila Zaitseva
Lyudmila.Zaitseva@sbg.ac.at

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1 Introduction

Today, most of the European first responders are well-trained and equipped for the routine emergencies, such as fires, traffic accidents and localized floods. Managing an incident of catastrophic dimensions, however, requires tools and capabilities beyond those used in a conventional emergency response. The magnitude and complexity of potential catastrophic events warrants that all European first responders are prepared to face the unique hazards associated with such catastrophes, whether they are caused intentionally or unintentionally.

The lack of adequate tools for improving situation awareness for first responders during the management of a catastrophe was criticised already by the US 9/11 Commission.[1] Since then, multiple efforts have been undertaken to use off-the-shelf products from the IT industry to provide low cost, ergonomically designed, computer-based solutions which can withstand the demanding environment of on scene operations and the stress and uncertainties associated with such a dynamic situation.

Due to the increasing complexity and fast advancing integration of large industrial processes, first responders will have to master industrial catastrophes, possibly coinciding with natural disasters, of a hitherto unprecedented scale, such as a strong earthquake, followed by a tsunami, triggering core melt in several units of a nuclear power plant (e.g., Fukushima Daiichi Units 1, 2, and 3 on 11 March 2011). Besides, many security experts concur that first responders are more likely than not to be exposed to novel, large-scale terrorist threats, possibly involving chemical, biological, radiological, or nuclear (CBRN) attacks.

Such large-scale incidents or catastrophes represent extreme operational challenges for first responders for the following reasons:

Large extent of damaged area: The large extent of the damage of a site experiencing a catastrophe usually makes it difficult to conduct search and rescue, fire-suppression, shoring and stabilisation processes. The scale of the disaster can force first responders[2] into a defensive status, i.e., extinguishing fires in some locations but having to let them burn in others (e.g., forest wild fires in Greece in summer 2007). 3D information of the area affected provides essential information about the extent of the threat due to the damaged structures and areas of increased safety risk.

Large number of victims: The large number of victims will necessitate that first responders will require an efficient triage system, identifying and categorizing victims with low-error rates (e.g., as a result of the earthquake in Haiti on 12 January 2010, 316 000 people were killed and 300,000 were injured).[3] This requires first responders to (a) know where to find them; (b) prepare for the different kinds of injuries they will have to attend to. All of these data can be derived from 3D modelling.

Uncontrolled release of toxic substances: Primary or secondary effects (e.g., explosions) can result in leaks in tanks or reservoirs, leading to the uncontrolled release of toxic substances into the environment frequently followed by a multi-agent dispersion in the atmosphere (e.g., radioactivity was released from the burning reactor during the Chernobyl nuclear power accident in Spring 1986 for

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[1] Thomas H. Kean (Ed.): *The 9/11 Commission Report*. W W Norton & Co Ltd, New York 2004, ISBN 0-393-32671-3.

[2] *First Responder* is defined as the member of an emergency response organisation arriving on scene of an incident or accident, such as a fire fighter, police or paramedic.

[3] US Geological Survey, Earthquake Hazard Program: Earthquakes with 1,000 or More Deaths since 1900; URL: http://earthquake.usgs.gov/earthquakes/world/world_deaths.php

more than ten days).[4] 3D modeling of the areas at risk from these releases improves the forecasting capability of crisis management (e.g., defining areas to be evacuated).

Inadequate risk assessment: The sheer scale of the incident will make it difficult to obtain information about the health- and safety risks present. Hazmat specialists increasingly require monitors and other assessment technologies to carry out a risk assessment. However, (a) a large disaster area makes it difficult to collect representative data in a short time; (b) large amount of smoke and dust have been known to cause false readings of detectors, contributing to erroneous risk assessment. 3D modelling used as input for decision support systems improves risk assessment.

Impeded uses of vehicles: Large piles of rubble and debris will pose serious difficulties for emergency response vehicles to reach the sites where their services are needed most. This will necessitate first responders to crawl over piles of rubble up to several meters high, resulting in staff members getting hung up on rebar sticking out of broken concrete, cutting themselves up.[5] Transport of victims off the incident site will have to be carried out largely by using stretchers, until the first responders can reach the designated vehicles. 3D modelling assists in identifying impassable roads and blocked access routes.

Such catastrophic scenarios are difficult, if not even impossible, to train for with a reasonable amount of funds and manpower. However, it is possible to *simulate* such catastrophic conditions by using computer models in training programmes. Besides, under actual catastrophic conditions computer-generated models can assist in improving situation awareness for the crisis management.

1.1 Objectives

The objectives of this Deliverable are twofold:

- Development of tools for generation of a computer-based 3D graphics model based on available information about targeted critical infrastructure.
- Development of tools for generation of 3D simulations based on threat scenarios (WP02) using models of critical infrastructure.

1.2 Methodology

The methodology applied adheres to (a) *Science-based modelling*, i.e., physics and engineering are used as a basis for 3D-modelling and assessment of the impact of blasts on structures and persons affected; (b) *Incident-based modelling*, i.e., actual catastrophic events of the past are used to provide a realistic input for the parameters to be modelled. Examples of real-world catastrophes are analyzed to improve the understanding of the difficulties in achieving adequate situation awareness in the complex and fast changing environment of a large-scale emergency.

All this information is fed into the simulation of the BRIDGE scenario, defined by Work Package 2, based on the 3D model of the virtual chemical facility CHEMCO near Cologne, Germany. It should be noted, that the 3D modelling results are presented in this report in the format of selected *screen shots*. The actual deliverable is a dynamic *film-like sequence* (camera-drive through the 3D model), ranging from aerial overviews of the complete facility to views of small installation details on site, as selected by the user.

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[4] OECD Nuclear Energy Agency, *Chernobyl: Assessment of Radiological and Health Impact*, 2002 Update of Chernobyl: Ten Years On, Chapter II: *The release, dispersion and deposition of radionuclides.*
[5] Thomas H. Kean (Ed.): *The 9/11 Commission Report*. W W Norton & Co Ltd, New York 2004, ISBN 0-393-32671-3.

Finally, the report describes the state-of-the-art in the field of 3D modelling applications for first responders, largely for the US, which is leading in embedding computer-generated models in training and the overall management of major incidents.

1.2.1 Operational Characteristics of Catastrophes

In this report a *Catastrophe* is defined as a high-consequence event, exceeding or threatening to exceed the response capability of the first responder organizations in the area. A catastrophe is indicated if one or more of the following phenomena are observed:

- Number of victims exceeds the capability of emergency services to assist victims in the area affected, i.e., conduit search and rescue operations, provide first aid, extinguish fires, limit the further spread of toxic substances, or provide physical security;
- Critical infrastructure is damaged to such an extent that emergency services can no longer provide sufficient protection of the system components still functioning;
- Societal infrastructure seizes to exist and results in wide spread social unrest and lawlessness.

A catastrophe can be caused by natural phenomena, industrial accident, or criminal intentional act, such as:

- *Natural Causes*: avalanche, blizzard, drought, earthquake, cold, flooding, heat wave, hurricane, meteorite, pandemic, rock and landslide, thunderstorm, tsunami, volcanic eruption, wildfire, wind;
- *Man-made Causes*: Equipment and hardware failure/human error; terrorism and sabotage (nuclear, radiological, chemical, biological, ecological, agricultural, cyber, conventional); civil unrest and riots; crime and violence; mass casualty event.

First responders will face four types of catastrophes:

- *Natural Catastrophe*: Natural catastrophes occur when extreme magnitude events of natural processes cause severe damage to society.
- *Technical Catastrophe*: A technical catastrophe is an event in which a significant number of people are injured or die as a result of human devices or activities, unrelated to conflicts, and attributed to operator error and/or equipment failure.
- *Natech Catastrophe:* A natech disaster is a technological disaster triggered by any type of natural disaster which results in significant adverse effects to the health of people, property, and/or environment.[6] Response efforts are likely to be required to attend simultaneously to both the technological disaster as well as the triggering natural disaster. More than one technological disaster may occur at the same time, as the natural disaster affects several industrial sites in one area. Many of the services and utilities expected to be used for the technological disaster (water, power, communications, etc.) may not be available due to the impact of the natural hazard.
- *Maltech Catastrophe:* A maltech disaster is a technological disaster trigged by any type of intentional malicious intent, including insider threats, which results in significant adverse effects to the health of people, property, and/or environment. [7] Interference with malicious intent has the potential to significantly increase the impact of an accident, especially if it is combined with natech events, making routine procedures inadequate. As adaptive adversaries, persons with malicious intent not only have the ability to change tactics as an attack unfolds but are also capable of concurrent and/or subsequent multiple attempts against infrastructures. Such acts are criminal and, as such, include additional legal and other implications, including a strong psychological impact on the public.

[6] NEDIES Workshop on *Analysis of Natech: Disaster Management*, 20-21 October 2003, Ispra, Italy.
[7] Igor Khripunov, Center for International Trade and Security (CITS), University of Georgia, USA (personal communication), May 2011.

Computer-based modelling used in this Deliverable is capable to simulate the operational characteristics of any of the above causes for catastrophes as well as all four types of catastrophes, provided there is still an adequate power supply and functioning communication in place.

1.2.2 Science-based Modelling

Blast Effects on Man and Structures

All models used in this study are *science-based*, i.e., the models reflect the principles of physics and engineering inherent to the explosive blast impact on structures and on the human body, as well as the distribution of toxic gases in the environment due to an explosion. The calculations account for the geometry of the target, materials used in its construction, reflection and damping effects, physical properties of human tissues and skeleton, and meteorological conditions on site and off site.

First responders and emergency preparedness officials alike benefit from viewing models of structural damage to buildings, injuries to victims and atmospheric concentration values of toxic substances due to an uncontrolled release due to the incident under consideration. This can be the case of participants in an exercise to hone preparedness skills, where exercise planners have an inherent challenge in creating drill scenarios that can be vividly imagined and thus accepted by the participating teams. Typically, first responders participating in an exercise must pretend how a damaged building or technical installation might look under catastrophic conditions, e.g., a major explosion devastating practically all of the site itself and the nearby surrounding area. By providing a graphical overview of blast-damaged areas or areas to be affected in due course resulting from a hazardous release, for instance, facilitates the task of communicating to all stakeholders the scale of the affected population and area.

Due to different accidental or intentional events, related to important structures all over the world, explosive loads have received considerable attention in recent years. Explosions are one of the most common causes for catastrophes in industrial facilities. However, it is not only the case for industrial accidents, but also in case of catastrophes caused by terrorism. The most common means of attack by terrorists are explosive devices of various forms and chemical composition. Therefore, modelling of explosions and their primary impact on targeted structures, on people present on site and off site, and the potential secondary effects in the surrounding area, are the focus of this research effort.

The effects of an explosion on structures can be: (a) Physical damage to the construction due to blast loads, fragments, ground-shock and heat effects of one or more explosions, or (b) Exposure of the structure and its users/inhabitants to toxic substances. This can have the following consequences (examples only):

- *Brisance Effect:* Shock waves of great intensity are due to the detonation of an explosive. The arrival of such a shock wave at the surface of a structure will generate intensive pressure waves, which in turn will lead to the disintegration of the material.[8]
- *Fracture*: If the explosive is surrounded by air, a pressure wave can fracture masonry and concrete structures.
- *Ground-shock*: Ground motions - associated with the passage of blast transients - develop as a result of the dynamic pressure pulse and are integrally related to the strains suffered by the soils. Ground motions can cause damaging vibrations in structures close to the detonation, regardless whether they are located above ground or buried.
- *Fire:* The use of explosives is one of the most common reasons for fire at structures. The heat generated by an explosion may cause secondary fires and secondary structural collapse.

[8] Smith PD, Hetherington, JG, Blast and ballistic loading of structures, Great Britain: Butterworth Heinemann Ltd. (1994).

- *Contamination*: Since the deployment of an explosive device can also be associated with the uncontrolled release of harmful substances, a structure can provide either protection against such toxic substances, or the structure itself can become the source of a toxic release (e. g., ruptured tank).

The destructive effects of an explosion on man and different structures as a function of peak pressure are summarized in Table 1 below.[9] They range from knocking down a person and breaking glass to structural collapse of buildings. The peak overpressure is largely determined by: (a) size of the explosive charge; (b) distance between the explosive charge and the targeted structure; (c) the medium surrounding the structure (typically air or water). For example, facade blast pressures in the Oklahoma City bombing due to a truck bomb (explosives: excess of 2 200 kg of ammonium nitrate fertilizer, nitro methane, and diesel fuel mixture) were in the order of 27 600 kPa.[10]

EFFECTS OF EXPLOSION	PEAK PRESSURE (kPa)
Glass shattering	5 to 35
Knocking down person	7
Collapse of wood partition	7 to 14
Collapse of cinderblock wall	14 to 20
Collapse of brick wall	50 to 55
Lung damage	100
Threshold for fatalities	240
50% Fatalities	345
99% Fatalities	700

Table 1 Effects of explosion on man and structural components for different peak pressure values.

In order for the user of a computer-generated model to understand the strength and limitations of the modelling results, it is beneficial to summarize the underlying physical process. The blast impact and any contamination of the environment potentially resulting from an uncontrolled release require the modelling of the following phases:[11]

Phase 1 (duration: milliseconds):

The explosion releases energy rapidly as light, heat, sound, and a shock wave. The shock wave consists of highly compressed air which travels radially outward from the source at supersonic velocities. As the shock wave expands, pressures decrease rapidly (with the cube of the distance) and, when it meets a surface that is in line-of-sight of the explosion, it is reflected and amplified by a factor of up to thirteen. Pressures also decay rapidly over time (i.e., exponentially) and have a very brief span of existence, measured typically in milliseconds. Diffraction effects, caused by corners of a building, may act to confine the air-blast, prolonging its duration. Late in the explosive event, the shock wave

[9] Adapted from Vincent Dunn, “Fire and Explosions,” URL: http://www.workingfire.net/misc12.htm. Last accessed 15 December 2011.

[10] The *Oklahoma City bombing* on 19 April 1995 claimed the lives of 168 people and injured more than 680. The detonation destroyed one third of the nine-story Alfred P. Murrah Federal Building, created a 9 m wide, 2.4 m deep crater, destroyed or damaged 324 buildings within a sixteen-block radius, destroyed or burned 86 cars, and shattered glass in 258 nearby buildings, resulting in a minimum damage estimated at $652 million (Mlakar, Sr., Paul F.; W. Gene Corley, Mete A. Sozen, Charles H. Thornton (August 1998). "The Oklahoma City Bombing: Analysis of Blast Damage to the Murrah Building". *Journal of Performance of Constructed Facilities* 12 (3): 113–119.

[11] FEMA, Building Design for Homeland Security, URL: http://www.fema.gov/pdf/plan/prevent/rms/428/fema428_ch4.pdf Last accessed 15 December 2011.

becomes negative, creating suction. Behind the shock wave, where a vacuum has been created, air rushes in, creating a powerful wind or drag pressure on all surfaces of the building. This wind picks up and carries flying debris in the vicinity of the detonation. In an external explosion, a portion of the energy is also imparted to the ground, creating a crater and generating a ground shock wave analogous to a high-intensity, short-duration earthquake. The products of the explosion spread fast. This process heats the atmosphere close to the point of detonation. This stage represents the fastest part in the complete process. Therefore, its dependence on meteorological parameters is negligible.

Phase 2 (duration: seconds to tens of seconds):

The cloud formed from the detonation products, hot air and debris expands and rises to a higher altitude, since the temperature inside is significantly elevated as compared to the temperature of the ambient atmosphere. Average density inside the cloud, the atmospheric density, aerial viscosity, speed and temperature distribution inside determine the dimension and velocity of the cloud.

*Phase 3 (*duration: tens to hundreds of seconds):

The cloud expands and rises until its average temperature reaches that of the ambient atmosphere. Inertia of the gas and buoyance levitate the cloud. Any further growth of the cloud is due to turbulence and diffusion mechanisms.

To protect property and persons working on sites that handle, store or transport large quantities of flammable materials, it is necessary to estimate the effects of pressure resulting from an explosion, whether the explosion occurs at a close or a distant location. In modelling the damage to buildings the following factors are taken into account: (a) Quantity of explosive; (b) Stand-off distance between building and explosive; (c) Assumptions about the building construction and materials used. The actual damages account for the direct blast and the associated component failure. The blast induced injuries are determined for a wide range of injuries (from eardrum rupture to lung collapse. lacerations and lethality).[12]

Blast due to Deployment of Explosives

This methodology assumes that a specific explosive has been deployed in order to inflict damage to a structure, e.g., a terror attack with an *Improvised Explosive Device* (IED) against a facility.

Pressure Calculations:

All pressures, both peak overpressure and peak dynamic pressure, are calculated based on the curves originally derived for nuclear blast effects scaled by dividing distance and height by yield (in metric tons) to the one-third power.

Pulse Duration Effect Calculations:

As the explosive yield increases, the corresponding pulse duration also increases. For a specified overpressure or dynamic pressure level, the longer the pulse duration the greater the damage. For a

[12]The assessment of the correct value of detonation energy is complex. Depending on, whether the value is chosen from the literature or it is calculated, generally, a ratio of 1.5 exists between the minimum and maximum values. Moreover, the composition of products in an actual detonation is not always the same for a given explosive. Factors such as density, temperature, initial degree of confinement, particle size and morphology and the size and shape of the load affect the pressure and temperature behind the detonation front. For details, see Tatom, F.B., and Tatom, J.W., "High Explosive Damage Assessment Model - Fifth Industrial Version-In the International System of Units (HEXDAM 5.2*) User's Manual", EAI-97-TR-004, Engineering Analysis Inc., Huntsville, Alabama, March 1997.

fixed scaled distance, $(\text{distance/yield})^{0,33}$, the overpressure or dynamic pressure is essentially independent of yield. Because of the effect of pulse duration, however, the damage level remains dependent on yield and will increase as yield increases.

Shielding Effect Calculations:

Shielding algorithm involves the use of finite line doublets from potential theory to simulate shielding of one structure component by another. Each structure component is characterized by its three dimensions: length (2d), width (2c), and height (b); and also by its orientation, Az. Note that in the negative Z-direction there is actually an identical image and thus, including this image (which makes the X-Y plane a plane of symmetry), the dimensions are 2c x 2d x 2b.

For shielding effects, the direction of the blast wave must be taken into account relative to the orientation of the shielding structure/component. The shielding effect of each structure/component is represented by three line doublets corresponding to the three trailing faces of the structure. The line doublets representing vertical surfaces (front, rear, or side wall), may be either horizontal or vertical, depending on the ratios of length-to-height and width-to-height for the structure/component. The line doublets representing horizontal surfaces (roof or floor) are always horizontal.

Damage/injury level computations:

These calculations are based on the incident pressure, either peak overpressure or peak dynamic pressure, which would occur at a distance from the burst point corresponding to the centroid of each structure/component, as projected into the horizontal plane at ground level. Such pressures are adjusted to take into account shielding and collateral effects as described previously. The dimensions and orientations of the structures/ components do not directly affect the calculations.

If the length or width of a structure is of the same order of magnitude as the distance from the primary detonation point, the automatic horizontal subdivision feature can be used. By means of such subdivision a structure/component can be divided into several smaller structures/components in order to determine the damage levels sustained by different portions of the original structure.

Blast due to Gas Explosion

This methodology assumes that the concentration of a gas/air mixture was sufficient to result in an explosion, e.g., detonation of a gas-filled tank.

Overpressure and Pulse Duration Computations:

Peak overpressure (pp) and pulse duration (t+) of the positive phase are calculated based on the multi-energy method. Both overpressure and positive phase duration are stored in dimensionless form as a function of dimensionless range. For each distinct vapour cloud (or sub-cloud) explosion the participating combustion energy (E) can be calculated according to the relation

$$E = m_f h_c$$

where

m_f = mass of fuel

h_c = net combustion energy

The impulses produced by all vapour cloud (or sub-cloud) explosions are summed algebraically for the calculation of damage/injury.

Cloud Radius-Height Relations:

The radius of the cloud, R_0, is a function of the cloud volume and cloud height, z_C. The radius of a spherical cloud, R_{0S}, is a function of volume only, according to the relation

$$R_{0S} = [3\, V_C / (4\pi)]^{1/3}$$

Secondary Explosions:

Each structure is considered a source of a secondary vapour cloud explosion, if it is damaged above a certain threshold. Secondary explosions produce collateral effects in the form of increased damage levels to nearby structures.

The computation steps associated with collateral effects are as follows:

1. A damage level sufficient to initiate a secondary vapor cloud explosion is assigned to each source structure.
2. A fuel type, fuel mass, and explosive strength are assigned to each source structure. If a structure cannot produce a secondary explosion, it is assigned no fuel type, zero fuel mass, and zero explosive strength.
3. For each secondary vapor cloud explosion, corresponding pressure and impulse values are computed for every other structure based on the distance R_{ij}, using the same procedures described earlier.
4. The maximum peak overpressure, produced by either the primary vapor cloud explosion or one of the secondary explosions, is computed. The impulses produced by all secondary explosions are added algebraically to the impulse produced by the primary explosion at each structure/component, with shielding effects taken into account.
5. Any additional secondary explosion, resulting from the peak overpressure and impulse at each structure, is determined. This step is repeated until all secondary explosions have been determined.

Damage/Injury Level Computations:

The damage/injury to each structure/component is based on the maximum peak overpressure, $(p_p)_{max}$, combined with the accumulated impulse, ΣI, reduced by shielding, and supplemented by secondary explosions. The adjusted values for $(p_p)_{max}$ and ΣI are used as inputs to a pressure-impulse diagram characteristic of the structure.

1.2.3 Incident-based Modelling

Incident-based modelling uses actual catastrophic events from the past to provide a realistic input for the parameters to be modelled. Since the main scenario in the BRIDGE project involves a large-scale chemical incident, real-world industrial accidents at chemical facilities have been analyzed to improve the understanding of their nature and the challenges they present to first responders.

Complex and fast evolving environment, danger of secondary, or domino, effects, such as fire, explosions, and toxic releases, sometimes accompanied by the lack of knowledge about the chemicals present on site and their amounts, pose particular risks for firefighters, police officers and emergency medical personnel. Table 2 below lists some of the recent industrial chemical accidents. Two of them with the worst consequences occurred in Europe – the Netherlands and France – and can provide a lot of insight into what kind of problems first responders are faced with during a chemical accident of that magnitude.

Explosion at SE Fireworks Plant, Enschede, The Netherlands (2000)

On 13 May 2000, a large-scale chemical accident occurred in the Dutch town of Enschede. What started as a small fire at the site of the SE Fireworks Company, rapidly evolved into a disaster, which destroyed an entire neighbourhood. A series of explosions occurred during the effort to extinguish the fire, injuring 947 and killing 21 people, including four fire-fighters.[13]

The first fireworks explosion occurred around 30 minutes after the initial report of the fire, attracting many people onto the streets of the city. This caused some additional deaths among the onlookers standing close to the site of the fire, but at the same time it may have saved the lives of people who otherwise would have been crushed by the demolished buildings of the final explosion. In total more than 600 houses, 40 shops and 60 small-scale-factories were destroyed, burned out or demolished by the great explosion.[14] Other sources put the number of destroyed homes as high as 1500.[15] Around 3500 people lived in the affected area of 5 square kilometres. About 100 of 180 tonnes of the fireworks stored in the factory warehouse exploded.

The following challenges and flaws have been identified in the response to the Enschede disaster:[16]

- In the first hectic hours after the last large explosions, municipal disaster command in particular had great difficulty gaining an overview of the extent of the disaster, and of the situation in the disaster area;
- The municipal fire brigade failed to obtain adequate information about the facility and the type of products it stored prior to engaging in fire suppression activities. As a result, the fire units had to act without proper information about the possible risks and dangers that they faced;[17]
- Although the general dangers of a fire at a firework factory were already known, the firefighters were surprised by the extent of the explosions;
- The nominated exclusion zone was too small and, therefore, subsequent explosions resulted in casualties among the members of the public and emergency service personnel;
- A large ammonia tank and released asbestos within the accident area both constituted additional serious hazards to the first responders working on-scene;
- Fire brigade, police and medical workers experienced great communication problems, both internally and with each other, because transmission equipment appeared not to be working, or only inadequately. The national emergency network offered no solution either;
- There was a considerable disruption of communication during the incident due to overloaded communication channels;
- Communication problems were also observed between Dutch and German firefighters, as the communication channels they used were not compatible;

[13] Viveka Björnhagen, Torbjörn Messner, Helge Brändström (ed): KAMEDO Report No. 82: Explosion at the Fireworks Warehouse in the Netherlands in 2000. Special Report. *Prehospital and Disaster Medicine*, Vol. 21, No. 2, March-April 2006, pp.: 123-5.

[14] Henk Voogd, "Disaster Prevention in Urban Environments," *European Journal of Spatial Development*, No. 12, September 2004; URL: http://www.henkvoogd.nl/pdf/refereed12.pdf

[15] "€8.5m paid to Enschede firework victims," DutchNews.nl, 19 September 2007; URL: http://www.dutchnews.nl/news/archives/2007/09/85m_paid_to_enschede_firework.php

[16] EU CAST Project Database on Emergency Response to Major Incidents (GA No. 218070).

[17] Oosting Commission (2001), Report on Enschede fireworks disaster, Final Report/Final Consideration, Ministry of the Interior and Kingdom Relations, The Netherlands, 1 March 2001.

	Event	Facility	Location	Country	Date	Casualties (Fatalities/Injuries)		Evacuees	Resources
1.	Series of explosions	SE Fireworks Facility	Enschede	The Netherlands	13 May 2000	21	950-1500	3500	300 fire-fighters, including 80 from Germany
2.	Chemical explosion	AZF (Azote de France) fertilizer factory	Toulouse	France	21 Sep 2001	31	3500	40000	1,046 firefighters from 13 districts and up to 950 policemen
3.	Explosion	Polyvinyl chloride (PCV) manufactu-ring facility	Illiopolis, Illinois	USA	23 Apr 2004	5	3	yes	
4.	Series of explosions	N.P. Johnsen's Fireworks Factory	Seest, Kolding	Denmark	3 Nov 2004	1	24	2000	332 firefighters and 55 vehicles
5.	Explosion	Isomerisation plant (ISOM), BP Oil Refinery	Texas City, Texas	USA	23 March 2005	15	170		75 local, regional and industrial emergency response units
6.	Series of explosions	Buncefield oil storage and transfer depot	Buncefield, Hemel Hempstead	UK	11 Dec 2005	0	57	2000	550 fire appliances
7.	Gas leak, fire, explosions	The Environmental Quality Company	Apex, North Carolina	USA	5 Oct 2006	0	30	Initially 17000, later reduced to 3300	54 firemen 51 police officers
8.	Explosion	CAI/Arnel Chemical Plant	Danvers, Massachusetts	USA	22 Nov 2006	0	10	77 families relocated	
9.	Series of explosions	T2 Laboratories Inc.	Jacksonville, Florida	USA	19 Dec 2007	3	33		
10.	Chemical explosion	Bayer CropScience Plant	West Virginia	USA	28 Aug 2008	2	8	40000 ordered to shelter in place	
11.	Propane explosion	Sunrise plant	Toronto	Canada	10 Aug 2010	2	0	12000	34 apparatus and 125 fire-fighters

Table 2 Examples of Chemical Accidents and Disaster (2000-2010).

- The emergency notification chain did not work as planned because the telephone network was overloaded. Many first responders were not alerted by their emergency rooms; the alarm was not given in a systematic or controlled manner. The heavy explosion and smoke worked as an alarm signal for many off-duty rescue personnel. As a result, the scaling up problem in the emergency rooms did not ultimately have any adverse effects;
- The fire and rescue service's command function did not work satisfactorily, which may, in part, have been due to the deaths of the four fire fighters early in the course of the event. After the immediate emergency response, command efforts were impeded by lack of clarity between the local authority and the overall disaster organization with respect to allocation of tasks and responsibility.

The most important lesson learned of the Enschede disaster is that the fire service of Enschede had no proper information about the facility or the products it made. Consequently, the inadequate situational awareness and risk assessment resulted to tactical errors, which led to the unnecessary deaths of firemen and members of the public.

A 3D virtual model of the facility, together with the list of substances and their amounts produced or stored at the site, could be of great help for the emergency services both in planning for and responding to such an incident in the future. It would provide a better situational awareness and contribute to a proper risk assessment.

Explosion at AZF Fertilizer Factory, Toulouse, France (2001)

An even more devastating chemical accident in the European Union to date occurred in France on 21 September 2001. At 10:17 hours on a Friday morning, a powerful explosion took place at Azote de France (AZF) fertilizer factory on the outskirts of Toulouse. Thirty people, most of them factory employees, were killed and about 3500 injured as a result of the explosion.[18] The detonation could be felt 80 km away and the Institute for Geophysics at Strasbourg registered the blast at 3.4 on the Richter scale, making it one of the biggest in industrial history.[19] The explosion, its TNT equivalent estimated between 20 and 40 t of TNT, produced a crater of about 65 m by 54 m in diameter and 7 m in depth.[20]

Many industrial buildings were demolished, and nearby residential buildings were in need of immediate evacuation. Some 27000 nearby homes were damaged, 11000 seriously, with crumbled walls and missing roofs.[21] Windows were shattered over a radius of 5 to 8 km.

The area affected by the blast can be divided into three zones:

- *High Destruction Zone* with a radius of 1 km from the explosion site, where the buildings were completely destroyed. This area included the chemical facility, as well as a big

[18] Louis Riddez, Siegfried Joussineau, Eva Magnusson (ed): KAMEDO Report No. 86: Explosion in the Artificial-Fertilizer Factory in France, 2001. Special Report. *Prehospital and Disaster Medicine*, Vol.22, No. 1, Jan-Feb 2007, pp.: 84-85.

[19] Marianne Arens and François Thull, "Chemical explosion in Toulouse, France leaves at least 29 dead," World Socialist Web Site, 25 September 2001; URL: http://www.wsws.org/articles/2001/sep2001/toul-s25.shtml.

[20] Nicolas Dechy, Thomas Bourdeaux, Nadine Ayrault, Marie-Astrid Kordek and Jean-Christophe Le Coze, "First lessons of the Toulouse ammonium nitrate disaster, 21st September 2001, AZF plant, France," *Journal of Hazardous Materials*, Volume 111, Issues 1-3, 26 July 2004, pp.: 131-138 (A Selection of Papers from the JRC/ESReDA Seminar on Safety Investigation Accidents, Petten, The Netherlands, 12-13 May, 2003).

[21] Michael Mayerfeld Bell, *An Invitation to Environmental Sociology* (Second Edition). Thousand Oaks California: Pine Forge Press, 2004, p. 110.

shopping centre with several supermarkets and a bus depot with over 150 buses, all of them burned down;

- *Serious Destruction Zone* within 2 to 3 km, which had the buildings left with damaged walls and/or without roofs. A hospital for 1200 beds (badly damaged, but fortunately operational), residential blocks (with about 20000 damaged apartments), and many businesses were located inside this zone;
- *Low Destruction Zone* within about 8 km, where the damage to the buildings was insignificant, but practically all windows were shattered. This zone included virtually the whole city centre. [22]

The explosion produced a plume of dust and smoke and, at first, it was not known whether it was toxic. As a huge orange cloud of gas, smelling of ammonia, started to move towards the city centre, located about 3 km from the blast, panic ensued in Toulouse. The spread of gas prompted the local authorities to close the airport and the main railway station and order evacuation of the whole metro system and some 90 schools in the area. 40,000 people — 10 percent of the city population — were made homeless for a few days. Electricity distribution system with more than 11,000 homes and university, school and public buildings was affected. The disaster cost the French government EUR 228 million and Total FinaElf, owner of AZF, more than 2 billion.[23]

The following challenges have been identified in the response to the Toulouse accident:[24]

- The alarm system at the factory was never activated;
- Major traffic problems quickly arose around the site, creating difficulties for the emergency services to reach the scene;
- Extensive damage also hindered rescue services in their efforts to reach the factory;
- A major disaster alarm was triggered in Toulouse 20 min after the explosion, signaling for a rescue effort to commence;
- The shockwaves were so powerful that police were inundated with reports of explosions in different parts of the city. It took three hours before it was established that there was only one blast and that there was no evidence of terrorist activity;
- The telephone network collapsed. The mobile phone network was overloaded, which hindered inter-agency communication between the fire, military and police forces. The phone lines were partly destroyed and could not be repaired until late in the evening;
- Rescue work began without a preliminary risk assessment for the rescuers. Only after 30 minutes did measurements show that the cloud of dust and smoke caused by the explosion had a "low" toxic content;
- The rescuers were particularly shocked by the complete dumbness among the people at the factory who survived the explosion, none of whom could speak. Only after a while, these employees started to recover and actively help the responders with actionable information.

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[22] Vzryv na khimicheskom kombinate v Tuluze [Explosion at Chemical Plant in Toulouse], *Osnovy bezopsnosti zhiznideyatelnosti* [Life Safety Basics] (Journal of the Russian Ministry of Emergency Situations, MChS), No. 6, 2002.

[23] Environmental Risk Reporting and Information System, *Learning from Major Accidents: Toulouse Tragedy 2001*, Accessed 15 December 2011; URL: http://www.erris.org/accidents/majaccidents/toulouse.html

[24] Database on Emergency Response to Major Incidents, EU CAST Project (GA No. 218070).

1.2.4 BRIDGE Scenario-based Modelling

Explosion at CHEMCO

BRIDGE Work Package 2 developed a hypothetical threat scenario as the basis for the R&D work of all other Work Packages. This scenario is based on the explosion in a virtual chemical factory named CHEMCO, located near Cologne in Central Europe. The modelling carried out by WP03 is based on the following assumptions:

- CHEMCO is in full operation with approximately 700 of staff members and visitors on site;
- At the time of the explosion it is daytime during the summer season;
- A tanker truck, loaded with petrol, detonates in close proximity to a tank farm containing dichloromethane.[25] The tank farm consists of 12 tanks with a total volume of 45000 m^3;
- The primary explosion of the tanker truck results in metal fragments damaging the chemical tank nearby;
- The impact of the primary explosive blast and metal fragments cause secondary explosions of 12 tanks filled with the toxic chemical dichloromethane;
- The primary and secondary explosions result in:
    - Major physical damage to the infrastructure of CHEMCO;
    - Large number of persons on site with multiple injuries;
    - Large number of lethally injured persons on site;
    - Uncontrolled release of toxic substances from CHEMCO.
    - Drift of a toxic plume towards a nearby major city.

Explosion at Critical Infrastructure

In addition, WP03 used reality-based scenarios to model threats to *Critical Infrastructure* as defined by the European Commission. EU Critical Infrastructure encompasses the following:[26]

- Electricity generation, transmission and distribution;
- Gas production, transport and distribution;
- Oil and oil products production, transport and distribution;
- Telecommunication;
- Water supply (drinking water, waste water/sewage, etc.);
- Agriculture, food production and distribution;
- Heating (e.g., natural gas, fuel oil, district heating);
- Public health (hospitals, ambulances);
- Transportation systems (fuel supply, railway network, airports, harbours, inland shipping);
- Financial services (banking, clearing, etc.);
- Security services (police, military, etc.).

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[25] Dichloroethane, commonly known as ethylene dichloride (EDC), is a chlorinated hydrocarbon and is used in the production of PVC. EDC is classified as a toxic carcinogen. It is corrosive and highly flammable. The chemical produces explosive vapour. Secondary products due to chemical reactions of dichloroethane can also be highly toxic. See 1,1-Dichloroethane, *eco-usa.net,* URL: http://www.eco-usa.net/toxics/chemicals/1,1-dichloroethane.shtml

[26] Council of the European Union, Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection, *Official Journal of the European Union*, L 345/75, 23 December 2008, URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:345:0075:0082:EN:PDF

2 State-of-the-Art in Crisis Management Modelling Applications

State-of-the-art in modelling applications in crisis management is represented largely by the US software products. The driving force behind this conceptual approach is the US Department of Homeland Security, which funds such the development of such products through the Infrastructure Protection and Disaster Management projects, some of which are listed below.[27] In contrast, the use of 3D modelling and simulation software by first responders in other parts of the world is only in a developing stage, e.g., SimSITE in Canada or CASSIDIAN software in the European Union.

Blast Analysis of Complex Structures Project

This project develops computational tools to quickly calculate structural responses to a range of explosives. It provides methods for blast engineers to calculate blast loads in dense urban environments and perform calculations to estimate the relationship between environmental conditions and blast loads.[28]

Blast/Projectile - Unified Blast Analysis Tool Project

This project provides improved modelling capabilities and faster running codes to facilitate accurate analysis of the impact of blast and projectile threats to diverse classes of infrastructure, with a focus on tunnels, bridges, dams, and complex urban environments. Improving modelling capabilities and building fast-running models will enable owners and operators to efficiently analyze vulnerabilities and inform implementation of protective measures. Fast-running codes will reduce simulation time from days to hours/minutes.[29]

Complex Event Modelling, Simulation, and Analysis (CEMSA) Project

This project focuses on interdependencies, cascading effects, and the dynamics of multi-event and multi-vector attacks. CEMSA will provide significant improvements in timelines, quality, and usability of information to provide decision makers up-to-date information to make informed decisions during an event. The project will leverage the capabilities developed for Critical Infrastructure Protection Decision Support System (CIPDSS) and sector-specific modelling, simulation, and analysis (MSA). [30]

Standard Unified Modelling Mapping Integrated Toolkit (SUMMIT) Project

This project allows emergency preparedness and management personnel to easily and rapidly discover, integrate, configure, execute, and view the results of the Nation's modelling and simulation resources and related data. The SUMMIT tool is the principal component of the Integrated Modelling, Mapping, and Simulation (IMMS) program. The IMMS program is enhancing the use of science-based tools for the emergency preparedness and management community. By creating an environment that allows linking of "best-in-class" modelling and simulation tools and underlying data, IMMS aims to decrease the time and cost needed to train for, analyze, and respond to real or potential incidents—while increasing preparedness effectiveness. [31]

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[27] U.S. Department of Homeland Security (DHS), Infrastructure Protection and Disaster Management Projects, URL: http://www.dhs.gov/files/programs/gc_1218480826191.shtm#3
[28] Ibid.
[29] Ibid.
[30] Ibid.
[31] Ibid. See also "New tool allows first responders to visualize post-event disaster environments," Sandia Labs News Release, 17 August 2011; URL: https://share.sandia.gov/news/resources/news_releases/summit/

Response Information Folder System (RIFS)

Alion Science and Technology Corp. developed a technology for first responder organizations and school officials called Response Information Folder System (RIFS). The interest in such simulation technologies spiked among universities and high schools in the wake of the Virginia Tech shooting. The RIFS technology offered by Alion enables law enforcement officers and other emergency responders to get a real-time video, data and 3D-model feed of local buildings as crises develop. Whereas normally first responders train for an event (e.g., shooting, hostage taking, fire, explosion, etc.) at a hypothetical facility, the RIFS system makes it possible to train for various scenarios in a specific facility, thus significantly improving the effectiveness of potential response.[32]

Emergency and Disaster Management Simulation (EDMSIM)

EDMSIM is an entity-based, real-time constructive simulation. EDMSIM trains the Emergency Operations Center (EOC) staff by replacing the traditional "Table Top model" and Master Scenario Events List (MSEL) exercises with a computer simulation. This provides more realistic inputs to the EOC and allows the exercise to be more dynamic and free-flowing than the traditional methods. EDMSIM contains a full-featured GIS component that allows you to locate events on the map and to lay out the exercise area on the ground. EDMSIM can automatically display all common commercial electronic maps. Maps can also be modified with layers of graphics, images, satellite photos, or even operational graphics. The GIS component of EDMSIM is powerful, yet simple to use. EDMSIM can display entity locations in 3D and can integrate with online mapping engines such as Google Earth and Microsoft's Virtual Earth. A unit organization can be created and symbols can be dragged and dropped on to the map with ease.[33]

Trimble Indoor Mobile Mapping Solution (TIMMS)

TIMMS is the optimal fusion of technologies for capturing spatial data for indoor and other GNSS denied areas of all sizes and locations. It provides both LiDAR and spherical video of a facility, enabling the creation of accurate, real-life representations of an interior space and all of its contents. The maps created are geolocated, meaning that the real world positions of each area of the building and its contents are known. Each pixel from the camera system and every point from the LiDAR have a latitude, longitude and elevation associated with it without the need of any external infrastructure to provide positioning information – TIMMS is totally self contained. TIMMS can be initialized immediately and can perform wide area mapping of a facility for extended periods of time. Once the data is processed, the resulting spatial data can be rendered in a 360º panoramic viewer, allowing the user to be fully immersed in the interior space, able to zoom, pan and measure items of interest as desired. Because TIMMS is a highly productive and reliable method for mapping any interior structure, all facility stakeholders can utilize and benefit from the TIMMS data. Those who will benefit most include Law Enforcement officials, Public Safety authorities and First Responders. Detailed 360 degree imagery provides situational awareness giving personnel the total picture of an indoor environment. LiDAR data can be used for accurate measurement of interior features and both data types can be accessed through the internet, giving decision makers in multiple locations

[32] Dan Verton, "Alion Tackles 3D Modeling for First Responders," Podtech.net, 18 May 2007; URL: http://www.podtech.net/home/3079/alion-tackles-3d-modeling-for-first-responders

[33] Applied Training Solutions, LLC, Emergency and Disaster Management Simulation. Last accessed 15 December 2011; URL: http://www.ipsysi.com/sub/edmsim.php

real time access to the same data. The data can be used for training and simulation purposes as well.[34]

Emergency Preparedness Training Simulator

3DInternet creates realistic simulations of your equipment, procedures in immersive and interactive environments, combined with advanced assessment systems. It is an effective learning tool for first responders, which helps to improve performance, reduce costs and maintain a state of readiness. Using Plume modelling calculations this highly realistic 3D Training Simulator can train first responders (military, police, fire/HazMat, and EMS) and incident commanders to prepare for, respond to, recover from, and prevent deliberate or accidental releases of hazardous materials from a nuclear plant, oil and gas pipeline break, train derailment, and within urban settings. Different emergency response agencies can work together to simulate an accident and see how each of them handles the situation. With the physics engine capabilities the software provides accurate plume modelling for different airborne chemicals as well as explosions. All procedural data is tracked in a database for review. Simulators can also be used to prequalify employees for the job, by immersing them into stressful simulations, which reflect the real world situations.[35]

SimSITE: The HLA/RTI Based Emergency Preparedness and Response Training Simulation

The emergency responders need to work in a coordinated, well-planned manner to best mitigate the impact of an emergency incident. Simulation systems provide a wider range of training at a much lower expense for emergency preparedness and response. It is identified as the only feasible approach when it is difficult to emulate real-life experiments. The software demonstrates the emergency training simulation for the SITE building at the University of Ottawa, where the real-time interaction and collaboration are achieved over HLA/RTI, the IEEE standard for distributed simulation and modelling. [36]

CASSIDIAN Crisis Management Simulation Software

In order to provide reality simulations of complex emergency situations, CASSIDIAN (An EADS Company) is developing software for first responders based on gaming technology. By taking 3D models of structures and environment and incorporating them into gaming software, Cassidian will provide a detailed crisis environment, which will include avatars as well as human behaviour engines.[37]

BRIDGE Modelling of Structure

In the BRIDGE project Work Package 3 provides a synthesis of different modelling approaches, aimed at providing an optimal solution for the different applications by first responders:

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[34] Trimble, Trimble Indoor Mobile Mapping Solution (TIMMS). URL: http://www.trimble.com/Indoor-Mobile-Mapping-Solution/pdf/TIMMSOverview.pdf. Last accessed 15 December 2011.

[35] 3DInternet, 3DInternet Solutions for Military & First Responders. URL: http://www.3dinternet.com/military.php. Last accessed 15 December 2011.

[36] Ke Liu et al., SimSITE: The HLA/RTI Based Emergency Preparedness and Response Training Simulation. Proceeding DS-RT '07 Proceedings of the 11th IEEE International Symposium on Distributed Simulation and Real-Time Applications, IEEE Computer Society Washington, DC, USA ©2007; URL: http://dl.acm.org/citation.cfm?id=1346035

[37] David Blore, “Game on: How software for leisure is helping responders.” *Crisis Response*, Vol. 7, Issue 2, pp.: 20-21.

- *Training application:* Assuming that there is sufficient time for preparing for the training exercise, a 3D model of the facility, its detailed infrastructure and surroundings is created, using 3ds MAX. This enables the first responders to familiarize themselves with the specifics of the installation prior to and after the incident, e.g., a large explosion in a chemical facility. The development of such a model requires access to structual and operational input data. Generally, the degeree to which the model reflects reality depends on the quality of the input information and the computing time available. It is noted that simply the time required for rendering of already completed 3D models takes typically several days of high speed computing. The output resembles reality close to photographic quality. The user can move through the modeled facility as if driving or walking through its different sectors, zooming in and out of details.
- *Application during on site crisis management:* During times of rapidly developing threats in a catastrophe, first responders on site need to carry out risk assessment as part of the crisis management. This requires a fast modeling approach, i.e., a 3D model of the facility needs to be available within 30 minutes at most. The concept selected in BRIDGE foresees the creation of a 3D HEXDAM- and VEXDAM-based model. The former models the impact of an explosion due to a bomb on a structure, the resulting physical damages and different degrees of harm to victims; the latter provides corresponding information for gas explosions. Both 3D models can be inserted into the corresponding geographical environment, e.g., GOOGLE Earth. Furthermore, photos or diagrammes describing the facility can be used as additional input data. The user of this model can view the model and the impact of the explosion from different angles, including birds-eye view. Furthermore, the propagation of the blast and the resulting damages are displayed as a dynamic event, e.g., the blast wave moving through a building in slow motion.
- *Critical Infrastructure Library:* The BRIDGE Concept establishes a library of generic 3D models, representing examples of Critical Infrastructure (CI) as defined by the EU Commission (power plants, airports, train stations, financial centres, etc.). The models were subjected to different magnitude of explosions. For example, using existing nuclear power plants, such as a French, Bulgarian and German nuclear power plant, a generic model of a storage pool for spent nuclear fuel rods was developed based on HEXDAM and subjected to an explosion. Such a generic model can be used by a first responder in two ways:
  (1) First approximation of the identifying high risk areas (e.g., buildings threatening to collapse after an explosion) ; Identification of high priority areas for search and rescue operations, using the graphic mapping of injured survivors;
  (2) Adapting the generic model with additional input data to approximate the actual lay out of the incidenc site, thereby reducing the uncertainty between the model and reality.

In order to corroborate the models developed, a series of test explosions was carried out in close collaboration with the underground test facility *Versuchsstollen Hagerbach* (VSH; Flums, Switzerland). VSH is partner in the BRIDGE consortium.[38]

[38] The results of these comparisons are subject of BRIDGE Deliverable D 3.2

3 Description of Modelling Software Used

Depending on the practical application of the model, different software was used to model the different structures and simulate the associated threat scenario. This section describes the characteristics of each software used.

3.1 3ds-MAX

Autodesk 3ds Max represents state-of-the-art for making 3D animations. It supports integrated 3D modelling, animation, rendering, and compositing tools. Due to the fully integrated *Character Animation Toolkit*, it is possible to animate, and light realistic characters and environments. The software features *Graphite Modelling* and CAT advanced character rigging, as well as powerful *Particle Flow System*. The *Nitrous* accelerated graphics provides the possibility to handle large data sets and iterate fast. The extensive polygon modelling and texturing toolset combines freeform sculpting, texture painting, and advanced polygonal modelling. *Object Paint* provides parametric replication of objects in a scene.

The multi-threaded *NVIDIA® PhysX®* engine creates dynamic rigid-body and soft simulations. *ProCutter* tool creates explosive effects. Rendering is multi-faceted and ranges from integrated *mental ray®* batch rendering software, a traditional scan-line renderer, *Quicksilver* GPU renderer, to the *iray®* “point-and-shoot” rendering technology.

In order to meet a high standard of interoperability, using *3ds Max Containers* it is possible to create and manage large, complex scenes and collaborate with others more effectively. Data can be exchanged with over thirty 2D and 3D data formats, including Autodesk® DWG® exchange technology, XML, FBX, OBJ and SAT. 3ds Max pipelines can be customized and extended using multiple development tools, including C# and .NET.

Custom import/export tools can be created by using the built-in file I/O and write procedural controllers that can access the entire state of the scene, or build batch-processing tools.In addition it can also be used for movie effects and movie pre-visualization. 3ds Max also features shaders (such as ambient occlusion and subsurface scattering), dynamic simulation, particle systems, radiosity, normal map creation and rendering, global illumination, a customizable user interface, and its own scripting language.

“Autodesk 3ds Max” will be used for demonstration purposes during the whole BRIDGE project.

3.1.1 Features

The software 3ds-MAX has the following features:

MAXScript

MAXScript is a built-in scripting language that can be used to automate repetitive tasks, combine existing functionality in new ways and develop new tools and user interfaces. Plugin modules can be created entirely within MAXScript.

Character Studio

Character Studio helps users to animate virtual characters. The system works using a character rig or "Biped" skeleton which has stock settings that can be modified and customized to the fit character meshes and animation needs. This tool also includes robust editing tools for IK/FK switching, Pose manipulation, Layers and Keyframing workflows, and sharing of animation data across different Biped skeletons. These "Biped" objects have other useful features that help accelerate the production of walk cycles and movement paths, as well as secondary motion.

Scene Explorer

Scene Explorer, a tool that provides a hierarchical view of scene data and analysis, facilitates working with more complex scenes. Scene Explorer has the ability to sort, filter, and search a scene by any object type or property (including metadata). It facilitates .NET managed code in 3ds Max outside of MAXScript.

DWG Import

3ds Max supports both import and linking of DWG files. It enables larger scenes to be imported with multiple objects.

Texture Assignment/Editing

3ds Max offers multiple operations for creative texture and planar mapping, including tiling, mirroring, decals, angle, rotate, blur, UV stretching, and relaxation; Remove Distortion; Preserve UV; and UV template image export. The texture workflow includes the ability to combine an unlimited number of textures, a material/map browser with support for drag-and-drop assignment, and hierarchies with thumbnails. UV workflow features include Pelt mapping, which defines custom seams and enables users to unfold UVs according to those seams; copy/paste materials, maps and colours; and access to quick mapping types (box, cylindrical, spherical).

General Keyframing

Two keying modes — set key and auto key — offer support for different keyframing workflows. Fast and intuitive controls for keyframing — including cut, copy, and paste — let the user create animations with ease. Animation trajectories may be viewed and edited directly in the viewport.

Constrained Animation

Objects can be animated along curves with controls for alignment, banking, velocity, smoothness, and looping, and along surfaces with controls for alignment. Weight path-controlled animation between multiple curves, and animate the weight. Objects can be constrained to animate with other objects in many ways — including look at, orientation in different coordinate spaces, and linking at different points in time. These constraints also support animated weighting between more than one target. All resulting constrained animation can be collapsed into standard keyframes for further editing.

Skinning

Either the Skin or Physique modifier may be used to achieve precise control of skeletal deformation, so the character deforms smoothly as joints are moved, even in the most challenging areas, such as shoulders. Skin deformation can be controlled using direct vertex weights, volumes of vertices defined by envelopes, or both.

Capabilities such as weight tables, paintable weights, and saving and loading of weights offer easy editing and proximity-based transfer between models, providing the accuracy and flexibility needed for complicated characters.

The rigid bind skinning option is useful for animating low-polygon models or as a diagnostic tool for regular skeleton animation.

Additional modifiers, such as *Skin Wrap* and *Skin Morph*, can be used to drive meshes with other meshes and make targeted weighting adjustments in tricky areas.

Skeletons and Inverse Kinematics (IK)

Characters can be rigged with custom skeletons using 3ds Max bones, IK solvers, and rigging tools powered by Motion Capture Data.

All animation tools — including expressions, scripts, list controllers, and wiring — can be used along with a set of utilities specific to bones to build rigs of any structure and with custom controls, so animators see only the UI necessary to get their characters animated.

Four plug-in IK solvers ship with 3ds Max: history-independent solver, history-dependent solver, limb solver, and spline IK solver. These powerful solvers reduce the time it takes to create high-quality character animation. The history-independent solver delivers smooth blending between IK and FK animation and uses preferred angles to give animators more control over the positioning of affected bones.

The history-dependent solver can solve within joint limits and is used for machine-like animation. IK limb is a lightweight two-bone solver, optimized for real-time interactivity, ideal for working with a character arm or leg. Spline IK solver provides a flexible animation system with nodes that can be moved anywhere in 3D space. It allows for efficient animation of skeletal chains, such as a character's spine or tail, and includes twist and roll controls.

Integrated Cloth Solver

In addition to reactor's cloth modifier, 3ds Max software has an integrated cloth-simulation engine that enables the user to turn almost any 3D object into clothing, or build garments from scratch. Collision solving is accurate even in complex simulations (image.3ds max.jpg).

Local simulation lets artists drape cloth in real time to set up an initial clothing state before setting animation keys.

Cloth simulations can be used in conjunction with other 3ds Max dynamic forces, such as Space Warps. Multiple independent cloth systems can be animated with their own objects and forces. Cloth deformation data can be cached to the hard drive to allow for non-destructive iterations and to improve playback performance.

Integration with Autodesk Vault

Autodesk Vault plug-in, which ships with 3ds Max, consolidates users' 3ds Max assets in a single location, enabling them to automatically track files and manage work in progress. Users can share, find, and reuse 3ds Max (and design) assets in a large-scale production or visualization environment.

3.1.2 Practical Application

Many recent films have made use of 3ds Max, or previous versions of the program under previous names, in CGI animation, such as ***"Avatar"*** and ***"2012"*** among many others, which contain a large amount of computer generated graphics from 3ds Max alongside live-action acting.

3ds Max has also been used in the development of 3D computer graphics for a number of video games. Architectural and engineering design firms use 3ds Max for developing concept art and pre-visualization.

Educational programs at secondary and tertiary level use 3ds Max in their courses on 3D-computer graphics and computer animation in many regions of the world.

3.1.3 Basic Modelling Techniques Applied

The following section describes the modelling techniques used in this Deliverable.

Polygon Modelling: Polygon Modelling is more common with game design than any other modelling technique as the very specific control over individual polygons allows for extreme optimization. Modelling started with one of the 3ds max primitives, and using such tools as bevel and extrude, adding detail to and refining the model.

NURBS or non-uniform rational B-spline: This method gives a smoothed out surface that eliminates the straight edges of a polygon model. NURBS is a mathematically exact representation of freeform surfaces like those used for car bodies and ship hulls, which can be exactly reproduced at any resolution whenever needed.

Surface tool/Editable patch object: The surface tool is for creating common 3ds Max splines, and then applying a modifier called "surface." This modifier makes a surface from every 3 or 4 vertices in a grid. It enables a user to interpolate curved sections with straight geometry (for example a hole through a box shape).

Predefined primitives: This is a basic method, in which one models something using only boxes, spheres, cones, cylinders and other predefined objects from the list of Predefined Standard Primitives or a list of Predefined Extended Primitives. Examples are shown in Figures 1 and 2.

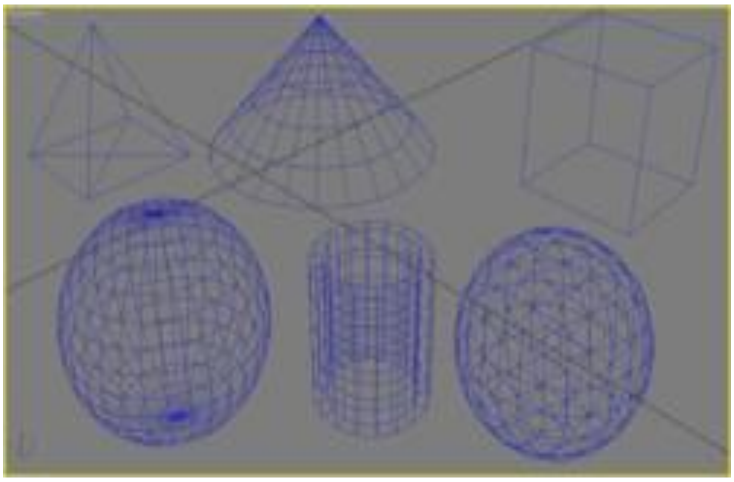

Figure 1 Some 3ds Max *Primitives* as they appear in the wireframe view of 3ds Max.

3ds Max Standard Primitives: Box (top right), Cone (top centre), Pyramid (top left), Sphere (bottom left), Tube (bottom centre) and Geosphere (bottom right).

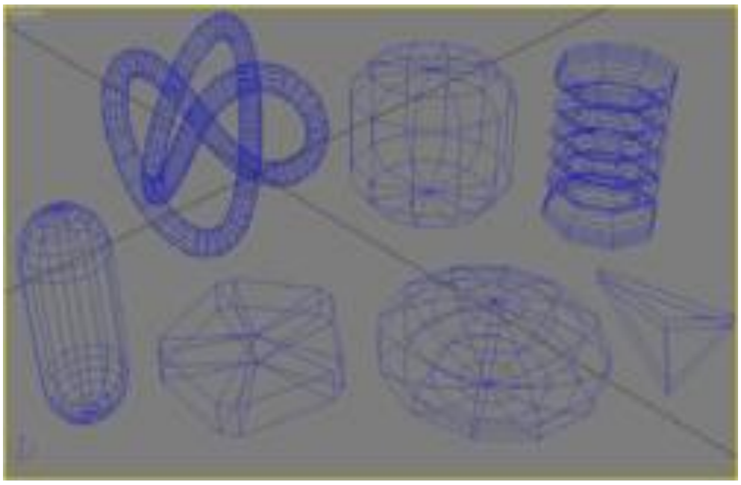

Figure 2 3ds Max *Extended Primitives* appearing in the wireframe view of 3ds Max.

3ds Max Extended Primitives: Torus Knot (top left), ChamferCyl (top centre), Hose (top right), Capsule (bottom left), Gengon (bottom, second from left), OilTank (bottom, second from right) and Prism (bottom right)

Rendering techniques: (a) Scanline rendering (global illumination, radiosity, and ray tracing); (b) Mmental ray (raytracing renderer with bucket rendering); (c) RenderMan (integrating *Max* into Renderman render farms); (d) V-Ray (substituting the standard and mental ray renderers); (e) Brazil R/S (photorealistic rendering system capable of fast ray tracing and global illumination); (f) FinalRender (capable of simulating a wide range of real-world physical phenomena); (g) Fryrender (physically based, unbiased and spectral renderer); (h) Arion Render (hybrid GPU+CPU interactive, unbiased raytracer) Third-party photorealistic renderer with plugins for 3ds max.

3.1.4 Minimum System Requirements

Application of the software requires the following minimum system characteristics:

- INTEL® Pentium®4 processor or equivalent with SSE2 technology;
- 2 GB RAM;
- 2 GB Swap space;
- 3 GB free hard drive space;
- Open GL-capable graphics card;
- Three button mouse;
- MICROSOFT® Windows® XP professional operating system (SP 3 or higher).

3.2 HEXDAM

HEXDAM shares many parts of its basic components with the also used VEXDAM (see section below). Both software programmes have nearly the same graphics for better comparison. Minimum requirements are low, but the analysis of complicated structures either needs a large amount of calculation time, or powerful hardware-systems to get acceptable results within a timeframe of minutes. HEXDAM represents the industrial version of the *High Explosive Damage Assessment Model.* It enables the rapid evaluation of damage experienced by each structure within a facility as a result of a primary explosion, and accompanying secondary explosions. Its primary application is analysis of manufacturing facilities. The code can also be used to evaluate terrorism and sabotage threats to a facility.

HEXDAM has the capability to model an unlimited number of structures, each with different dimensions and structural properties and theoretically also an unlimited number of personnel (depending on calculation time available). The *Parametric Analysis of Single Structure* (PASS) capability allows the user to determine the influence of various important independent variables on pressure and damage experienced by an individual structure within a facility. HEXDAM utilizes widely accepted dynamic pressure and overpressure curves to predict the pressure level at each structure/person location. Structure shielding, based on the three-doublet advanced shielding algorithm, and secondary explosion effects are calculated, and damage/injury levels are determined for each structure/person.

HEXDAM produces output in the form of damage/injury tables, before-blast and after- blast displays, pressure and damage/injury contour plots, and damage/injury-versus-distance graphs, all in colour. Advanced graphical features include three-dimensional graphics in the form of oblique projections, as well as two-dimensional horizontal and vertical cross sections for both pressure contour and damage/injury contour plots.

3.2.1 HEXDAM Capabilities

HEXDAM enables the user to model the following effects and their consequences:

- Prediction of blast damages to 104 basic structure types, plus any user-defined structure types;
- Prediction of blast injury to 28 body components comprising the human body (other parts can be designed externally);
- Compatibility with *Vulnerability Assessment of Structurally Damaging Impulses and Pressures* (VASDIP) software;
- Prediction of blast damage/injury to both overpressure-sensitive and dynamic pressure-sensitive structures;
- Prediction of shielding effects by each structure on surrounding structures based on the three-doublet advanced algorithm;
- Prediction of blast damage/injury resulting from secondary explosions triggered by the initial (primary) blast;
- Capacity to model an unlimited number of individual structures and/or body components within a facility;
- Capability to model elevated structures;
- Automatic or user-specified subdivision of structures;
- Generation of pressure and damage contours;
- Zoom feature for all graphical displays;
- *Parametric Analysis of Single Structure* (PASS).

3.2.2 Minimum System Requirements

Application of the software requires the following minimum system characteristics:

- IBM PC or compatible;
- Hard disk drive;
- Printer/plotter (for hardcopy);
- Colour monitor and graphics card;
- Windows 95 or better;
- 640 K bytes system RAM;

- Math co-processor.

INPUTS:

- Primary explosion:
  - Location (including height);
  - Yield;
- Individual structures:
  - Location;
  - Dimensions (length, width, height);
  - Orientation;
- Structure/body component type:
  - 104 basic inanimate types;
  - 19 human body component types;
  - User-defined types.

OUTPUTS:

- Before-Damage Display - Provides 3D oblique projection in colour of all structures/body components being modelled;
- Damage/Injury Table - For each structure/body components provides pressure level and damage assessment;
- After-Blast Display - Provides same 3D oblique projection in color as Before- Damage but also indicates damage/injury level to each structure/body component;
- Damage/Injury versus Distance Graph - Provides color-coded plot of damage/injury levels to all structures/body components versus distance from primary explosion;
- Pressure Contours - Provides 3D oblique projection and 2-D horizontal and vertical cross sections of over-pressure and dynamic pressure contours of entire layout in colour;
- Damage/Injury Contours - Provides 3D oblique projection and 2-D horizontal and vertical cross sections of damage/injury contour plots for any structure/body component in colour;
- Parametric Analysis - Provides plots of variation of overpressure, dynamic pressure, and damage to a single structure as a function of the yield and the location of the burst;
- 3D-Animations of different kind of pressure waves for presentations.

3.2.3 Types of Structures Covered

The software is able to take into account the following structures and specifics:

- Structural elements (7 different types): aluminium, asbestos, brick, concrete, glass, steel, wood;
- Composite structures (97 different types): bridges, buildings (commercial/administrative, industrial, residential, hangars, magazines, shelters, underground structures, transportation equipment, aircraft, railroad, earth-moving equipment, naval vessels, vehicles), communications/electrical equipment, industrial equipment, gas and oil storage tanks, User-defined structures;
- Compatible with “VASDIP“.

3.2.4 Types of Body Components Covered

Modelling of the damages inflicted to man covers the following body parts:

- *Soft Tissue*: Eardrums, Larynx, Lungs, G.I. System;

- *Bones*: Skull, Cervical Vertebrae, Clavicle, Ribs, Thoracic Vertebrae, Pelvis, Lumbar Vertebrae, Humerus, Radius, Ulna, Metacarpals, Femur, Fibula, Tibia, Metatarsals.

3.2.5 Computational Process

The high explosive model follows the following sequence of computations:

- Pressure calculations;
- Pulse duration effects;
- Shielding effects;
- Secondary explosions;
- Damage/injury levels.

The basic inputs to HEXDAM provide all the necessary information about primary and secondary explosions as follows:

- Location (including height);
- Yield;
- Damage threshold for secondary explosion;
- Yield for secondary explosion.

3.3 VEXDAM

VEXDAM represents the vapour cloud explosion counterpart to the *High Explosive Damage Assessment Model* (HEXDAM). Like HEXDAM this software has been designed to allow the rapid evaluation of damage experienced by each structure within a facility as a result of a primary explosion, and any accompanying secondary explosions produced by vapour clouds at any elevation. Its primary application is analysis of petrochemical fuel storage and refining/manufacturing facilities. The code can also be used to evaluate terrorism and sabotage threats to different kind of structures.

The program has the capability to model an unlimited number of structures, each with different dimensions and structural properties, including elevated or underground structures. The *Parametric Analysis of Single Structure* (PASS) capability allows the user to determine the influence of various important independent variables on damage, overpressure, and impulse experienced by an individual structure within a structure.

VEXDAM utilizes dimensionless curves of overpressure and pulse duration versus range, based on the multi-energy method, to predict overpressure and impulse at each structure/person location. Structure shielding, based on the three-doublet advanced shielding algorithm, and secondary explosion effects are calculated, and damage/injury levels are determined for each structure.

VEXDAM produces output in the form of damage/injury tables, before-blast and after-blast displays, overpressure, impulse, and damage/injury contour plots, and damage/injury-versus-distance color-graphs. Advanced features include three-dimensional graphics in the form of oblique projections, as well as two-dimensional horizontal and vertical cross sections for overpressure, impulse, and damage/injury contour plots.

3.3.1 VEXDAM Capabilities

The software has the following capabilities:

- Capability to model elevated vapour clouds;
- Blasts produced by as many as ten sub-clouds within primary vapor cloud;
- Compatibility with *Vulnerability Assessment of Structurally Damaging Impulses and Pressures* (VASDIP) software;
- Damage prediction for 104 basic structure types, plus any user-defined structure types;
- Damage prediction for overpressure-sensitive and dynamic pressure-sensitive structures;
- Injury prediction for 28 body components comprising the human body;
- Use of the three-doublet advanced algorithm to predict shielding effects by each structure on other structures;
- Prediction of blast damage resulting from secondary vapour cloud explosions triggered by the primary vapour cloud blast;
- Capacity to model an unlimited number of individual structures/persons within a facility;
- Capability to model elevated structures;
- Automatic or user-specified structure subdivision;
- Generation of overpressure, impulse, and damage contours (3D oblique projections, plus 2D horizontal and vertical cross sections);
- Zoom feature for all graphical displays;
- *Parametric Analysis of Single Structure* (PASS).

3.3.2 Minimum System Requirements

Application of the software requires the following minimum system characteristics:

- IBM PC or compatible;
- Hard disk drive;
- Colour plotter;
- Colour monitor and graphics card;
- Windows 95 or better;
- 640K RAM;
- Math co-processor recommended.

INPUTS:

- Ambient conditions;
- Primary explosion:
    - Identity of fuel;
    - Number and location of sub clouds;
    - Mass of fuel in each sub cloud;
    - Explosive strength of each sub cloud;
- Individual structures:
    - Location;
    - Dimensions (length, width, height);
    - Orientation;
- Structure/person type:
    - 104 basic inanimate types;
    - 19 human body component types;
- Explosive threshold for secondary explosions;
- Secondary explosion characteristics:

  - Identity of fuel;
  - Mass of fuel;
  - Explosive strength.

OUTPUTS:

- Before-Blast Display - Provides 3D oblique projection in colour of all structures/persons being modelled;
- Damage Table - For each structure/persons provides overpressure, impulse, and damage/injury levels;
- After-Blast Display - Provides same 3D oblique projection in colour as Before-Blast but also indicates damage/injury level to each structure/persons;
- Damage/Injury versus Distance Graphs - Provides colour-coded plot of damage/injury levels to all structures/persons versus distance from primary explosion;
- Pressure Contours - Provides 3D oblique projection and 2D horizontal and vertical cross sections of overpressure and impulse contours of entire layout in colour;
- Damage/Injury Contours - Provides 3D oblique projection and 2D horizontal and vertical cross sections of contour plots of damage levels to any structure/persons in colour;
- Parametric Analysis - Provides plots of variation of overpressure, impulse, and damage to a single structure as a function of the explosion characteristics and the location of the vapour cloud.

3.3.3 Types of Structures Covered

The software is able to take into account the following structures and specifics:

- Basic Structural elements – as for HEXDAM;
- Composite structures – as for HEXDAM.

3.3.4 Types of Body Components Covered

The output of the software covers the same body parts as HEXDAM, i.e., it is fully compatible.

3.3.5 Computational Process

The vapour cloud explosion model follows the following sequence of computations:

- Overpressure and pulse duration calculations;
- Impulse calculations;
- Cloud radius-height relations;
- Shielding effects;
- Secondary explosions;
- Damage/injury level computations.

The basic inputs to VEXDAM are designed to provide a description of a primary explosion and one or more structures/persons located in the vicinity as follows:

- Ambient Conditions (Atmospheric Pressure; Atmospheric Temperature);
- Vapour Cloud – Primary (Fuel Type);
- Vapour Cloud – Sub-clouds (Location; Mass of Fuel or Volume of Vapour-Air Mixture; Explosive Strength).

4 Results for BRIDGE Scenario-based Modelling

This section contains examples of the results using 3ds-MAX for the modelling of the virtual facility CHEMCO prior to the explosion and the explosion itself. The modelling results enable the user to carry out 3D camera-drives through the facility.[39] It is possible to zoom in and out of each of the modelled components, thereby providing the user with a close-up view or more distant overview. Also, the user can select an aerial view above the facility.

The threat scenario modelled corresponds to the scenario description provided by Work Package 2, i.e., a major explosion in CHEMCO resulting in an uncontrolled release of a toxic chemical into the atmosphere. The following assumptions have been made:

- *Primary explosion*: Petrol in tanker lorry: 35 m^3 (fully loaded);
- *Secondary explosions*: 12 tanks filled with a total of 45 000 m^3 dichloroethane;
- *Number of staff and visitors present at CHEMCO at time of explosion*: 700.

Due to the multiple explosions and subsequent fire on site, the cooperation of emergency services from many dedicated organizations is necessary to regain control over the situation. The incident resulted in a large number of dead and injured. The toxic cloud is assumed to start drifting towards a nearby major city, necessitating decisions about evacuation.

4.1 Pre-blast CHEMCO Facility

The virtual CHEMCO facility has been modelled as sited outside the city of Cologne, Germany. The facility is located in a rural area, surrounded by meadows.[40]

Figures 3 to 18 show different views of the virtual chemical facility *CHEMCO* prior to the incident, using *screen shots*. The actual Deliverable is a dynamic, movie-like sequence of scenes. At any time, the user is able to select any particular detail of the modelled structure and focus on it.

[39] In this report, accompanying the actual deliverable, screenshots show different camera views.
[40] The facility has been placed in the approximate location of an actually existing chemical facility located between Cologne and Bonn (Germany).

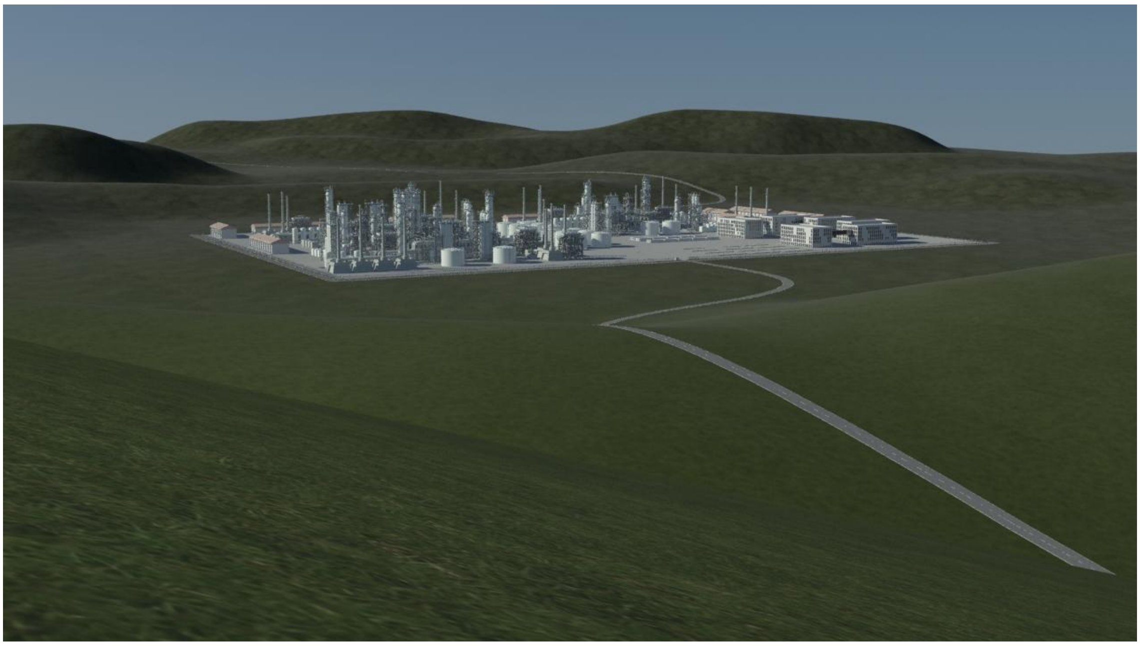

Figure 3 Aerial overview of CHEMCO chemical facility.

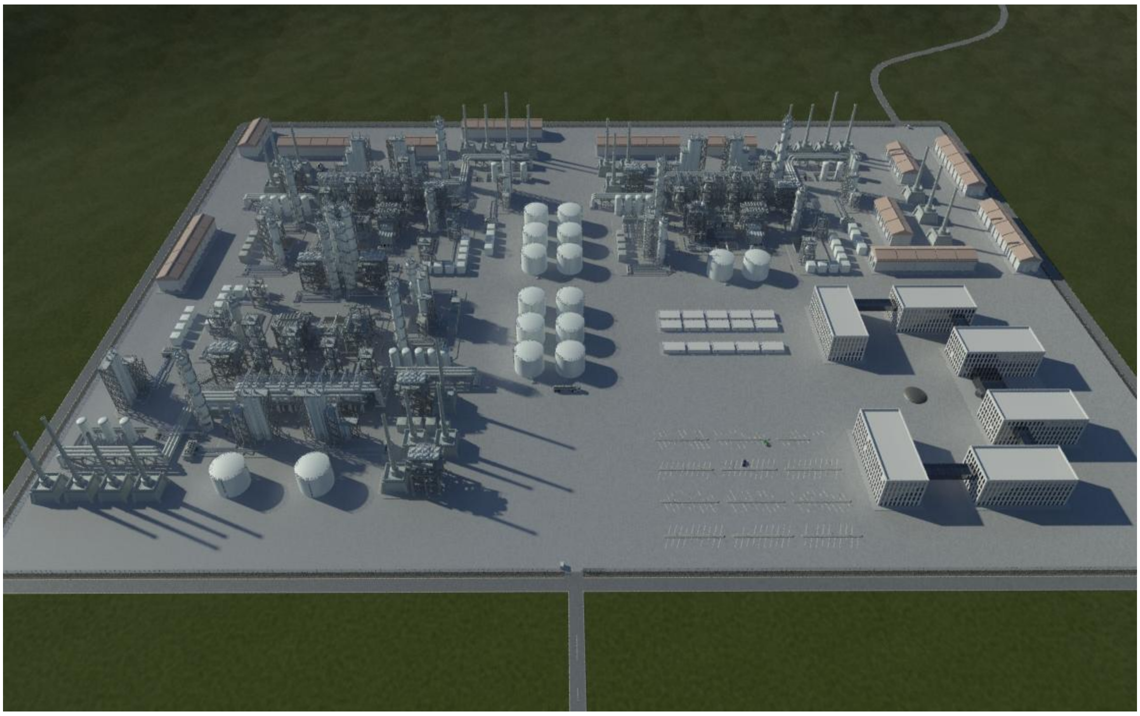

Figure 4 Bird-eye view of CHEMCO facility.

Figure 5 Perimeter fence of CHEMCO facility.

Figure 6 Administration at CHEMCO facility.

Figure 7 Parking lot at CHEMCO facility.

Figure 8 View of production site at CHEMCO facility.

Figure 9 View of production site at CHEMCO facility.

Figure 10 View of production site at CHEMCO facility.

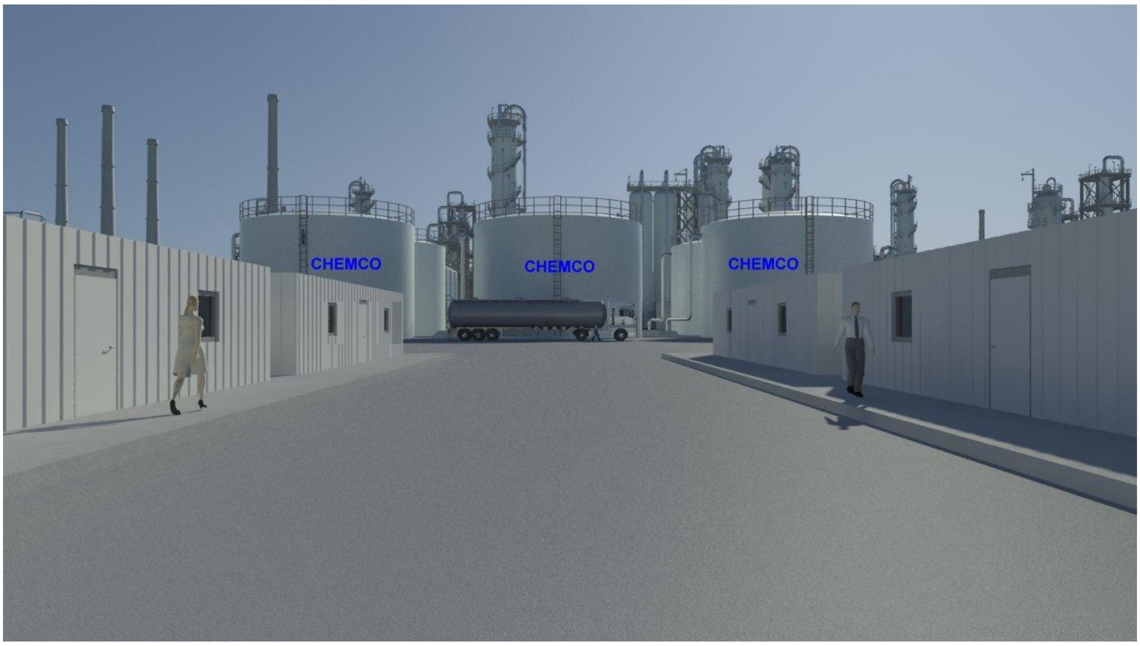

Figure 11 Laboratories at CHEMCO facility.

Figure 12 View of production site at CHEMCO facility.

Figure 13 View of production site at CHEMCO facility.

Figure 14 View of production site at CHEMCO facility.

Figure 15 View of production site at CHEMCO facility.

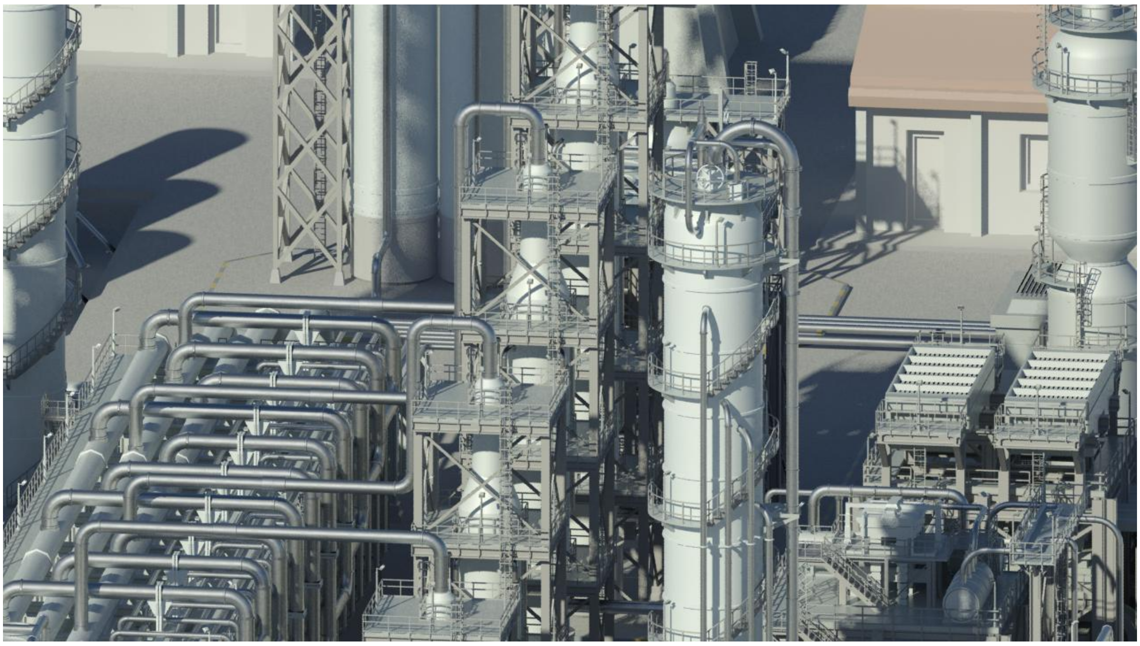

Figure 16 View of production site at CHEMCO facility.

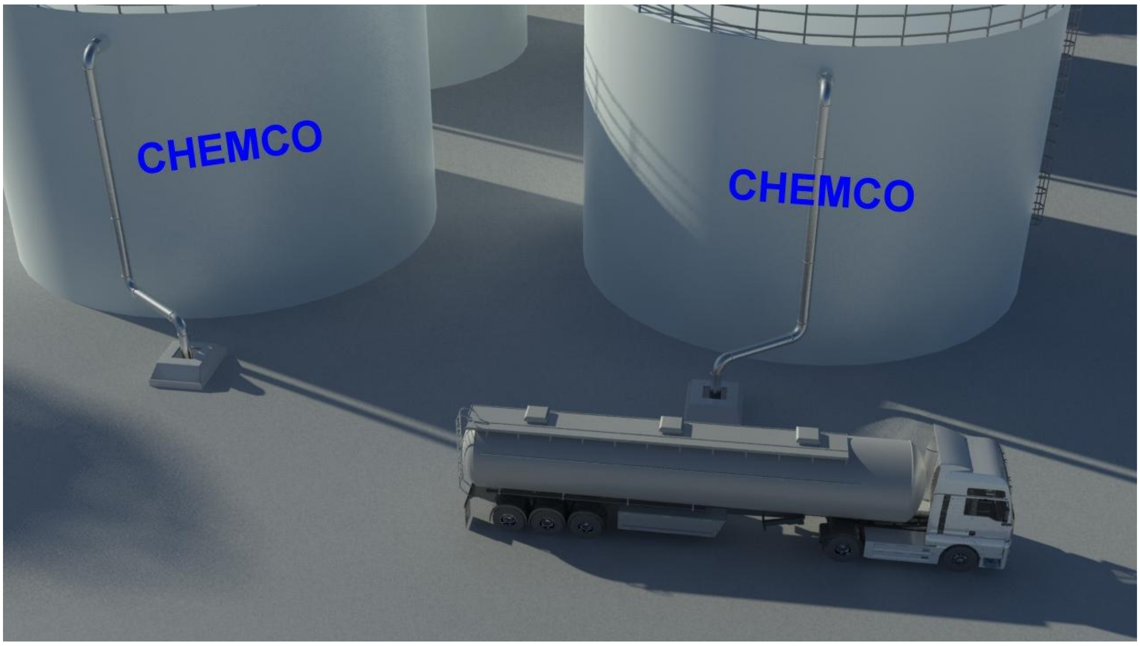

Figure 17 Petrol-filled tanker lorry adjacent to dichloroethane tanks.

Figure 18 Petrol-filled tanker lorry adjacent to dichloroethane tanks.

4.2 On-site Damages at CHEMCO Facility

Figures 19 to 28 show different views of the *CHEMCO* facility shortly after the incident.

Figure 19 Initial detonation.

Figure 20 Expansion of primary explosion.

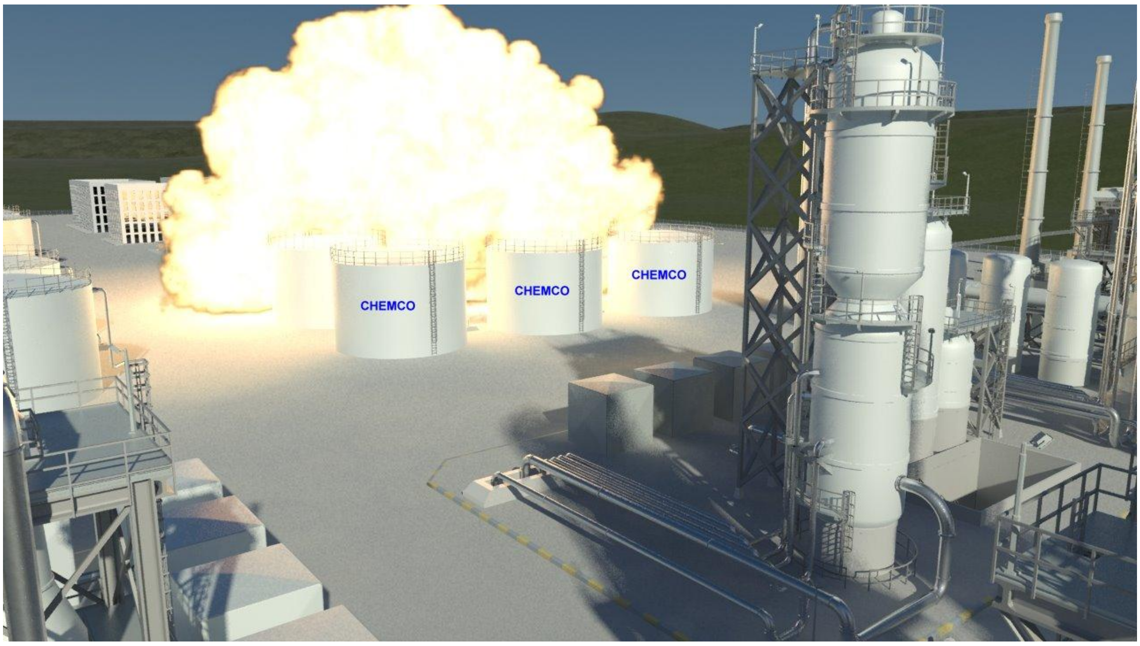

Figure 21 Expansion of primary explosion.

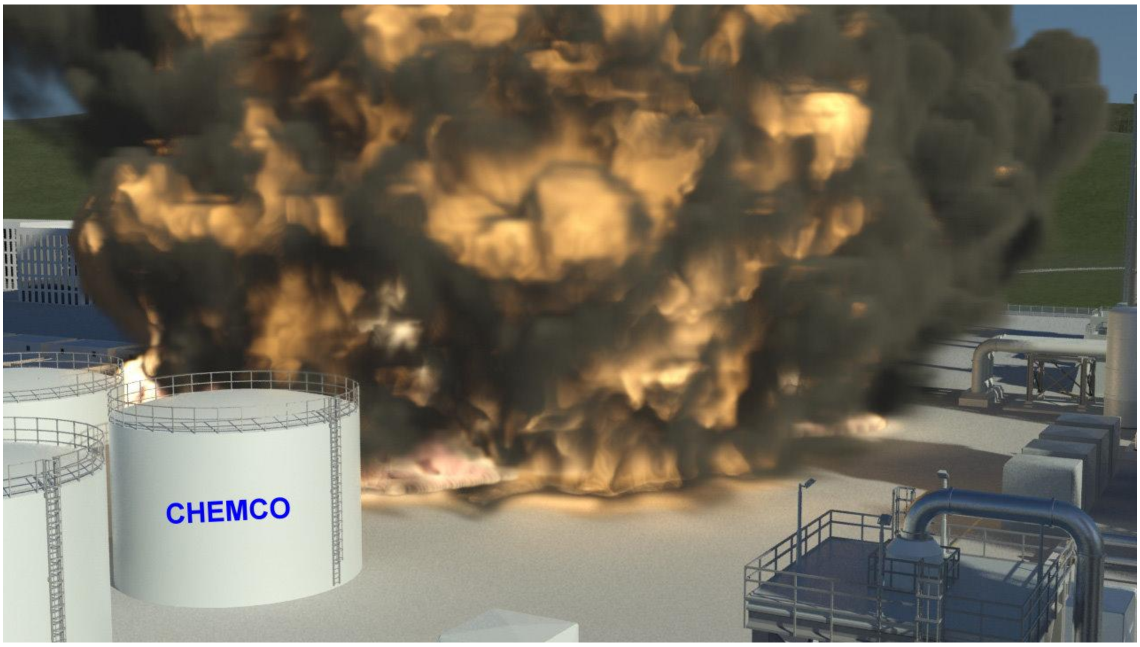

Figure 22 Expansion of secondary explosion.

Figure 23 Fire engulfing tanks.

Figure 24 Expansion of smoke.

Figure 25 Expansion of fire and smoke.

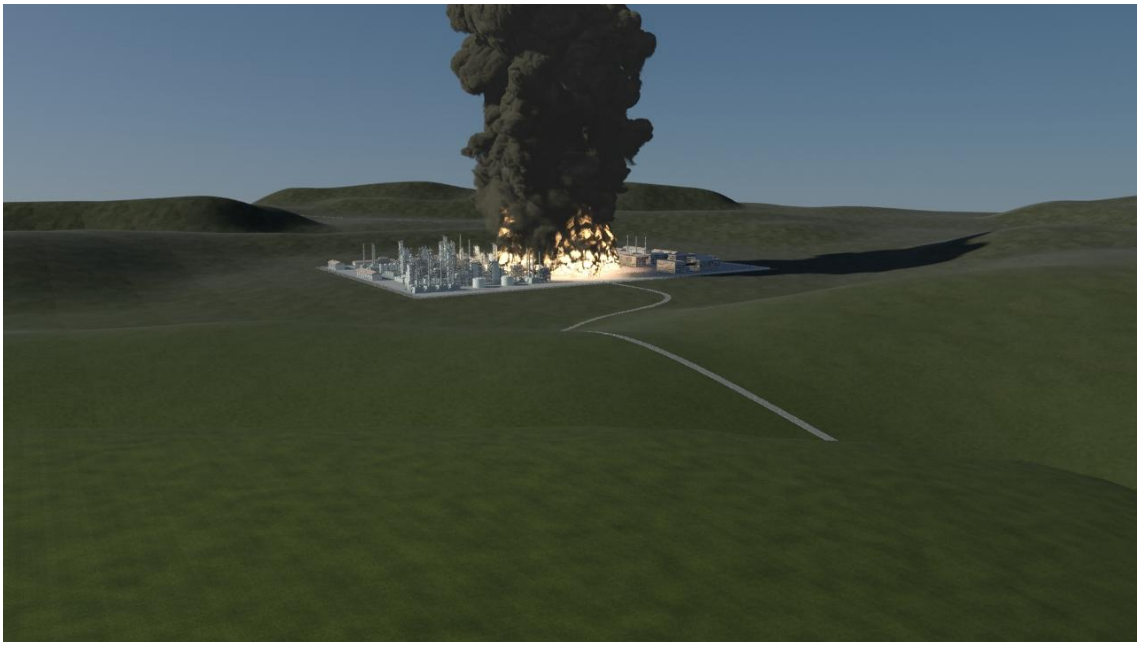

Figure 26 Arial view facility and toxic cloud.

Figure 27 Rise of toxic cloud.

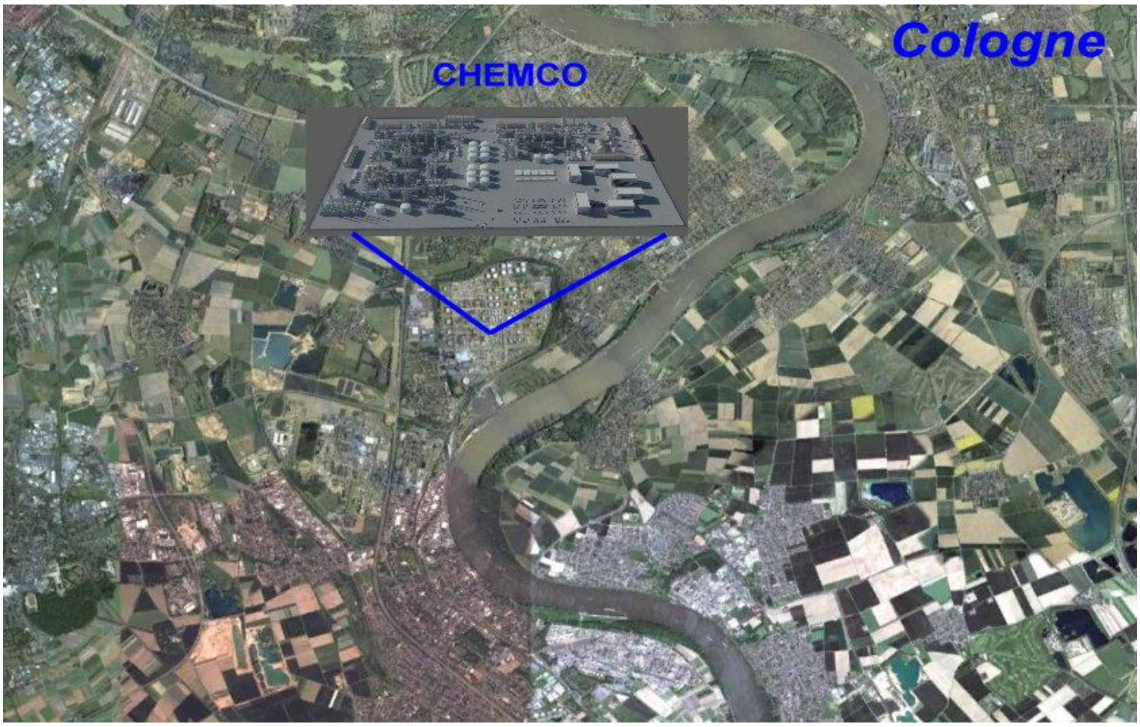

Figure 28 Assumed location of CHEMCO facility.

5 Results for Incident-based Modelling of EU Critical Infrastructure

In addition to modelling the CHEMCO facility, Work Package 3 also engaged in the modelling of generic examples of EU *Critical Infrastructure* (CI). The sections below describe several examples of the EU critical infrastructure, which were modelled based on actually existing constructions and representing the common features of some of the most important of such CI system in the European Union. For each CI category modelled (power plant, financial centre, Liquefied Natural Gas terminal, railway station, subway station, airport) features of three important existing facilities were used as basic input parameters for the generic model development, using HEXDAM.

5.1 Power Plant

The scenario selected represents a major nuclear power plant in an EU Member State. Each nuclear power plant has a *vital area,* which is its most vulnerable location with regard to operational safety, if attacked from within (insider threat) or outside. Details of such potential attack scenarios are classified.[41] However, if a breach of reactor containment and/or physical damage to spent fuel pond is due to external causes, this will lead to inadequate cooling of the system and thereby to a major uncontrolled release of radioactivity into the environment. Concurrent hydrogen explosions will destroy the building housing nuclear component and are accompanied by the outbreak of multiple fires. Prevailing winds transport a radioactive cloud to neighboring EU Member States, which results in transboundary radioactive contamination of the environment. The nuclear power plant modeled represents a combination extracted from the following major EU nuclear power plants: Chooz (France), Isar (Germany), and Kosloduje (Bulgaria).

The **Chooz Nuclear Power Station** (French: *Centrale nucléaire de Chooz*) lies in the municipality of Chooz in the Ardennes department, France, on the Meuse in a panhandle protruding into Belgium, between the French city of Charleville-Mézières and the Belgian municipality of Dinant. The first reactor Chooz A, an early PWR design, was shut down in 1991 after an operational life of 22 years. Two units of the N4 reactor design are currently operation, Chooz B1 and Chooz B2. Designed for a net power output of 1450 MWe, power was uprated to 1500 MWe in 2003.A fourth nuclear reactor, of the EPR type, is under study by EDF.[42]

The **Isar Nuclear Power Station** (German: *Kernkraftwerk Isar*) lies in the municipality of Essenbach in the department of Bavaria in Germany. Block 1 was closed in 2011 after the Fukushima accident, but the newer Block 2 (first critical in 1988) will be active until 2022.[43]

The **Kozloduy Nuclear Power Plant** (Bulgarian: KKW Kosloduj) is a nuclear power plant in Bulgaria situated 200 kilometres north of Sofia and 5 km east of Kozloduy, a town on the

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[41] EU Project Grant Agreement No. 218070, COMPARATIVE ASSESSMENT OF SECURITY-CENTERED TRAINING CURRICULA FOR FIRST RESPONDERS ON DISASTER MANAGEMENT IN THE EU (CAST), Deliverable 3.5 *Catastrophic Terrorism* (EU classified).

[42] EDF (France), Chooz: Le site de Chooz est situé dans une petite enclave française des Ardennes belges (Chooz Nuclear Power Station Official Website). URL: http://prestataires-nucleaire.edf.com/edf-fr-accueil/prestataires-du-nucleaire-edf/centrales-nucleaires/chooz-54050.html Last accessed 10 December 2011.

[43] E-ON (Germany), Kernkraftwerk Isar: Hintergrund-informationen (Isar Nuclear Power Station Official Website). URL: http://www.eon-kernkraft.com/pages/ekk_de/Standorte/Isar/index.htm Last accessed 10 December 2011.

Danube river, near the border with Romania. It is the country's only nuclear power plant and the largest in the region. The construction of the first reactor began on 6 April 1970. Kozloduy NPP currently manages two pressurized water reactors with a total output of 2000 MWe. **Units 5 and 6**, constructed in 1987 and 1991 respectively, are VVER-1000 reactors. By 2014 they will be upgraded to reach a capacity of 1100 MWe each.[44]

Description of scenario: A group of terrorists breaks through the security perimeter surrounding a nuclear power plant (NPP) and attacks the side wall of a spent-fuel-pool (250 kg TNT-equivalent assumed – symbolized as orange cube in Figure 29).

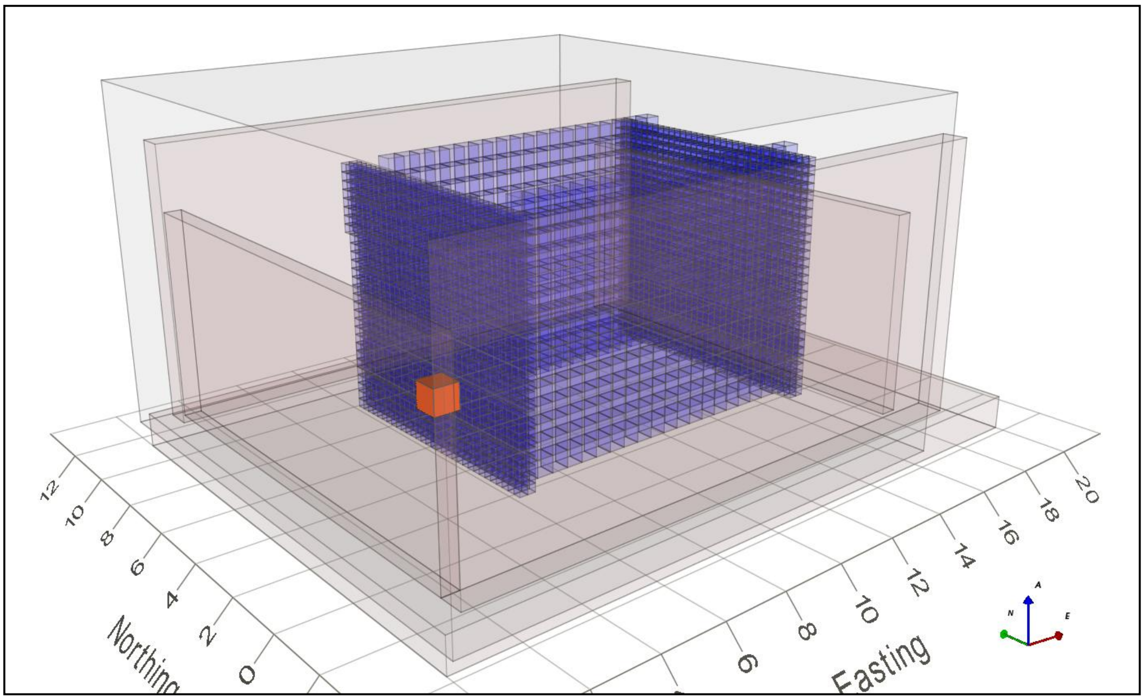

Figure 29 Transparent view of spent-fuel-pool with symbolized blast charge.

Results: The explosive load of 250 kg is sufficient for the complete destruction of the pool, as can be seen in Figure 30 below (blast wave destroys wall completely reaching even the opposite wall of the pool).

[44] "АЕЦ Козлодуй" ЕАД (Bulgaria), Kozloduy Nuclear Power Plant Official Website. URL: http://www.kznpp.org/. Last accessed 10 December 2011

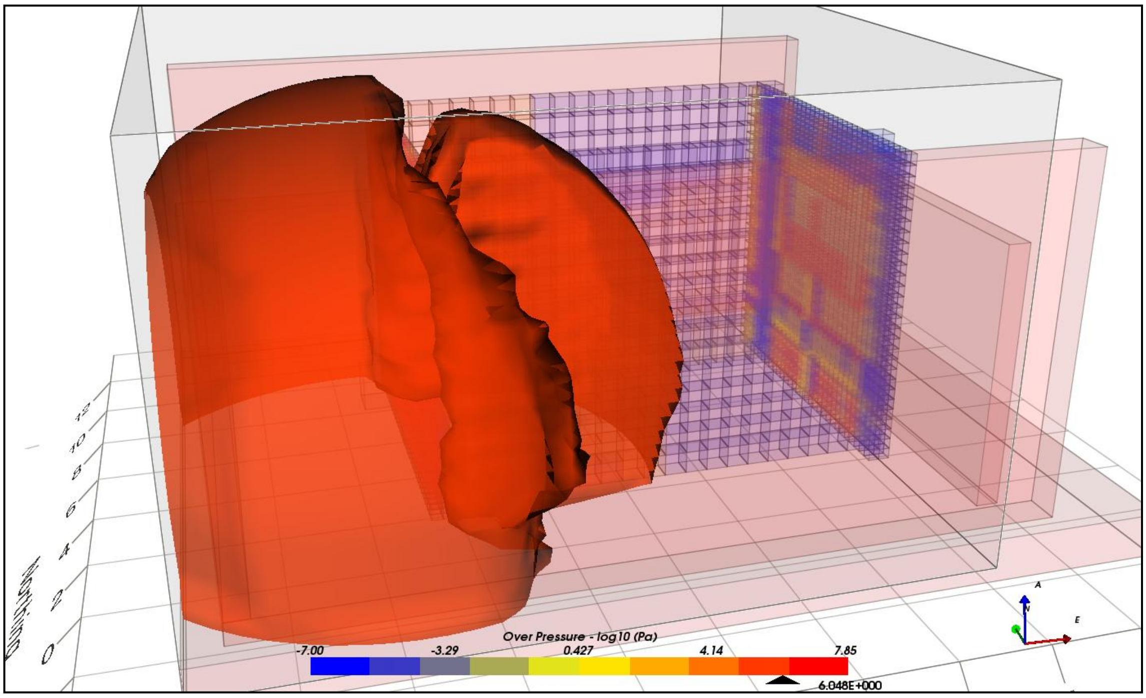

Figure 30 Blast wave destroying side wall.

5.2 Financial Centre

The scenario selected represents an important financial centre in an EU Member State. A financial centre functions as the hub for major financial transactions at the national and international level. Losing the operational integrity of such a hub, e.g., due to a truck bomb, will have significant consequences on the economic and political stability of large areas. [45]

The financial centre modeled represents a combination extracted from major buildings of the most important EU financial centers in Paris, Madrid and London.[46]

Description of scenario: A large truck bomb (5000 kg TNT-equivalent assumed) is positioned in the underground garage of a major financial center. Figure 31 shows the steel skeleton of the building as the main load bearing structure.

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[45] On 10 April 1992 an IRA truck bomb in London's financial district killed three and causes hundreds of millions of pounds worth in damage. On April 24 1992 another IRA truck bomb in London's financial district killed one and caused heavy damage again. URL: http://www.guardian.co.uk/uk/2005/jul/07/terrorism.july73. Last accessed 15 December 2011

[46] Information was obtained from following architectural databases extracting information from different kind of major building structures presented in http://en.structurae.de/ and http://www.seaint.org/. Last accessed 12 December 2011

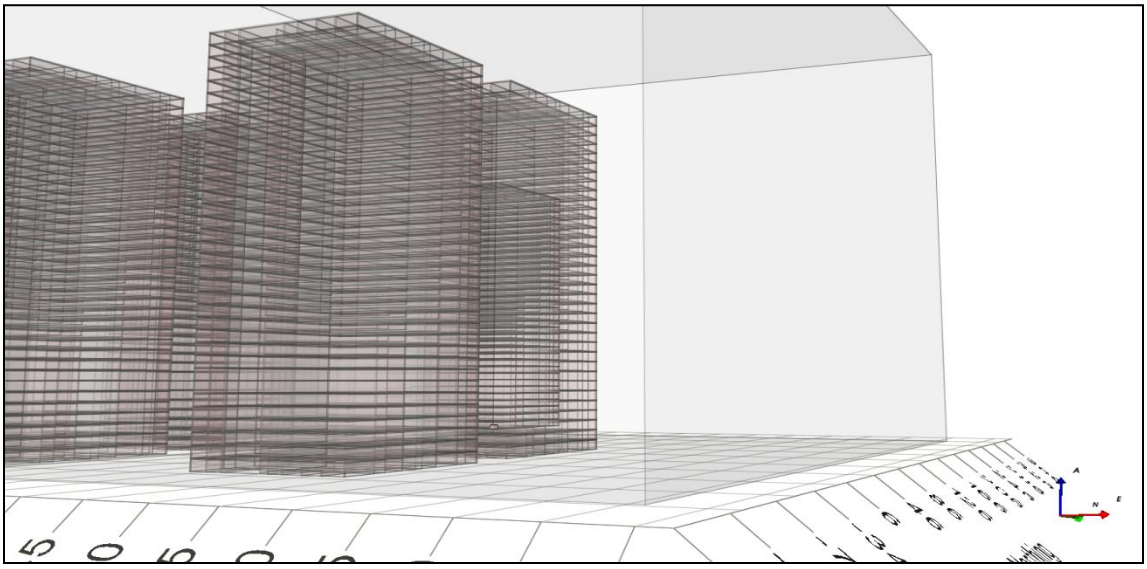

Figure 31 Steel structure of modern financial centres (simplified).

Results: The whole financial center will collapse due to the complete destruction of the skeleton in the lower 7-10 structural levels, resulting in an estimated death rate of thousands (depending on the time of detonation), not counting seriously people nearby. In Figure 32, the upper part of the building is depicted as undamaged by the explosive yield, however, the total damage of the lower section leads to a collapse of the upper part. Other buildings in the vicinity will remain standing, but the blast wave is still strong enough to destroy a great amount of windows in the blocks nearby and injure people standing in the streets up to a distance of more than 500m (not shown in Figure 32).

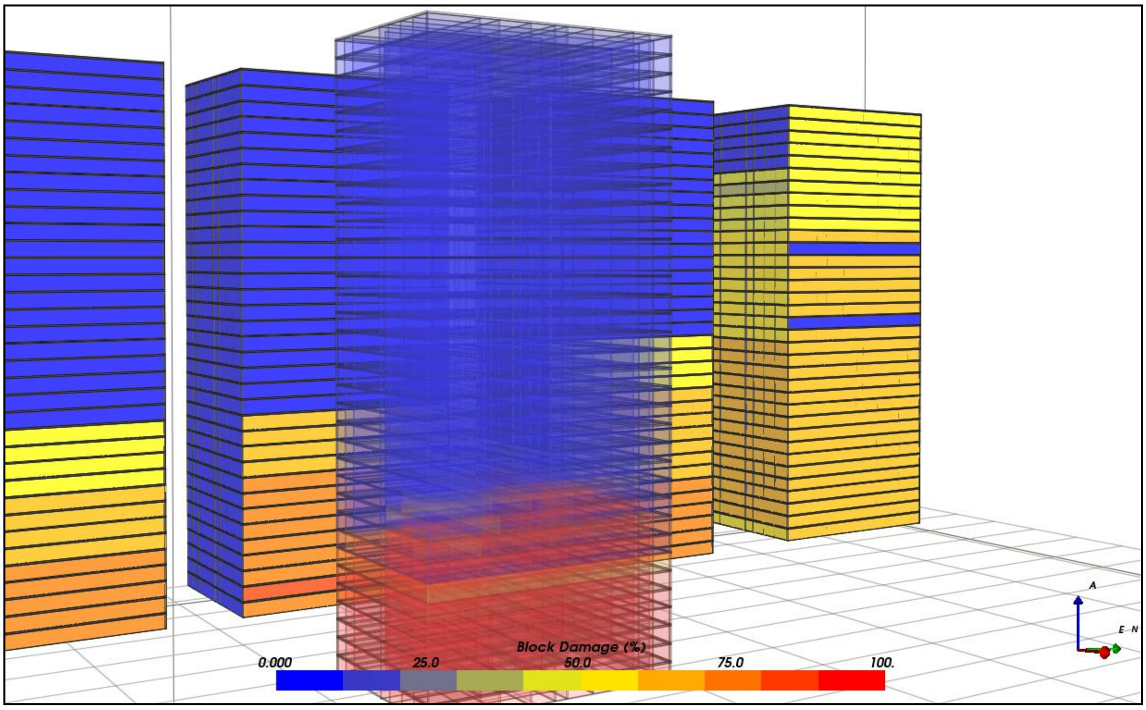

Figure 32 Blast damage on the centres (red colour represents complete destruction).

5.3 Liquefied Natural Gas Terminal

The scenario selected represents an important Liquefied Natural Gas (LNG) Terminal in an EU Member State. An explosion at such a terminal or an external fire near several storage LNG vessels causes heating of the contents and pressure build-up. Since there is constant heating, the metal weakens and eventually fails. Once the liquid is heated above its boiling point, the vessels containing the pressurized liquid rupture and results in a BLEVE (*boiling liquid expanding vapor explosion*). The flammable substance, that the resulting cloud of the substance will ignite after the BLEVE has occurred, forms a fireball and possibly a fuel-air explosion (*vapor cloud explosion*). Domino effects are likely due to multiple potential causes.[47]

The LNG Terminal modelled represents a combination extracted from the following major EU LNG-installations: Bilbao (Spain), Rotterdam (Netherlands) and South-Hook-LNG (United Kingdom).[48]

Description of scenario: A large LNG-tanker explodes while being unloaded in a harbour near an administrative centre (explosive yield: 5000 t of TNT-equivalent). In this scenario the tanker is anchored at a distance of 500-1000 m from the buildings.

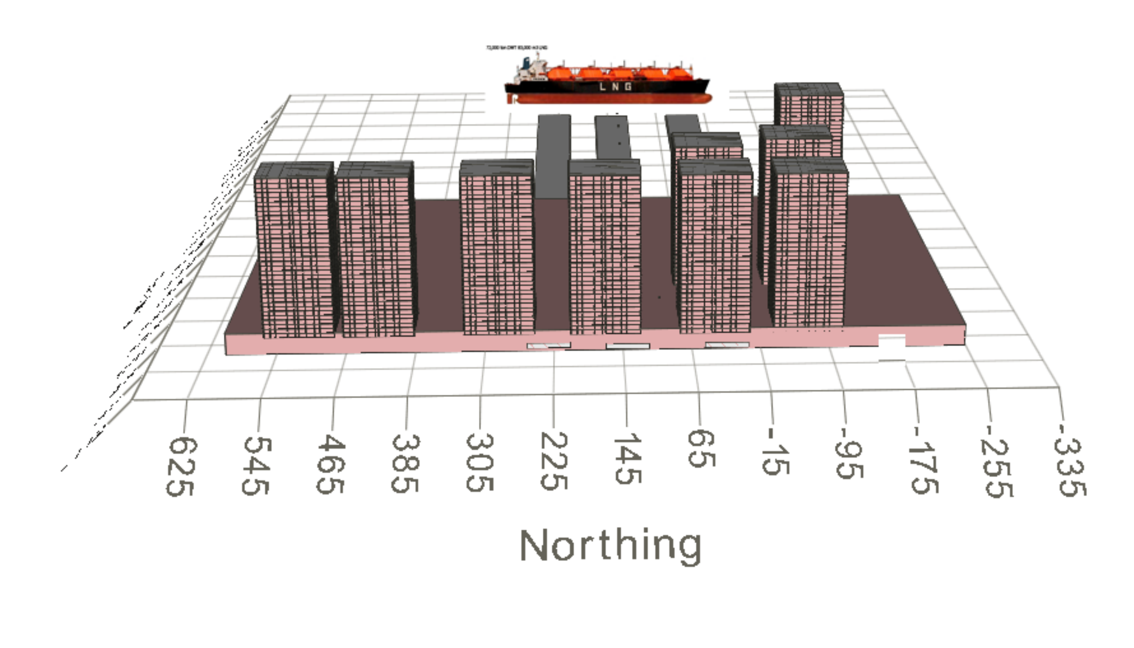

Figure 33 Simplified LNG-terminal adjacent to a large business centre.

[52] In case of an offshore LNG tanker accident near an inhabited US coast, up to 70 000 casualties are to be expected (The California Energy Commission, *Liquefied Natural Gas in California: History, Risks and Siting*; July 2003).

[48] Information of LNG terminals and LNG tankers was obtained using following websites (model does not represent a specific LNG-terminal in existence, but consists of a realistic combination from assumptions based on the given information): http://en.wikipedia.org/wiki/Liquefied_natural_gas
http://www-static.shell.com/static/media/downloads/speeches/lcook_speech_oilandmoneyconf.pdf
http://en.wikipedia.org/wiki/List_of_LNG_terminals
http://www.shipbuildinghistory.com/today/highvalueships/lngactivefleet.htm
http://www.eia.gov/oiaf/analysispaper/global/lngmarket.html
http://www.our-energy.com/liquefied_natural_gas_lng.html Last accessed 12 December 2011.

Results: There are no survivors inside a radius of more than 1000 m if not protected by very massive structures. As can be seen in Figure 34 the resulting blast wave is significantly weakened by the steel structures of the buildings, but nevertheless the chance of survival inside the buildings is low and equals zero outdoors up to a distance of 2000 m.

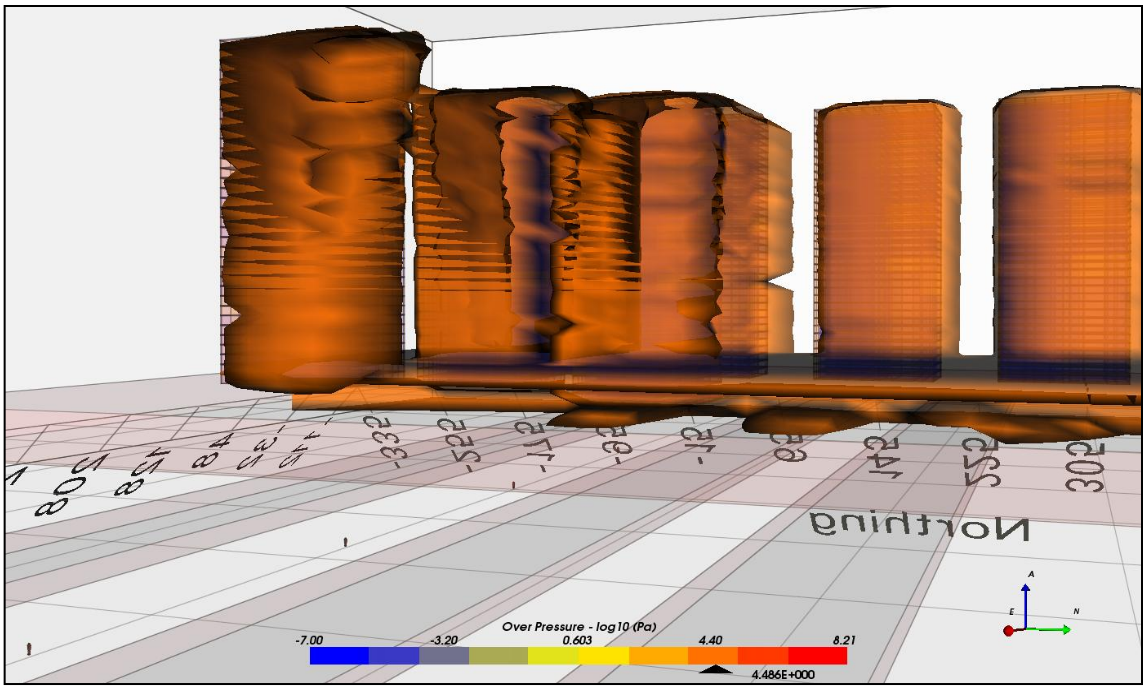

Figure 34 Blast wave of pressure wave impacting on buildings.

5.4 Railway Station

The scenario selected represents a railway station in the capital city of an EU Member State. Typically such a station is crowded with departing and arriving passengers for about 24 hours a day. Often such stations are also part of a larger complex, housing shops and offices. A coordinated attack series either by suicide bombers, wearing an explosive belt or carrying a bomb in bag or suitcase, or terrorists covertly placing improvised explosive devices (IEDs) at several locations in the station, can inflict mass casualties. Similar impact on the railway station would be due the timed detonation of explosives on several of the arriving trains.[49]

The density of the crowd in a big arrival hall of a major railway station was calculated from pictures taken in railway stations in Munich, Berlin and Paris (resulting in an optimal target for a suicide bomber, carrying only a small amount of explosives).

Munich Central Station (*München Hauptbahnhof*) is the main railway station of the city of Munich in Germany. It is one of the three long distance train stations in Munich. The station serves about 350000 passengers a day, which puts it on par with other large stations in

[49]On 26 November 2008, two terrorists entered the passenger hall of the Chhatrapati Shivaji Terminus – a historic railway station in Mumbai, – opened fire and threw grenades at people. Armed with AK-47, the terrorists killed 58 and injured 104 people. *The Economic Times* (India), 17 June 2009.

Germany, such as Hamburg and Frankfurt (Main) Hbf. The mainline station is a terminal station, the subterranean S-Bahn and U-Bahn stations are transit-stations.[50]

Berlin Central Station (*Berlin Hauptbahnhof*), is the main railway station in Berlin, Germany. The station is classified as a Category 1 station, one of twenty in Germany. The station serves about 300000 passengers a day.[51]

Paris Est (*Gare de l'Est*) is one of the six large SNCF termini in Paris. It is one of the largest and the oldest railway stations in Paris, the western terminus of the Paris–Strasbourg railway and the Paris–Mulhouse railway.[52]

Description of scenario: A suitcase bomb is brought to a crowded central hall of a major train station. The bomb is placed centrally between groups of waiting people. The structure of the hall will not suffer much damage, despite of some broken windows, but the number of injured and dead will be significant.

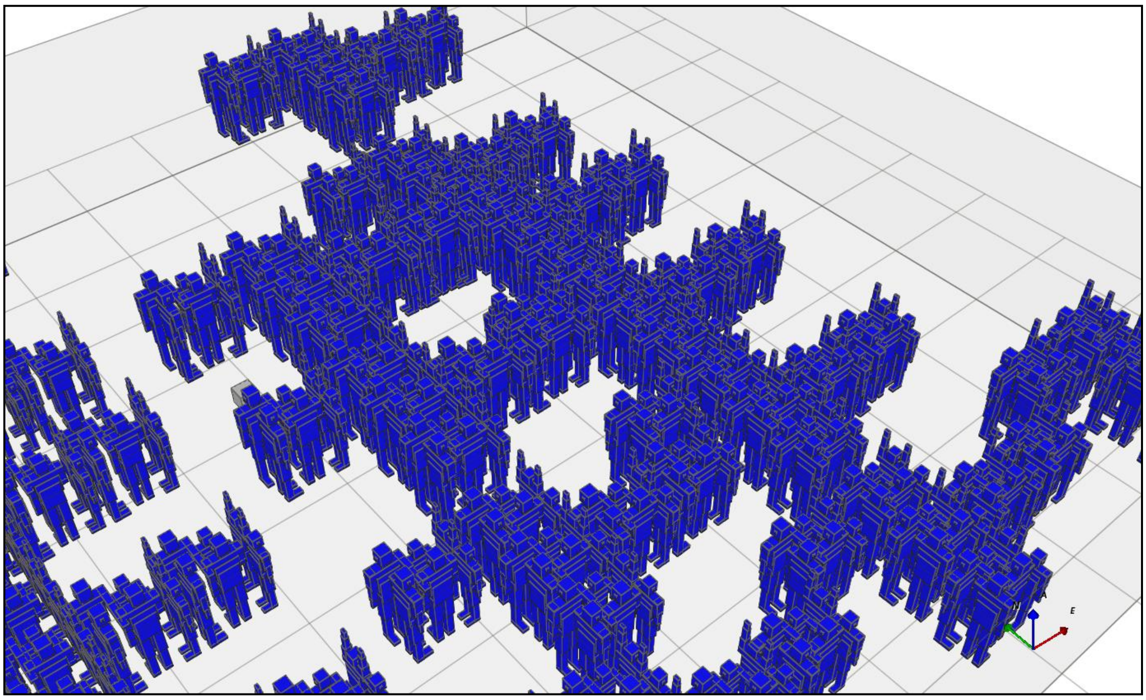

Figure 35 Crowded situation on a railway station hall.

Results: Due to the crowded situation a large number of dead an injured people can be anticipated, even from a “small” bomb load of the assumed 15 kg of explosives. All kind of injuries will occur simultaneously, followed by panic, which itself will result in further

[50] Basic information of the railway station and approximate hall-sizes (dimension of central hall is far too big for affecting blast waves in this model, so exact dimension are not necessary) obtained from http://en.wikipedia.org/wiki/München_Hauptbahnhof. Last accessed 25 November 2011.
[51] http://www.bahnhof.de/site/bahnhoefe/de/ost/berlin__hauptbahnhof/berlin__hauptbahnhof.html. http://en.wikipedia.org/wiki/Berlin_Hauptbahnhof. Last accessed 25 November 2011.
[52] http://en.wikipedia.org/wiki/http://en.wikipedia.org/wiki/Gare_de_lEst. Last accessed 25 November 2011.

difficulties for all first responders involved. A large amount of different injuries can be seen in the blast-related-effects seen in Figure 36.

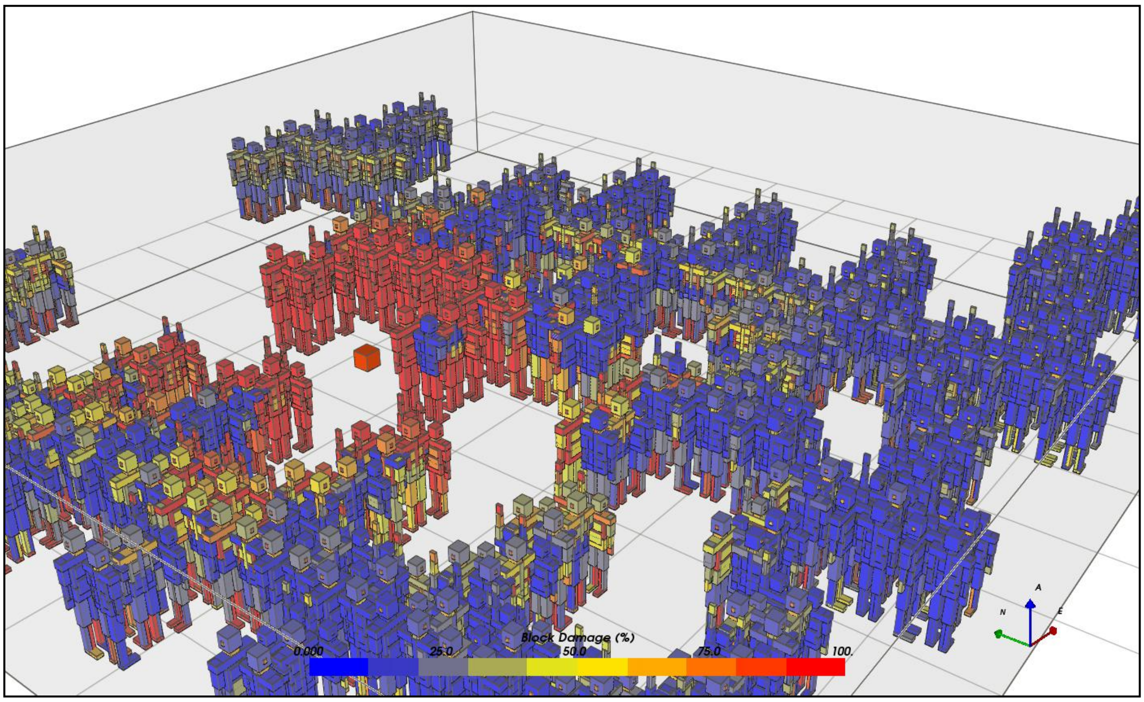

Figure 36 Injured body parts after suitcase bomb explosion (15 kg TNT-equivalent).

5.5 Subway Station

The scenario selected represents an underground metro-station in the capital city of an EU Member State. Typically the platform of such a station is crowded with departing and arriving passengers for about 20 hours a day. Often such stations are also part of a larger complex, housing shops and offices. A coordinated attack series either by suicide bombers, wearing an explosive belt or carrying a bomb in bag or suitcase, or terrorists covertly placing IEDs at several stations, can inflict mass casualties.[53]

The subway station modelled represents a combination extracted from existing subway systems of Paris, Vienna and London.

The **Paris Métro** or **Métropolitain** (*Métro de Paris*) is the rapid transit metro system in Paris, France. The network's sixteen lines are mostly underground and run to 214 km in length. There are 301 stations (384 stops), of which 62 facilitate transfer to another line.[54]

[53] On 7 July 2005 three bombs were detonated onboard London Underground trains within fifty seconds of each other. Including the attack on the bus, altogether fifty-six people, including the four suicide bombers, were killed by the attacks and about 700 were injured. See BBC News, "List of the bomb blast victims," 20 July 2005, URL: http://news.bbc.co.uk/2/hi/uk_news/4668245.stm Last accessed: 15 December 2011.

[54] Large subway systems have more than 100 stations of many different dimensions and passenger numbers, depending on date and time. So a wide range of destruction and number of casualties may occur making a comprehensive adaption of the model essential. Basic information obtained from http://en.wikipedia.org/wiki/Paris_Metro Last accessed 21 November 2011.

The **Vienna Metro (***U-Bahn***)** is a rapid transit metro system consisting of five lines. More than 1.3 million passengers use the Vienna U-Bahn every day.[55]

The **London Underground** (*The Tube* or *The Underground*) is a rapid transit system serving a large part of Greater London and some parts of Buckinghamshire, Hertfordshire and Essex in England. It is the oldest underground railway in the world, the first section of which opened in 1863 on what are now the Circle & Hammersmith & City lines and part of the Metropolitan line.[56]

Description of scenario: A suitcase bomb is brought into a typical underground station (intentionally a smaller station was modelled, without too much airspace available, for creating a different situation as in Section 5.4). The bomb is placed centrally but only a few persons are waiting for the train. Due to the enclosed situation the resulting blast wave differs from scenario shown in Figure 36.

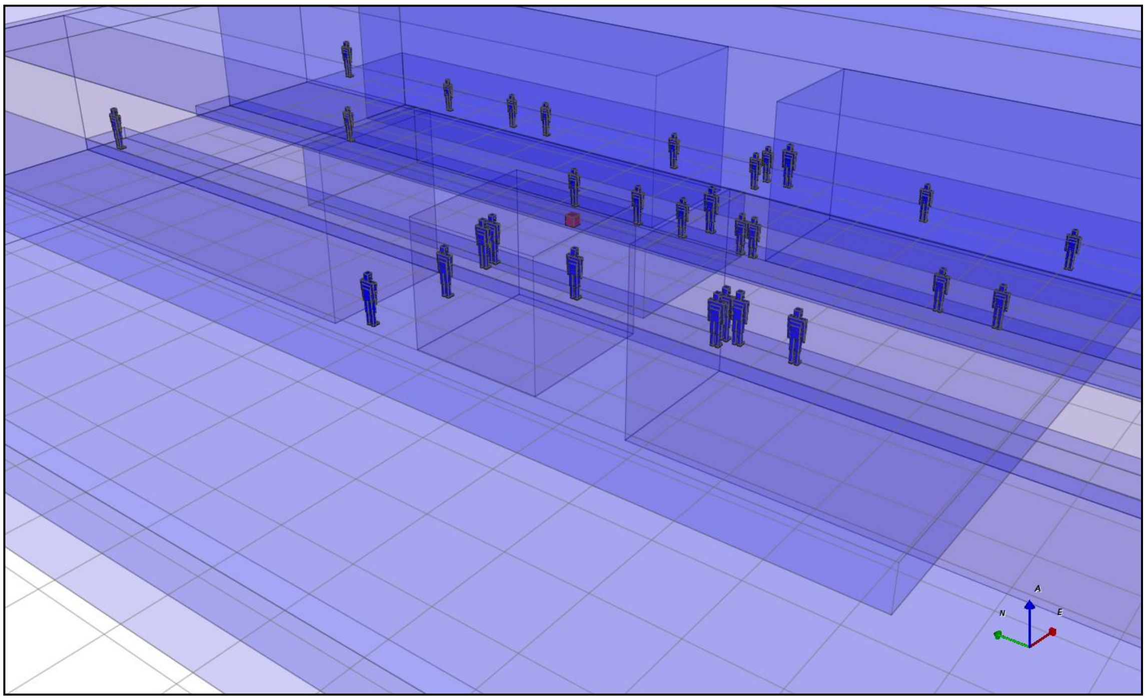

Figure 37 Model of a small underground station.

Results: Due to the enclosed situation the resulting blast waves (see Figure 38) differ significantly from the one in large halls (e.g., at airport and major train station) due to reflections on surrounding walls, resulting in more severe injuries on people (even on those people standing quite far away).

[55] Basic information obtained from http://en.wikipedia.org/wiki/Vienna_Subway. Last accessed 21 November 2011.
[56] Basic information obtained from http://en.wikipedia.org/wiki/London_Tube. Last accessed 21 November 2011.

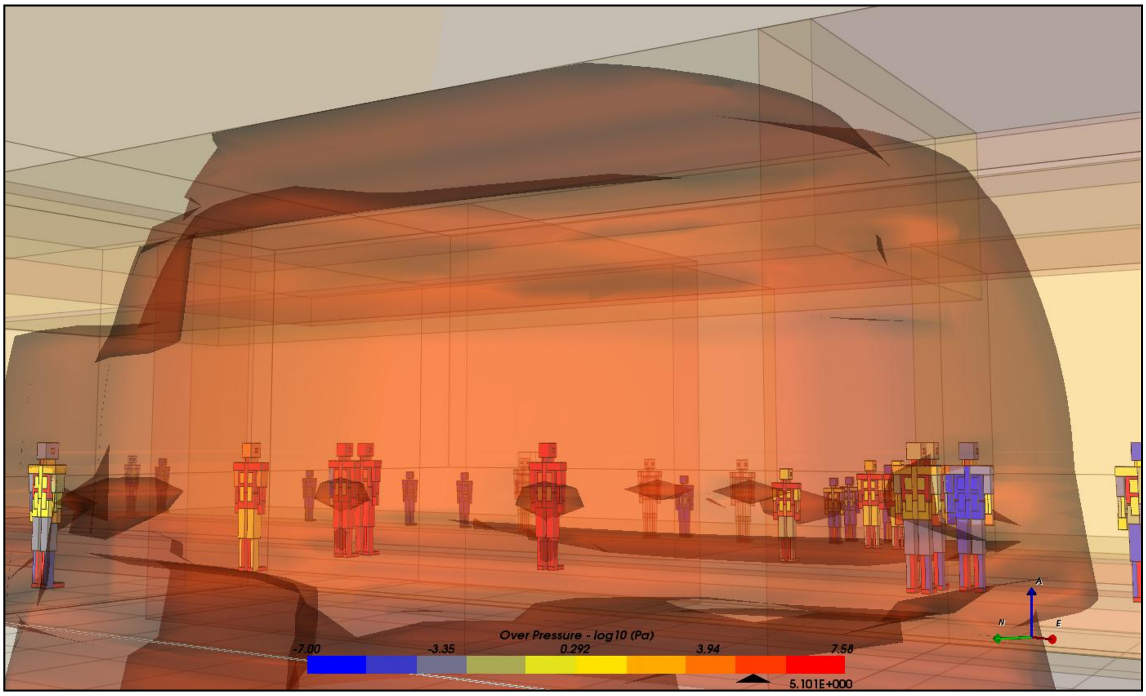

Figure 38 Blast wave and resulting injuries inside the underground train station.

5.6 Airport

The scenario selected represents the departure hall of an international airport in an EU Member State. Due to the high population density (e.g., at check in counters), a terrorist attack can result in a large number of victims. Furthermore, the predominantly concrete construction with large glass panels makes this section of an airport building particularly vulnerable to explosions. Since there are basically no security- or luggage controls in the departure area, this sector of any EU airport is at elevated risk for a terror attack. This is particularly the case for a suicide bomber pretending to queue at a check-in counter. Similarly, an attack with a car bomb crashing into the building through the glass façade has a high probability of success.[57]

The airport departure hall modeled represents a combination extracted from structures (either existing or planned) of five major EU airports described below.[58]

[57] On 30 June 2007 a four-wheel drive vehicle, loaded with propane gas cylinders, attempted to break through the glass doors of the Terminal at Glasgow Airport. See BBC News, "Blazing car crashes into airport," 30 June 2007, URL: http://news.bbc.co.uk/2/hi/6257194.stm. Last accessed 15 December 2011.

[58] Modern departure halls on major airports are mostly constructed without load bearing structures inside for economical reasons, so major blast waves are not deflected by massive structures. Basic information obtained from Wikipedia sites, some details like used materials from homepages of the airports themselves (last accessed on 5 December 2011):
http://en.wikipedia.org/wiki/London_Heathrow_Airport
http://www.heathrowairport.com/
http://en.wikipedia.org/wiki/Paris-Charles_de_Gaulle_Airport
http://www.aeroportsdeparis.fr/ADP/en-gb/passagers/home/
http://en.wikipedia.org/wiki/Leonardo_da_Vinci-Fiumicino_Airport
http://www.airport-technology.com/projects/leonardodavinci

London Heathrow Airport or **Heathrow** (IATA: **LHR**, ICAO: **EGLL**), in the London Borough of Hillingdon, is the busiest airport in the United Kingdom and the third busiest airport in the world (as of 2011) in terms of total passenger traffic, handling more international passengers than any other airport around the globe. It is also the busiest airport in the EU by passenger traffic and the third busiest in Europe given the number of traffic movements, with a figure surpassed only by Paris-Charles de Gaulle Airport and Frankfurt Airport.

Paris-Charles de Gaulle Airport (IATA: **CDG**, ICAO: **LFPG**) (French: *Aéroport Paris-Charles de Gaulle*), also known as Roissy Airport (or just *Roissy* in French), in the Paris area, is one of the world's principal aviation centres, as well as France's largest airport. In 2010, the airport handled 58,164,612 passengers and 525,314 aircraft movements, making it the world's seventh busiest airport and Europe's second busiest airport (after London Heathrow) in passengers served. It also is the world's tenth busiest and Europe's busiest airport in aircraft movements. In cargo traffic, the airport is the fifth busiest in the world and the busiest in Europe, having handled 2,054,515 metric tonnes of cargo.

Leonardo da Vinci-Fiumicino Airport (Italian: *Aeroporto Leonardo da Vinci di Fiumicino*) (IATA: **FCO**, ICAO: **LIRF**), also commonly known as Fiumicino Airport, is Italy's largest airport with 36.3 million passengers served in 2010, located in Fiumicino. The airport, based on total passenger numbers, it was the sixth busiest airport in Europe, and the world's 29th busiest airport in 2011.

Munich Airport (IATA: **MUC**, ICAO: **EDDM**) (German: *Flughafen München*) Between 1995 and 2006, passenger numbers doubled from under 15 million per annum to over 30 million. Munich Airport is the second busiest airport in Germany in terms of passenger traffic behind Frankfurt Airport, and the seventh busiest airport in Europe, handling 34,721,605 passengers in 2010. It is the world's 30th busiest airport in terms of international passenger traffic, and was the 30th busiest airport in the world in 2009.

Madrid-Barajas Airport (Spanish: *Aeropuerto Internacional de Madrid-Barajas*) (IATA: **MAD**, ICAO: **LEMD**) is the main international airport serving Madrid in Spain. In 2010, over 49.8 million passengers used Madrid-Barajas, making it the country's largest and busiest airport, and in 2009 it was the world's 11th busiest airport and Europe's fourth busiest airport.

Description of scenario: A truck bomb (5 000kg TNT) is positioned between two airport departure halls (Figure 39). Since the lorry is situated outside the halls, it is likely to avoid controls via security-personal.

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http://www.rome-airport.info
http://en.wikipedia.org/wiki/Madrid-Barajas_Airport
http://www.aena-aeropuertos.es/csee/Satellite/Aeropuerto-Madrid-Barajas/en
http://www.rsh-p.com/render.aspx?siteID=1&navIDs=1,4,23,648
http://en.wikipedia.org/wiki/Munich_Airport
http://www.munich-airport.de/en/company/ausbau/index.jsp.

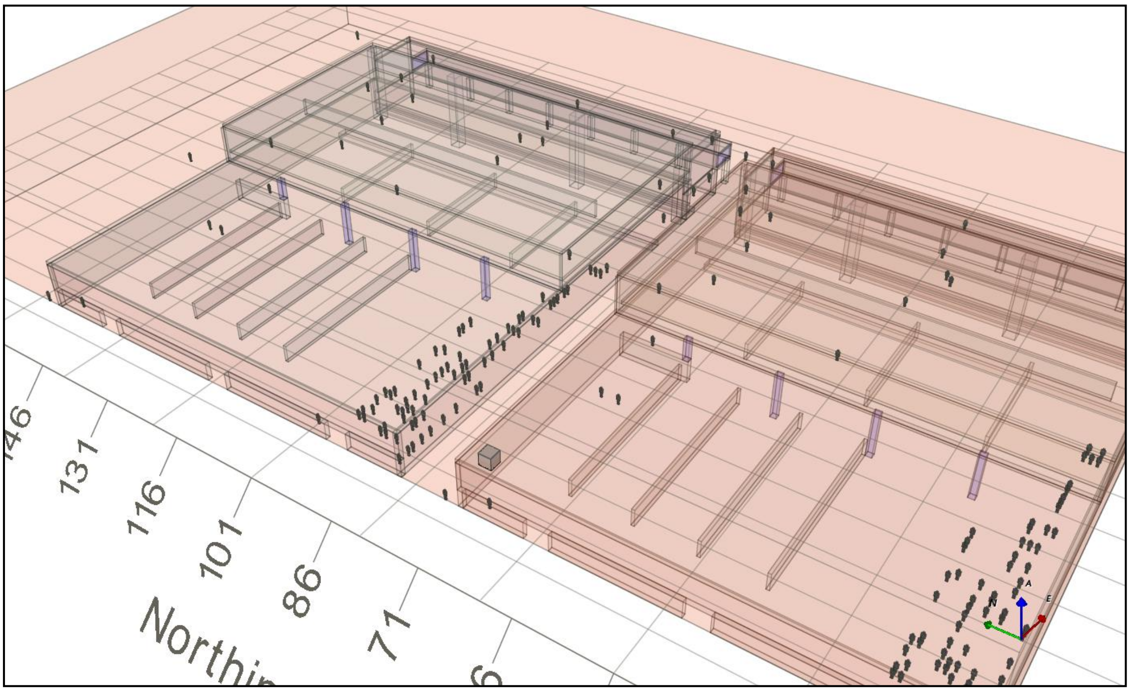

Figure 39 Two adjacent departure halls of a central airport.

Results: Both halls are destroyed completely resulting in a high number of deaths (actual number depending on the amount of persons inside both halls). Injured people will be found even hundreds of meters away from the center of explosion if not protected by shielding. Even thick hall-walls would not be able to reduce the power of the blast significantly. Figure 40 shows the extension of the blast wave depicting the limit of lethal pressure values, i.e., all people inside this zone have no chance of survival. People outside this zone may also have been killed via secondary effects, like collapsing of structures or shrapnel-effects.

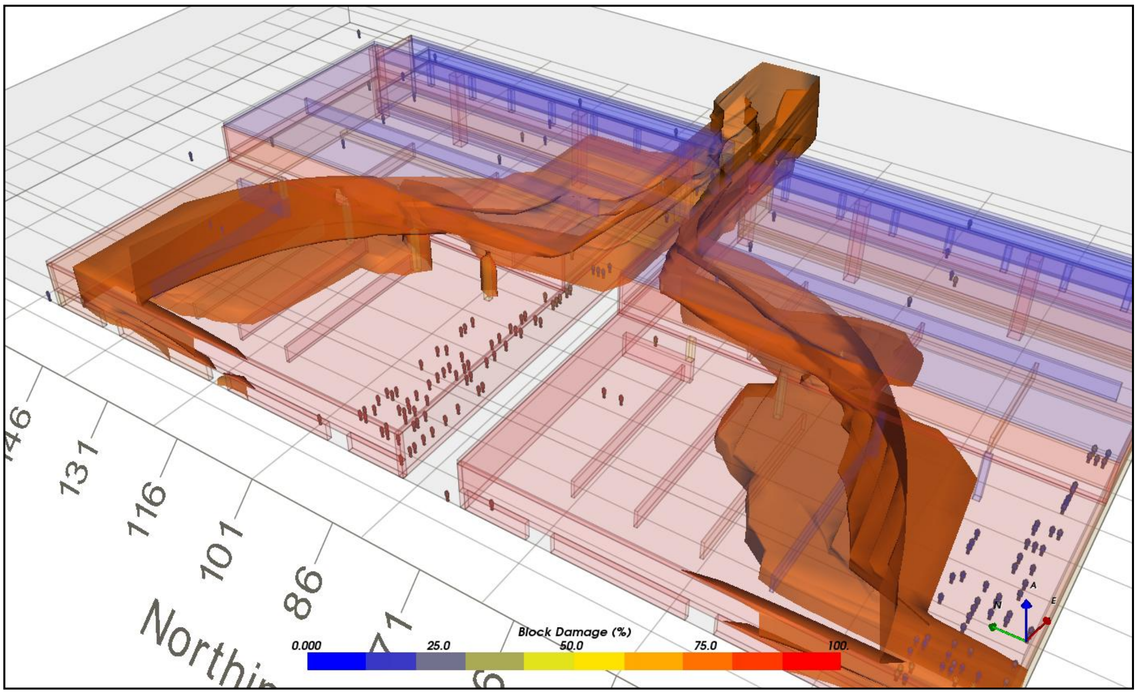

Figure 40 Expanding Pressure wave of the detonation.

6 Practical Application of Modelling for First Responders

BRIDGE 3D modelling software tool should serve foremost as a *training aid* for EU first responders. The BRIDGE 3D modelling tool will help emergency preparedness professionals and first responders to prepare and train for potential major incidents and disasters. Training is of key importance in mitigating damage that might arise from industrial accidents, terrorist attacks or natural disasters. Modelling will enhance the effectiveness of training while reducing the time and cost associated with preparing for, analyzing and responding to real or potential incidents.

Furthermore, modelling will assist in *enhancing situational awareness* during an actual incident. A 3D view of the damaged structures and their surrounding environment will give first responders a better understanding of the incident, its impact and potential development, thus improving their situational awareness. This, in turn, will lead to making better tactical and strategic decisions to save lives and mitigate damage.

Whether 3D modelling is applied for training of first responders, or by crisis managers to assist in decisions on scene, in either case it facilitates *risk assessment.* Thereby, 3D modelling supports first responders to regain control over the hazardous situation**.**

3D models used in training curricula facilitate the visualization of complex buildings and systems, the presentation of abstract hazards, and enable the trainees to share information with regard to location and terrain. It enables trainees to evaluate potentially catastrophic losses (structural damage to buildings, fatalities, injuries, and business interruption). It strengthens the capability of the trainee in collaborating with architects, emergency managers and security organizations on how to address and mitigate risks.

Also, the 3D-computer models developed in this project assist in improving the situation awareness on scene by filling the gap between the – frequently incoherent information produced by an event and the information needed for crisis management. Thereby, the models improve the ability of the emergency teams to respond to a catastrophic event in a more efficient manner and ensure a higher level of consistency of the interaction between different organisations responding to the catastrophic event. This is achieved by:

(a) *Speedy size-up:* Faster perception of the hazardous situation
(b) *Integrated risk assessment:* Contributing to the comprehension of all potential hazards involved
(c) *Forecast capability:* Projection of the current status into the future in order to regain control over the situation, particularly in disasters with extremely high dynamics or long-duration disasters.

Provided sufficient time is available (typically 15 to 30 minutes), the involvement of an advisor trained in computer-modelling and access to live meteorological data is foreseen, an incident commander is able to take the following actions based on the first modelling results on scene:

- Adjustment of the *Hot Zone*;
- Adjustment of acute countermeasures, particularly during the first 30 minutes;
- More accurate decisions on people on site potentially at risk;
- Increased precision in the forecast of population groups and areas threatened by contamination;
- Adaptation of the countermeasures in view of rapidly changing meteorological conditions and/or material properties;
- Control of the effectiveness of countermeasures;

- Comparison of the results of measurement with the result of the analysis of the effects as well as the material data and critical values from dedicated reference sources;
- Increase accuracy in the determination of the affected area and the effect of countermeasures on areas likely to be affected in the short-, mid- and long-term, jointly with other authorities where necessary (re-directing traffic, closing off public transport, taking production facilities out of service, evacuating property);
- Examination of the necessity of follow-up action to protect the population (evacuation, provisions, accommodation) as well as object-related protective measures (facilities for securing and supplying to the public, e.g., production of drinking water, energy provision etc.);
- Reducing the probability of duplication of efforts by different authorities;
- Providing a common basis for subsequent collaboration with authorities (e.g., environmental authority) and companies providing specialist services;
- Delivering a structured input of data to be archived in a documentary record of the incident.

7 Conclusions

Computer-based modelling enables first responders and crisis management organisations to deal with incidents of any magnitude, from small scale routine accidents to catastrophes. The method can be applied to model a natural catastrophe, technical catastrophe, *natech* catastrophe and *maltech* catastrophe. In some of these cases computer modelling is the only feasible way to prepare for events of such magnitude, since simulating them in an exercise may represent either an unacceptable risk to all participants, or result in unreasonably high environmental damages and/or cost. However, all of such situations can be simulated by computer modelling at no risk to man or the environment at considerably lower efforts and expenses than in field exercises.

If the catastrophe reaches a dimension, which necessitates first responders to work within a rapidly evolving, diverse and multijurisdictional environment, this is typically coupled with limited or quickly changing situational understanding. Using computer-based modelling enhances the effectiveness of pre-event planning, equipping, training, and evaluation. By creating a common visual basis between all stakeholders involved in crisis management, modelling enhances the effectiveness of these activities while reducing time and cost needed to train for, analyze and respond to real or potential incidents of any magnitude – from daily routine accidents to rare event catastrophes.

If sufficient time is available and skill at hand, such models can be created well in advance, representing in a most detailed manner all features considered essential for assessing the potential threats and deciding on the effectiveness of mitigating countermeasures.

It is possible to use either existing generic models, or create new models on scene; the latter can be achieved in many cases within about 30 minutes, depending on the level of detail required. However, adaptation of an existing generic model or creation of a new model would require the availability of a first responder trained in computer modelling on duty at the crisis management centre, or access to a trained person on line.