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Considering critical infrastructures in the land use planning policy around Seveso plants

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ABSTRACT

The damages following major accidents in chemical facilities highlight civil society vulnerability to these risks. Many countries have drafted guidelines to prevent such accidents and to reduce the consequences for humans and environment. However, the consequences of such accidents on critical infrastructures (CI) and the cascading effect that may result are rarely considered.

In Europe, the Seveso Directives set out the major principles underlying prevention policy for these risks. Consequently, European Member States must assess the risks to which establishments (schools, hospitals, ...) are exposed. However, in evaluating risks, only scenarios involving accidents which directly harm humans are generally studied. Damages which could cause the failure of a CI, necessary for the proper functioning of the territory, are not directly considered.

This study briefly presents the risk quantification approach used in the Walloon Region (Belgium), which does not consider CIs interdependencies but can be adapted to do so. To illustrate the benefits of considering CI, the results of a simulated explosion in Montreal (Canada) are presented and show that taking CIs into account is more than relevant.

A possible line of approach is proposed to allow the risks related to CI failures to be addressed in the Walloon method.

1. Introduction

Over the last half-century, several major accidents have occurred in chemical plants in different member states of the European Union. The social, economic and environmental damages, as well as loss of human life, were considerable.

That is why in 1982 the member states enacted *Directive 82/501/EC*, better known as the *Seveso Directive I* (Council of the European Union, 1982). As a result, all member states must follow a common approach to the prevention of major accidents. Based on the quantity of dangerous substances present in excess of a first or second threshold value (minimal quantities), many facilities have since become *Seveso lower-tier* or *higher-tier* establishments. The Directive was revised in 1996 and renamed the *Seveso II Directive* (Council of the European Union, 1996), then amended in 2003 (Council of the European Union, 2003). The latest update was done in 2012 and bears the name *Seveso III Directive* (European Parliament and Council of the European Union, 2012). This version is applicable since June 2015.

The overarching purpose of the *Seveso Directive* is to apply all the necessary measures to prevent major accidents and, in the event an accident does occur, to limit its consequences for human beings and the environment. One of the main tools to meet the latter objective is land-use planning around Seveso sites.

The Seveso II Directive adopted in 1996 by the European Union states that domino effects should be included in risk analyses for chemical plants. Large literature is available about modeling and prevention of domino effects in industrial facilities (Reniers and Cozzani, 2013; Necci et al., 2015; Darbra et al., 2010). However, in Belgium little concern is addressed about domino effects related to infrastructures in the surroundings of a Seveso site.

In Belgium, land-use planning is a regional responsibility. Consequently, the Public Service of Wallonia is responsible for issuing an opinion on any land-use project in the vicinity of Walloon Seveso sites. In Wallonia, the process governing land-use planning around high-risk facilities involves two steps: first, the risk around the facilities in question must be quantified; second, this risk must be managed. In other words, it is necessary to determine what kind of land use is acceptable.

This process evaluates the risks of having establishments (homes, schools, hospitals, etc.) close to a Seveso site based on

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the number of people likely to be there and their vulnerability. In evaluating these risks, only accident scenarios that give rise directly to harm to human beings are taken into account. Damages that could cause the failure of a critical infrastructure (CI) that is located nearby and is necessary for the proper functioning of the territory are not considered. The consequences of the failure of the CI for other CIs are not taken into account either. Nevertheless, all these kinds of damages could compromise the territory's functioning. Due to the interdependencies among CIs, the increased dependency of civil societies on the resources and services these infrastructures provide, and the increasing urbanization of cities, these consequences could be increased and affect more than just the zone hit by the anticipated direct damages (Zimmerman, 1996). Consequently, more people, businesses and CIs would be affected.

In this context, risk assessment must also take account of these vulnerabilities, which have not been studied much in the case of major accident risks (Erwann, 2003).

In this article, the risk quantification method used in the Walloon Region will be described briefly and we will show that, to take CIs into account, this approach would need to be adapted. For that, a concrete example of a case, developed by the Polytechnic School of Montréal, is presented to show that indirect damages due to the failure of a CI can be huge. Thanks to a joint Wallonia/Quebec project, a possible line of approach that will make it possible to consider risks due to CI failures have been proposed.

2. Land-use management in the Walloon Region

The management of land-use planning in the Walloon Region can be summarized in two major steps. The first step consists in quantifying the risk around Seveso facilities so that, in a second step, the land in the vicinity of these high-risk sites can be better managed. The risk quantification method chosen by the Walloon Region is a technique similar to the Quantitative Risk Assessment (QRA) method. To respond to the need to define the concept of appropriate distance between Seveso facilities and areas frequented by the public, the Walloon Region decided to introduce the concept of vulnerable zone around these Seveso sites. The vulnerable zone can be defined as an area in which the effects of accidents that are harmful to people or property can be observed, with a non-negligible probability of occurrence. The concepts of consequences (harmful accidents) and probabilities are clearly in evidence here.

In this subsection, the risk quantification method developed by the Polytechnic Faculty of Mons will be presented first, then we will describe how the Walloon Region manages planning on the basis of the iso-risk curves this method generates.

2.1. Description of the risk quantification methodology applied in the Walloon Region

The probabilistic approach used in the Walloon Region follows the workflow presented in Fig. 1.

This methodology is based on the concept of individual risk, which can be defined as "the annual frequency of experiencing a given damage due to an accident in the facility for a person located at a point considered to be permanent and unprotected."

To apply this method, Phast Risk QRA software, marketed by DNV (Det Norske Veritas) Software, is used to calculate individual risk. The application of this methodology and the values of the many parameters used in the software have been described in several articles (Delvosalle et al., 2006a,b).

Note that, contrary to a classic QRA approach, the risk quantification method developed in the Walloon Region is based on the effect thresholds corresponding to the appearance of the first irreversible damages to health, and not to lethality. The effect thresholds used for the three types of effects considered (overpressure, toxic and thermal) are set out in the Walloon Region's handbook (Service Public de Wallonie, Direction Générale des Ressources Naturelles et de l'Environnement, Cellule Risques d'Accidents Majeurs, 2005) and presented in Table 1. A recent review of approaches and Regulations related to thresholds for domino effects and safety distances is given in the paper of Alileche et al. (2015).

The different steps of the methodology lead to the determination of risk for each scenario studied for all the dangerous facilities on the site. These different contributions are then added together to obtain the overall risk posed by the Seveso site.

The results are presented in the form of iso-risk curves (annual frequency), which connect points with identical risk.

Based on these curves, the Walloon Region decides whether or not to grant a permit to build in proximity to a Seveso site, as a function of the type of project and the risk level.

2.2. Management of vulnerable zones

To better manage land-use planning in the vulnerable zones defined by iso-risk curves, the Public Service of Wallonia developed a matrix-type tool to support decisions regarding whether or not a construction project should be authorized near a Seveso site (see Fig. 2). The individual risk accepted for a given environment depends on the specific vulnerability of this environment to industrial risk. In general, the more occupants there are and the less autonomous they are, the lower the individual risk that will be tolerated. This matrix is reported in Fig. 2.

A project located in proximity to a Seveso site will be accepted if:

- A Type A project is not included inside the 10^{-3}/year iso-risk curve;
- A Type B project is not included inside the 10^{-4}/year iso-risk curve;
- A Type C project is not included inside the 10^{-5}/year iso-risk curve;
- A Type D project is not included inside the 10^{-6}/year iso-risk curve.

3. Taking critical infrastructures into account in the Walloon Region's methodology

As Fig. 2 shows, the land-use planning policy around Seveso facilities provides that any Type A infrastructure that does not require the presence of people (water tower, electric pylon, transformer, telephone antenna, etc.) can be constructed quite close to the boundary of the industrial site. That implies that CIs, which generally correspond to Type A structures, can be built close to Seveso facilities without any restrictions. This is because the risk assessment process considers only direct harm to the public.

Nevertheless, an exercise carried out in Montreal to simulate the explosion of a ship carrying chemicals in a port infrastructure clearly shows the importance of considering risks related to the failure of a CI. This exercise proved that the failure of a CI resulting from such an accident can affect the public indirectly because of the interdependency among CIs. By not taking this kind of "indirect" risk into consideration, the Walloon Region is underestimating the actual risk posed by Seveso facilities in its land-use planning.

The next section briefly outlines the problems affecting CIs and the effects of the simulated explosion on CIs on the territory of the city of Montreal.

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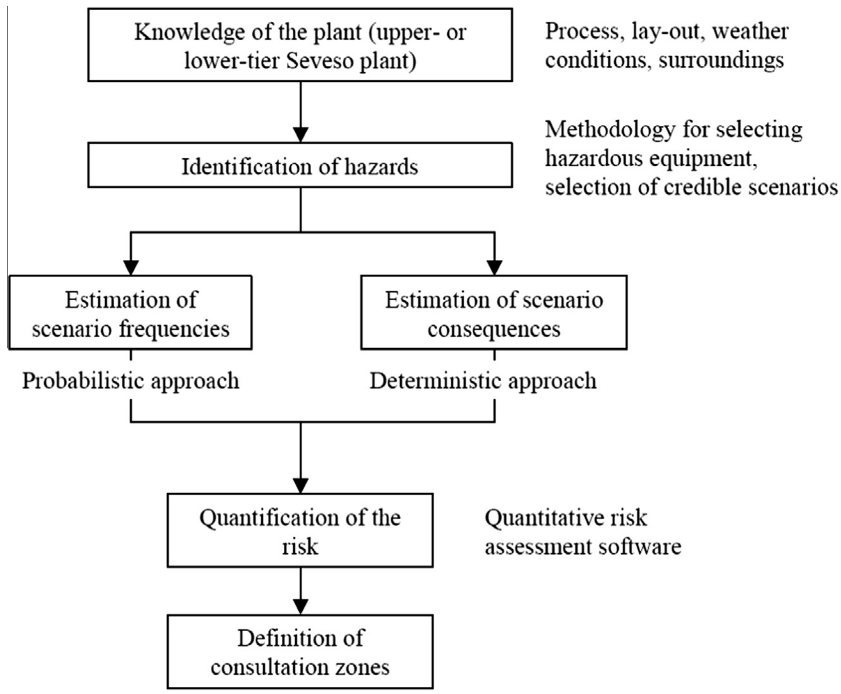

Fig. 1. Steps in the external risk quantification method used in the Walloon Region (Delvosalle et al., 2006a).

Table 1
Effect thresholds in the Walloon Region (Service Public de Wallonie, Direction Générale des Ressources Naturelles et de l'Environnement, Cellule Risques d'Accidents Majeurs, 2005).

Type of effect	Effect thresholds considered
Thermal effect	6.4 kW/m^2 for 20 s
Overpressure effect	50 mbar
Toxic effect	LBW (Dutch life-threatening value – VROM (NL)) similar to ERPG3 (Emergency Response Planning Guidelines (Service Public de Wallonie, Direction Générale des Ressources Naturelles et de l'Environnement, Cellule Risques d'Accidents Majeurs, 2013, American Industrial Hygiene Association, 2013))

3.1. Problems related to critical infrastructures and their interdependencies

The proper functioning of a society depends on its ability to ensure the provision of resources and services that are essential to its economic and social activities. Water, electricity, natural gas, telecommunications, transportation (of goods and people), etc., are all indispensable resources and services. The supply of these resources is largely dependent on the proper operation of essential systems, also known as essential or critical infrastructures. These CIs constitute the core of any modern community. In this regard, the United States Department of Homeland Security defines CIs as infrastructures that are "vital to the health, safety and well-being of populations, as well as the normal functioning of institutions and the country's economy" (U.S. Department of Homeland Security (DHS), 2013). Likewise, in Europe, *Directive 2008/114/EC* (Council of the European Union, 2008) covers the protection of CIs. They are described as, among other things, "essential for the maintenance of vital societal functions." However, the European definition of CI integrates the concept of cross-border impacts.

CIs are organized into highly complex, interrelated and interdependent systems. This kind of organization is a necessary evil: it makes it possible to provide the more far-flung areas of a community with resources and services, but it can also act as a vector for propagation, or even amplification, of CI failures. Such failures can generate cascade effects that extend well beyond the physical location where the first failure occurred. In fact, a failure appearing in one system can propagate not only within that system but also to other systems, through their interconnections (domino effects) (Rinaldi et al., 2001; Peerenboom et al., 2002; Robert and Morabito, 2002).

Despite the many interdependencies and interconnections that exist among CIs, it is undeniably true that their scope is often underestimated. This situation means that, although first-order dependencies are relatively well managed, higher-order dependencies cause problems, because they are not well known. Such inadequate knowledge means that higher-order dependencies can affect systems in a much more insidious way through domino effects (Little, 2002, 2004). The result is an event that affects additional sectors of a territory, resulting in significant loss and damage.

The simulation of an explosion of a ship transporting chemicals in the port of Montreal made it possible to highlight the problem of CI failures resulting from a major accident such as an explosion. To make it easier to simulate the consequences of an explosion, a prototype expert system (called *DOMINO*) was used. This prototype tool was developed further to work initiated by the *Centre risque & performance* (CRP) at the École Polytechnique de Montréal, along with managers of the principal systems in the cities of Montreal and Quebec and representatives of civil security. In addition to providing the possibility of simulating the consequences of a technological hazard, *DOMINO* also allows users to simulate the consequences of a natural hazard (flood, earthquake, etc.) or of the unavailability of any resource provided by CIs in terms of domino effects. During each simulation, this tool makes it possible to quickly see the propagation in time and space of potential domino effects that could affect CIs.

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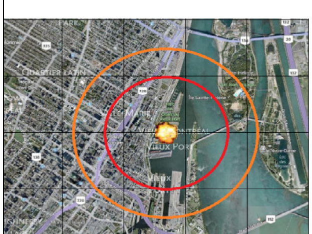
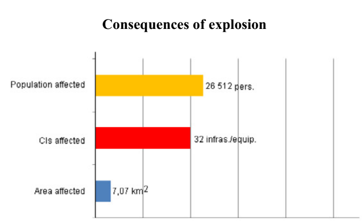
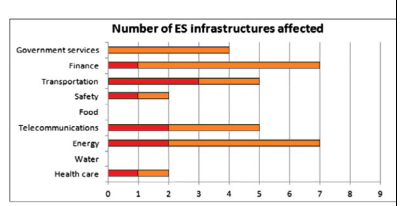
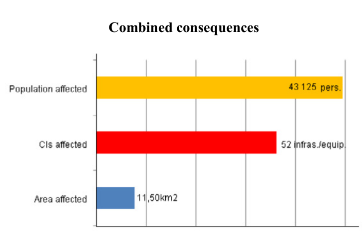
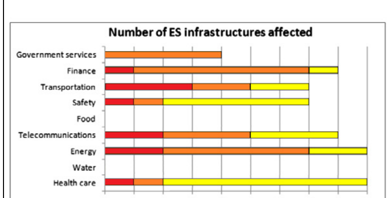
	Individual risk		
	10^{-3} to 10^{-4} per year	10^{-4} to 10^{-5} per year	10^{-5} to 10^{-6} per year
Type A: Technical structures and facilities directly related to geography (water intakes, water towers, filtration stations, radio transmitters and relay stations, wind turbines, etc.)	OK	OK	OK
Type B: Buildings that will accommodate a limited number of people who are mostly autonomous adults (workshops, logistics, small businesses, etc.)	Warning	OK	OK
Type C: Buildings that will accommodate an unlimited number of people who are mostly autonomous adults (homes, workshops or offices with more than 100 people, school buildings or residences for secondary or postsecondary education)	NO	NO	OK
Type D: Buildings that will accommodate vulnerable people with limited autonomy (health care institutions, seniors' homes, schools and residences for children less than 12 years old, prisons and detention centers)	NO	NO	NO

Fig. 2. Decision support matrix for applications located within a vulnerable zone (Service Public de Wallonie, Direction Générale des Ressources Naturelles et de l'Environnement, Cellule Risques d'Accidents Majeurs, 2013).

Table 2 below presents the simulation of the potential effects of the explosion on CIs in the territory of the city of Montreal. For reasons of confidentiality, the infrastructures that are affected are not identified in this table. For this exercise, the impact of the explo-

Table 2
Use of *DOMINO* to analyze the consequences for CIs of an explosion.

DOMINO simulation	Statistics	Identification of ESs affected	Notes
			• Explosion in the port. • Radius of impact : 1km – 1,5km • Massive evacuation of multiple buildings (hospitals, offices, etc.). • Potential loss of service in public transit and road transit. • 42 critical assets located in the 1km – 1,5km radius
			• Total of 52 assets of CIs impacted by the explosion and/or the electricity outage and/or the telecommunications outage. • Over 43 000 persons affected by the explosion and/or the electricity outage and/or the • Total impacted area of over 11km^2.
Legend : ○ Disrupted infrastructure	○ Disrupted infrastructure with potential to fail	● Failed infrastructure	

sion on equipment and infrastructures was analyzed generally, without considering the specific impacts related to overpressures.

The first row in the table shows the first stage of the simulation. The two circles represent the 1-km and 1.5-km radii of impact that was determined for this simulation. This corresponds to an impact zone of approximately 7 km^2. This information (radius of impact and geographic epicenter of the explosion) are given to *DOMINO* as input parameters to determine the geographic location of the impact zone. The inputting of this data enables the tool to identify the CI infrastructures and equipment located inside the impact zone and the consequences of their failure. In this case, the outcome was 32 infrastructures or items of equipment belonging to CIs and 26,500 people affected by the accident.

The second row of the table presents the combined effects of failures of CI equipment (electricity, telecommunications and transportation) located within the impact zone. As Table 2 shows, the expanded impact zone associated with all the consequences of the explosion at the port far exceeds the radius of impact associated with the explosion itself. In total, this expanded impact zone represents an area of more than 11 km^2, which contains 52 infrastructures or equipment belonging to CIs. The population affected by the consequences of the explosion is now estimated at more than 43,000 people instead of the 26,500 in the initial impact zone.

The results of this exercise also indicate that the consequences of such an explosion would affect not only road, power and telecommunications infrastructures but also several fire halls and police stations located inside the radius of impact. This presupposes that help would have to come from farther away, which would mean longer response times. As well, a major hospital is situated in the 1-km impact zone, and its evacuation (if necessary) would soon result in a shortage of ambulances to evacuate people injured by the explosion. In addition to all of these direct and indirect consequences of the explosion, one must also remember that such an event would generate major financial losses for the whole of Canada.

To sum up, this simulation showed that domino effects can significantly expand the impact zone well beyond the area defined by the 1-km and 1.5-km radii of impact. This case is a perfect illustration of why it is important to consider CIs and their interdependencies when assessing risks related to major accidents.

3.2. Possible consequences of the failure of a critical infrastructure

As a result of this exercise, we can state that, in the event of an accident at a Seveso facility that triggers the failure of a CI, three kinds of consequences can be anticipated:

(1) Consequences for the population of a loss of a service (e.g., power outage);
(2) Consequences for a neighboring facility of a loss of a service that could lead to a second accident (e.g., lack of cooling water leading to the overheating and destruction of a reactor or tank);
(3) Consequences for response by emergency services (e.g., closing of a road leading to the facility, water unavailable to put out a fire).

None of these three kinds of consequences is currently taken into consideration in the Walloon Region's land-use planning policy. Nevertheless, the second kind of consequence, for example, an accident in a facility that had no direct "victims", could potentially trigger a secondary accident whose consequences might be much more serious, due to a domino effect.

In addition, the loss of certain CIs could also directly impact the effectiveness of emergency services' response in the event of an accident (third kind of consequence). Indeed, if the construction of CIs were avoided in zones that could lead to their failure in case of an accident at a neighboring facility, response services could focus only on resolving the emergency, without worrying about a possible domino effect or a loss of resources (typically water) that could prevent them from acting effectively.

We should also note that, if critical infrastructures were identified in the land-use planning study, it could enable response services to modify their emergency and response plans and thus better anticipate the actual situation they would face in an emergency (e.g., change the location of a pumping station or add a water reserve for use in case of fire).

3.3. Managing the territory around technological risk zones

To take these "indirect" risks into account, it would be appropriate to develop a new approach to managing exclusion zones around Seveso sites. In this new approach, it would be necessary to consider zones including other infrastructures that contain hazardous materials as well, such as railroad tracks used to transport these materials. CIs may exist or may be built in all these zones. However, it is important to incorporate a damage assessment of these infrastructures into risk analyses. In such cases, a deterministic approach seems most appropriate.

This new approach could be based on the method that is already used, but without taking the probabilistic component into consideration. However, two fundamental steps must be reviewed: the selection of the accident scenarios studied and the effect thresholds used.

3.3.1. Selection of accident scenarios

First, it is clear that in studying accident scenarios that could lead to the damaging of a critical infrastructure, scenarios that involve only toxic effects on humans need not be considered. Indeed, only scenarios generating radiative and overpressure effects are able to damage a CI. Environmental effects (e.g., contamination of drinkwater) can be included in the assessment.

In addition, unlike the probabilistic approach used to determine iso-risk curves, the aim of this new initiative is to determine the maximum extent of accident effects in all directions around the site.

The simplest solution would be to consider the scope of worst-case scenarios for each Seveso facility. However, this solution could lead to overly large effect distances, meaning that it would be impossible to apply the exclusion zone in practice.

A compromise might have to be made with regard to the credibility of the worst-case scenario: thus, a scenario with a lesser scope but greater credibility should be selected.

3.3.2. Effect thresholds

A fundamental question in the development of a methodology to determine the zone within which CIs may suffer damage is deciding what effect thresholds to apply.

Of course, it is obvious that effect thresholds corresponding to irreversible damages for a human being (i.e., 6.4 kW/m^2 for 20 s for thermal effects and 50 mbar for overpressure effects) are entirely irrelevant for this purpose.

The effect thresholds in this case should correspond to the smallest value that could affect the most sensitive element of the CI. To determine these thresholds, studies should be done for each type of effect (thermal and overpressure) and for each CI.

Another approach would be to work with thresholds established in studies of domino effects. The type of damage considered here is entirely equivalent to the damage of a structure due to an accident in a "neighboring" structure. In this field, the Polytechnic Faculty of Mons carried out a study for the federal ministry (Levert et al., 1997), in which a methodology was developed that made it possible to determine a zone around equipment in which other facilities can be impacted. In this study, the effect thresholds proposed for radiative and overpressure effects were 8 kW/m^2 and 160 mbar, respectively, corresponding to the lower limit for serious damage to unprotected structures.

These thresholds could be a valuable first approximation in determining effect zones, even if only for preliminary calculations.

4. Issues related to the consideration of critical infrastructures

CIs are composed of a set of equipment items and infrastructures. The functions of those different elements are very variable. Some are directly related to the production, transportation and distribution of resources, while others are dedicated to control. The operators of CIs know the criticality of this equipment. On the other hand, the assessment of the vulnerability of these elements to technological risks must be strengthened, and in some cases actually implemented. A qualitative approach is recommended in order to bolster knowledge of the behavior of different CI units in dangerous situations generated by overpressure, radiation, and potentially spills or releases of corrosive products.

With regard to overpressure created by explosions, there are numerous possible situations. For example, a transformer station contains many components that can tolerate varying degrees of overpressure. It is evident that a set of bars will have a different level of resistance than a remote control station located in a shelter. Similarly, a water tower can withstand greater overpressure than a relay antenna for cell phone transmission. The equipment attached to this antenna will be affected before there is any deformation of the metal structure. In this context of multiple possible situations, the best approach would be to catalogue all potential impacts on key elements of CIs as a result of overpressure. It would then be possible to determine the minimum distance for storing flammable or explosive products to ensure that they cannot damage CIs' infrastructures. Charts relating effect distances to the explosible mass could enable CI managers and operators, as well as civil security authorities, to take this kind of situation into consideration.

This kind of information can also be used in monitoring the transportation of hazardous materials. Of course, once risky situations are identified, it will be possible to plan measures to protect or reinforce equipment.

For situations involving flammable materials, similar analyses can be done to those for the effects of overpressure on CIs, but this time based on radiant flux. The problem of thermal radiation appears particularly important in analyzing the vulnerability of telecommunications systems. Even if infrastructures such as telecommunications towers are not themselves destroyed, receiving or emitting equipment in the area would probably be affected. This brings us to the important issue of the level of impact on a piece of equipment, which must include parameters both of destruction and of disruption.

With explosive materials or petroleum products, recent accidents (e.g., Lac-Mégantic in Quebec, Canada) have shown that explosions at the outset of an event can be followed by fires later on. It would be a good idea to evaluate this succession of phenomena (explosions followed by radiation) in terms of damages to CI equipment, including underground equipment such as fiber-optic cables for telecommunications.

In addition to these two dangerous phenomena, other less obvious but equally problematic situations could arise. Consider the case, for example, of the formation of a cloud of corrosive products. What impact might it have on a metal structure (such as a relay antenna)?

Spills of toxic products can also affect underground electrical or telecommunications equipment, including units inside facilities such as transformer stations and underground lines. These phenomena seem to be less problematic but they cannot be systematically ignored, especially in urban areas.

These analyses could potentially make it possible to define certain protective measures for specific facilities, such as a protective wall to deflect overpressure waves near an electrical facility. CI managers, of course, should use this information when they deploy new technologies, such as those for wireless telecommunications. As for civil security and emergency planning, these analyses of potential impacts on CIs are important parameters that must be taken into account in view of their growing consequences for the general population and the increasing complexity of managing crises.

5. Conclusions

The aim of this paper was to demonstrate that the land use planning approach, in the Walloon Region, underestimate the risk around Seveso plants by not taking into account the critical infrastructures.

The Walloon methodology to rule the land use planning has been presented and the problematic of the CI has been exposed.

The consequences due to the failure of CI has been highlighted with a concrete example. The result of this example shows that, indeed, the failure of a CI due to a first accident, can have a much larger impact than the accident himself.

After that, a possible line of approach to take the CI into account in the Walloon Region land use planning methodology has been described.

Finally, some issues for the consideration of CI's in land use planning have also been discussed.

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