Article

Application of Chemical Monitoring and Public Alarm Systems to Reduce Public Vulnerability to Major Accidents Involving Dangerous Substances

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Abstract: As a result of economic development and an increase in the volume of industrial production, the use of dangerous substances is increasing despite the fact that most industrial facilities are committed to the principles of environmental protection and sustainable development. Protection of human health and the environment is ensured at the local level by the local safety system. Major accidents typically have an off-site impact that also affects the general public. The most significant asymmetric event is when toxic substances are release into a populated area following a major accident. Early warning systems can significantly reduce the harmful consequences of major accidents that may occur. The operation of a reliable and effective chemical monitoring and public alarm system can be used as a basic device of defence. This ultimately means restoring the symmetry of the local safety system. It was an important scientific objective in Hungary to identify the facilities endangering the population where it is necessary to install chemical monitoring and early warning external protection systems. In this context, the main objective of this study was to present dangerous plant identification methodology and to analyse and evaluate the results of the application of this methodology.

Keywords: dangerous establishment; major accident; chemical monitoring system; population protection; system failure

1. Introduction

In accordance with the data of Global Disaster and Coordination System, the occurrence of natural and manmade disasters, as well as major accidents, is almost a daily practice [1]. Major accidents involving dangerous substances, like other phenomena, often have serious consequences for the establishment where the accident happened and its surroundings, and the impact can extend beyond national borders. Statistical data provided by the Major Accident Reporting System operated by Major Accident Hazard Bureau declared that a large number of about 20–35 major accidents per year occurred in the Member States of the European Union in the last 10 years [2]. Major accidents that may occur at dangerous establishments during production, processing, or storage of dangerous substances can sometimes have catastrophic effects on human health and can contaminate surface and groundwater, soil, or the built environment [3]. The safe operation of dangerous establishments is ensured by a local internal safety system in the territory of the dangerous establishment, as well as offsite in a settlement endangered by the establishment. Breaking the symmetry of these systems can lead to asymmetric processes, such as major accidents.

The safe operation of dangerous technologies used in dangerous establishments is made sustainable by the operators through technical, management, and control measures.

The measures introduced by the operator serve the appropriate unity and symmetry of the local safety system. However, despite the introduction of these safety measures, there is a risk of failure of the local safety system. Technology failure, human error, or external causes can result in the asymmetry of the local safety system, leading to failure involving loss of containment events such as the release of dangerous substances into the air. These incidents through major accident scenarios can take the form of an explosion, fire, or the spread of toxic substances. These incidents can disrupt the local safety system order, eventually leading to asymmetric events and finally to an emergency situation in the form of a major accident. This process can also have not only internal (onsite) and subsequent domino effects, but also a major impact on the population living offsite in the vicinity of the dangerous establishment.

Risk and consequence analysis procedures, methods, and software are used to ensure the safe operation of the systems. Many process safety, loss prevention, and system safety engineering scientific works deal with the risk-based assessment approaches of these processes. We have seen significant progress in standardizing and harmonizing the utilization of risk analysis technologies in industrial activities in the late 1990s and early 2000s [4]. The application of excellent theoretical safety management tools is widespread using safety barrier diagrams [5] for the proper application of prevention and consequence reduction measures. One of the most significant scientific and technical studies of the relatively diverse literature in the field of hazard identification, management, and control is the well-known publication dealing with Loss Prevention in the Process Industries [6].

In general, the local safety system symmetry can be ensured by the introduction of prevention, preparedness, and response measures. The application of these measures aims to reduce or eliminate the major effects and consequences of asymmetric events, such as explosions, fire, and the spread of toxic substances. Risk and consequence analysis procedures, models, and technical databases used in process industries are collected into the so-called coloured books developed by TNO (the Netherlands Organization for applied scientific research), based on the purple book dealing with the procedures of quantitative risk analysis [7].

The internal safety system of the dangerous establishment is, thus, linked primarily to the external safety system of the population living in the vicinity of the establishment. Internal and external emergency planning measures are the main management means of ensuring the coherence between these two systems. The implementation of an external safety system is possible by introducing population protection measures [8]. The most common population protection measures included in external protection plans are onsite and offsite sheltering and evacuation, which are mostly affected by the available time frame [9]. In the case where toxic substances spread, the monitoring of dangerous substances and the introduction of the public alarm (early warning) measure have been inadequate in the majority of major accidents. In this case, the primary method of protecting of the population is staying at home, while closing and sealing the doors and windows (sheltering in place) [10]. The determination of the affected area (danger zone), area of public information, and distance for evacuation of a major accident is also critical for the successful response activities [11,12]. The choice between population protection measures (evacuation and sheltering in place) used in cases of chemical accidents involving toxic substance release is a vital decision-making action that mainly depends on the time available for decision making and implementation of protection activities [13]. In the case of dangerous establishments, the installation and usage of a chemical monitoring and public alarm system is an excellent tool for reducing or eliminating the possible consequences of major accidents [14].

Considering the above, it can be determined that emergency management is a complex system that requires symmetry between internal and external emergency management systems.

At the international level, the Hyogo Framework for Action valid for the period 2005–2015 [15] was determined as a major priority action to identify, assess, and monitor disaster risks and enhance early warning. The industrial accident's action program [16] of the UN ECE Industrial Accident Convention [17] is implemented in line with the priorities of the

Sendai Framework on Disaster Risk Reduction program for the period 2015–2030 [18]. The Implementation Guide for Manmade and Technological Hazards [19] developed under the auspices of Sendai Framework Program specifies as a main objective to develop and maintain multisectoral rapid early warning and alert systems. The guidance document for industrial accident emergency planning [20] prescribes the importance of the installation of early warning systems, which contains suitable technical equipment for event detection and assessment of warning and alert relevance. The realization of the need for major accident risk reduction on a European level is also supported by the adaption, transposition, and enforcement of international and European Union's environment safety regulations. The requirement for the protection against the adverse effects of major accidents have been declared by the so-called Seveso Directive [21].

The operators covered by the Seveso Directive must prove to the National Competent Authority (furthermore: authority) by validation of safety documentation that they do not pose a greater risk to the environment than the socially tolerable level. On the other hand, the operators of the site—in order to address the residual risk—must be prepared to deal with potential onsite emergency situations.

The results of the evaluation of safety documentation are evaluated and validated by the authority on three main areas:

1. Determination of the safety distance. On the basis of safety documentation, the authority shall designate the boundaries of the danger zone around the establishment dealing with dangerous substances. The operator shall maintain adequate safety distances between the establishments and—among others—the residential areas, public buildings, and the main transport routes.
2. Introduction of emergency planning measures. According to the operators' internal emergency plan, an external emergency plan must also be prepared for the safety of population.
3. Preparation of the affected population. Populations that are likely to be affected by a major accident must be provided with appropriate and clear information on the applied safety measures and behavioural rules in cases of emergencies.

The immediate environment of many dangerous establishments has become densely populated as a result of urbanization. This makes it significantly difficult to ensure the minimum safety distance and provide an efficient emergency planning process.

The protection of the population by the application of internal and external emergency planning measures is a complex process, in which situation various installed and mobile emergency response devices can be used [22]. This statement is even more relevant, when the major accident occurs together with the release of toxic substances or flammable substances which form an explosive mixture with air. The extent of the effects on the population depends on a number of factors. One of the most important parameters of the toxic substance spread is the exposure time of dangerous substances. By using lines of defence, exposure time and human loss can be reduced significantly, or the adverse effects can be eliminated completely.

In this case, the effectiveness of the introduction of external emergency planning measures depends primarily on the immediate detection of released dangerous substances and the timely alert of the affected population [23]. According to the authors' opinion, the chemical monitoring and public alarm systems set up in the vicinity of dangerous establishments can be widely used to solve this problem.

The authors of this article identified the following main research objectives:

*   introduction of design information on chemical monitoring and public alarm systems, which include the evaluation of the management process of introducing the population protection measures in the event of a major accident and determination of endangered area of the major accident;
*   presentation of the unique methodology developed for the deployment of chemical monitoring and public alarm systems and the key principles of their application.

The present study can be used to develop and further develop preliminary risk analysis methodologies for the protection of the population, to establish the ranking procedures of settlements according to the threats of manmade disasters, and to prepare development plans for chemical monitoring and public alarm systems.

2. General Design Information on Chemical Monitoring and Public Alarm System

2.1. Evaluation of the Management Process of Introduction of Population Protection Measures

In this section, the authors examine how the chemical monitoring and public alarm system is integrated into the system of population protection measures appearing in the external emergency plans. The lack of safety distances and urbanization also cause difficulties for the authority in the preparation of the external protection plan, because, in the event of a major accident involving dangerous substance, tens of thousands of people could be affected in a short time.

The municipal external emergency planning system is mainly based on the application of well-designed population protection (civil protection) measures [24]. Population protection measures such as withdrawal of the population in their homes (sheltering in place) or evacuation operations play a significant role in emergency management systems [25].

A number of models [26,27] have been developed for evacuation that take into account human behaviour and movement. These models mostly deal with indoor and outdoor evacuations in small settlements and large cities. However, these models do not approach population protection measures in a complex way, but focus exclusively on the evacuation process. In fact, the population protection measure is a complex process that contains the following steps: incident detection, evacuation order issue, delivery order to public via transmitters, preparation for evacuation, movement through the evacuation network, arrival at safety zone, and verification phase [28]. The application of these phases in a special case of a major accident involving dangerous substances is shown in Figure 1.
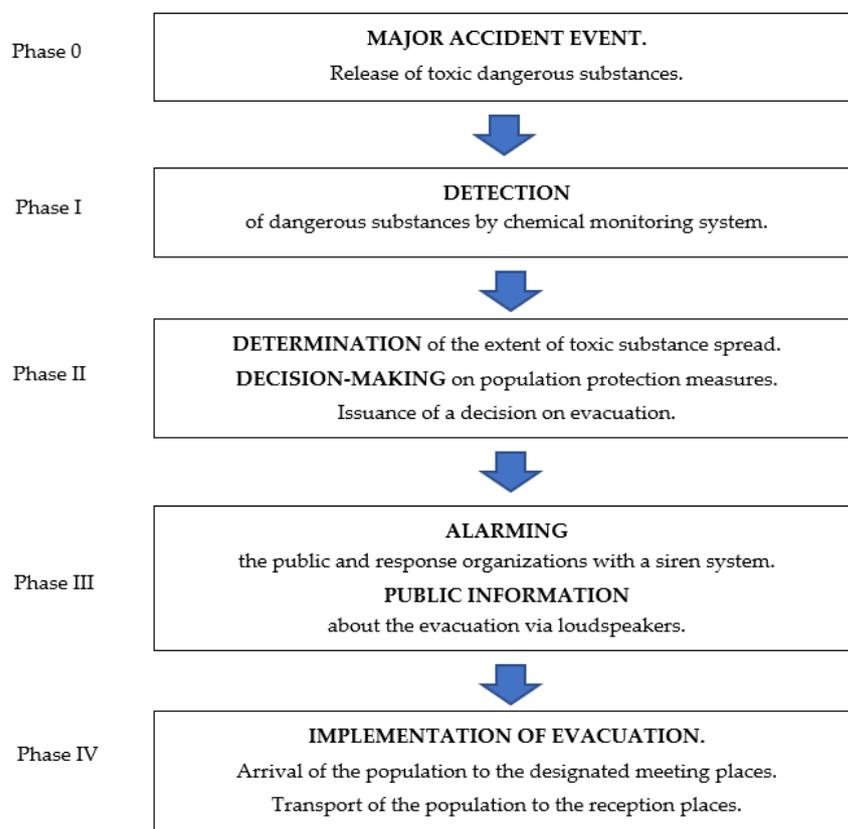

Phase 0

MAJOR ACCIDENT EVENT.
Release of toxic dangerous substances.

Phase I

DETECTION
of dangerous substances by chemical monitoring system.

Phase II

DETERMINATION of the extent of toxic substance spread.
DECISION-MAKING on population protection measures.
Issuance of a decision on evacuation.

Phase III

ALARMING
the public and response organizations with a siren system.
PUBLIC INFORMATION
about the evacuation via loudspeakers.

Phase IV

IMPLEMENTATION OF EVACUATION.
Arrival of the population to the designated meeting places.
Transport of the population to the reception places.

Figure 1. Evacuation phases for major chemical accidents. Source: own research.

It can be determined from an evaluation of Figure 1 that Phases I–II have key roles in the evacuation process during the implementation of the population protective measures. It can be clearly understood that the efficient and timely operation of the major accident detection phase (Phase I) is the basis for the reliable operation of the proper evacuation process. Starting from this moment, we calculate the evacuation time. In the case of a major accidents involving dangerous substances, such as at the time of, for example, a nuclear accident, early warning significantly increases the time available to prepare for evacuation (Phases IV). The chemical monitoring system provides the appropriate technical data for the official authority decision making in order to issue an evacuation order. In this way, the area affected by the adverse effects of major accidents can be identified and action can be taken to inform the public through a public alarm system (Phase III). We can conclude that, when a major accident involving dangerous substances occur, it can be detected in the early stages, alerting that the civil population can be manageable in a much shorter period of time. In consequence, the population will be able to achieve public protection measures that will minimise the consequences of major accidents, because the population is only exposed to the effects for short time.

In addition to the examination of emergency behaviour, it is also extremely important to examine the technical processes of the spread of toxic substances. In order to issue an evaluation order, it is essential to identify the endangered area using the consequences of the accident.

2.2. Determination of Endangered Area of Major Accident Involving Dangerous Substances

As already stated, in order to determine the endangered area, the spread of toxic substances must be determined. Internationally accepted procedures and methodologies for calculating the endangered area from the release of toxic substances can be found in the publications of the Dutch National Institute of Public Health and the Environment. [29,30]. In case of the dispersion of a toxic gas (vapour), the concentration and the density of the gas (vapour) will decrease with time. The concentration of the toxic gas (vapour) based on the Dutch technical sources [29] (4.69) will be subject to various parameters in the case of immediate release, which can be determined using the following simplified equation:

$$c\ (x, y, z, t) = f\ (Q, x, y, z, u, i, s, n, \delta, t), \tag{1}$$

where Q is the mass (kg) of gas (vapour), x is the distance on the axis (m), y is the distance from the axis (m), z is the height from the ground (m), u is the wind speed considered (m/s), i is the vertical stability within the atmosphere (without dimensions), s is the gas (vapour) density (g/m3), δ is the dispersion constant, n is the surface roughness (without dimensions), and t is the time passed since the emission (s) (in cases of immediate emission) (see [31] p. 35).

The cause of effect on human life and probability of mortality can be determined using the so-called probit "Pr" function. The probability of death, P_{lethal}, is calculated using a probit, Pr, as follows (see [30], p. 23):

$$P_{lethal} = 0.5\ x \left[1 + \mathrm{erf}\left(\frac{\mathrm{Pr} - 5}{\sqrt{2}} \right) \right], \tag{2}$$

where

$$\mathrm{erf}\ (X) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt. \tag{3}$$

The probit for exposure to toxic substances is indicated using the following relationship:

$$\mathrm{Pr} = a + b\ ln \left(\int c^n dt \right), \tag{4}$$

where Pr is the probit associated with the probability of dying (-), a, b, and n are constants for the toxicity of a substance (-), C is the concentration at time t (mg·m^{-3}), and t is the exposure time (min) (see [30], p. 24).

The extent of the damage and the probability of death depend on the concentration and the exposure time beyond the material property when a toxic material is released into the open air.

2.3. Information on the Main Reasons for Installation of Chemical Monitoring and Public Alarm Systems

Due to the national legal obligation on the protection against major accidents, the majority of plants producing and using dangerous substances install some type of fire detection, gas detection, or process control monitoring system. These systems are primarily suitable for informing the operator on the occurrence of abnormal processes, drawing the attention of employees to the application of appropriate personal protection devices. However, these systems do not provide exact information on emergency situations. There is also no information on whether it is necessary to take population protection measures. The decision-making mechanism for taking population protection measures can, therefore, take longer and may even be based on subjective judgment.

Following the national legislation on the protection of major accidents involving dangerous substances, the input data on the risks posed by dangerous establishments dealing with dangerous substances are available to the authority for the realisation of external emergency system. The Seveso authority assessed and approved the condition of safe operation of dangerous establishments from the point of view of industrial safety and population protection.

In order to protect the population living in the vicinity of the dangerous establishments, external emergency plans have been prepared, and the application of these plans has been practiced. During the preparation of external emergency plans, it was proven that, in the case of many high-risk establishments, which are situated in densely populated environments, the installation of an effective chemical monitoring and population alarm system is required. Recognition of this principle provides the basis for the national project in which the Hungarian Competent Authority responsible for the implementation of the Seveso Directive the National Directorate General for Disaster Management planned and developed chemical monitoring and public alarm systems in the vicinity of the most dangerous Seveso establishments. The system has 627 public alarms and 410 chemical monitoring stations in the surroundings of 20 plants, and it can be used to alert about 455,000 people across the country [32].

The chemical monitoring and public alarm system provides a basis for the external emergency planning, ensuring the detection of accidents that may affect the population on one hand and the alert of the affected population on the other.

2.4. The Functioning Base for the Chemical Monitoring and Population Alarm System

In the case of major accidents, dangerous substances can be released into the open air that can diffuse in the form of gas. The concentration of the airborne gas is measured by installed gas detection equipment (monitoring stations), while the gas transmitter devices forward the measured data to the emergency services of the Regional and Capital Disaster Management Directorates that operates on a 24 h basis. The installation of the monitoring stations is recommended in the proximity of the fences surrounding the dangerous establishment, by taking into consideration the technical and legal conditions of the installation.

Figure 2 presents schematically that the chemical monitoring stations were installed with an average density of 20° in the vicinity of the plant with circular coverage in all directions. The dangerous installation is marked in yellow. The direction of the gas propagation is marked in red, building in the inhabited area indicates in blue and the monitoring stations are marked in green [32].
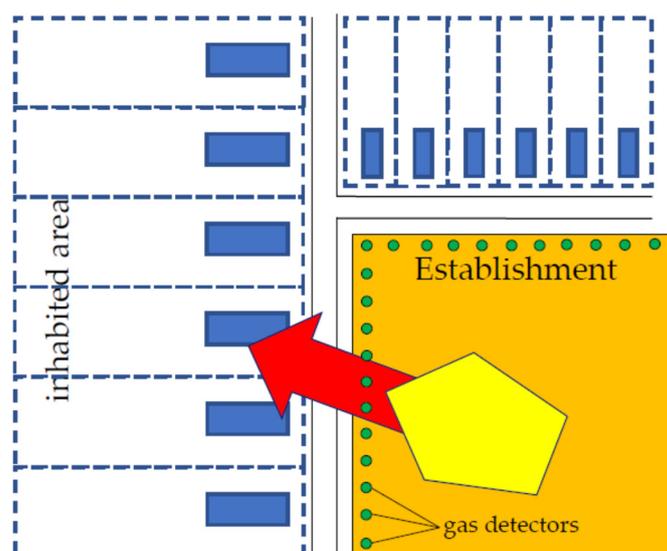
Figure 2. Installation of gas detectors (schematic figure). Source: own research.

Defining the signal and alert levels of the monitoring stations had a high priority. The signal and alarm levels had to be determined for the monitoring stations, for which the introduction of public protection measures was already justified. At the same time there is enough time to filter out any false alarms. According to the rules of procedure in case of a major accident, the results of the measurements are evaluated and then, if necessary, the affected population is alerted and informed via the siren system (alarm stations) [32].

3. Materials and Methods

A unique methodology developed for the determination of venue for installing of the chemical monitoring and public alarm system is presented below.

3.1. Examination of System Design Conditions for Chemical Monitoring and Public Alarm Systems

The chemical monitoring and public alarm systems are an important element of external emergency planning; the monitoring system is integrated into the internal and external emergency plans, as well as into the process of introducing population protection measures. During the design of the system, a so-called monitoring plan must be prepared. The plan determines a location, a number, and a density of monitoring stations.

To determine the installation priority of the system on the basis of objective indicators, the following design aspects must be taken into account: the presumed consequences of major accidents for the population; the technical conditions for the installation of the system; the time and conditions potentially available for population protection tasks taken into account in the external emergency plans; the number of sources of danger; the cost-effectiveness of the installation of the system. On the basis of the toxic materials propagation model and the specifications of the measuring instruments (sensitivity, selectivity, etc.), the location and density of the monitoring stations can be determined. The installation locations of the monitoring stations are shown on a map.

The monitoring stations are used to measure and transmit meteorological data of the air, to detect the concentrations of predetermined dangerous substances in the air of the environment of a dangerous establishment. According to the principle of territorial protection, the monitoring stations are placed between the affected settlements and the sources of danger (dangerous establishment). It is recommended that the installation for the system endpoints be located in the directions that need to be protected. The number (density) of monitoring stations can be determined on the basis of major accident consequence modelling and calculation. In this regard, we need to choose signal and alarm concentration levels for the dangerous substances taken into consideration. We

need to take into account that disaster management primarily examines "out-of-fence" emergency impacts.

We can distinguish between two types of monitoring stations: plant and settlement stations. Plant monitoring stations should be located at the boundaries of the dangerous establishment so that they can cross the path of the dangerous substance cloud toward residential areas. The distances between the endpoints are calculated and displayed using consequence analysis software, where the location of the release of the dangerous substance is based on the events with the lowest cloud width. We also determine the presence and concentration of a dangerous substance cloud in the territory of the inhabited area using the so-called settlement monitoring stations. It is possible to issue the end of the disaster signal on the basis of the negative data on the presence of dangerous substances using settlement measuring stations.

3.2. Method Used for the Identification of the Location of the Chemical Monitoring and Public Alarm System

The first and perhaps most complex step in setting up a chemical monitoring and public alarm system, given the 'cost–benefit' principle, is to determine the list of dangerous establishments where the system should be set up. We can establish a relative order between the dangerous establishments and affected settlements taking into account the population vulnerability index, which is the weighted sum of a number of other index components.

The safety report usually provides an answer to what establishments and what kind of dangers threaten the population. Therefore, each dangerous establishment must be assessed separately in this respect. There are certain minimum conditions for installing the system, in the absence of which it is not justified to install a system in a given settlement. Where these conditions are met, a system can be installed.

According to the first minimum requirement, the inhabited settlement must be in the endangered area (danger zone) of the establishment, or the inhabited settlement must be close to the endangered area within the maximum possible propagation distance of the cloud containing dangerous substances. If the settlement is affected by the endangered area, the installation of the systems must be considered. It may be appropriate to consider the installation of the systems if the settlements may be affected by a cloud of toxic or combustible substances. The reason for that is that the maximum possible distance of the effects is several times larger than the distance between the source of the accident and the settlement, and the direction of the settlement is the same as the most probable wind directions defined in the wind rose.

If the settlement is affected by the endangered area, as the next step, it must be examined whether the given major accident endangers the lives of several people.

Thereafter, it should be verified that the external emergency plan includes urgent population protection measures, such as evacuation. The application of these measures takes a certain amount of time, which is included in the external emergency plan.

Another important aspect is that the continuous detection of dangerous substances in the event of a major accident should be technically realised. Usually, the dangerous establishment should operate such a dangerous substance detection system.

The justification of the installation can be further increased by the nature of the topography, which mostly increases the vulnerability of the settlement.

The choice of installation sites of the monitoring stations is based on the safety documentation (safety report and external emergency plans) of the dangerous establishments on one hand and the specifics of the surrounding environment of the dangerous establishment on the other.

For the selection of the installation places of the chemical monitoring and public alarm system, the justification for the installation of the technical equipment system was determined by a relative ranking method, according to the following formula:

$$K = 5 \times K_1 + 2 \times K_2 + K_3 + K_4 + K_5 + K_6 + 3 \times K_7 + 10 \times K_8, \tag{5}$$

where K is the resulting index, and K_1, K_2, K_3, K_4, K_5, K_6, K_7, and K_8 are the index components that determine the justification for installing the system.

The K_1 index component is the projected retail consequences of an accident in a dangerous establishment with the most serious residential consequences. The value of the index component can vary from 0 to 10 as follows:

- The value is 0 if it can be assumed that in the settlement or part of the settlement no life would be endangered as a result of a major accident.
- The value is 2–5 if it can be assumed that the hypothetical major accident will take the lives of one or more people in the settlement or part of the settlement.
- The value is 6–8 if it can be assumed that the hypothetical major accident in the settlement or part of the settlement will take the lives of many people.
- The value is 9–10 if it can be assumed that the hypothetical major accident in the settlement or part of the settlement will result in a mass death toll.

The part of the settlement affected by the level lines of the danger zone (10−5, 10−6 fatal events/year), the nature of the accident (grid-point component resulting from a given accident), population density, protection data, etc., may provide an answer to the approximate number of casualties of the hypothetical major accident. If the abovementioned factors were not known precisely, professional assumptions had to be made.

The K_2 index component is taking into account the time available to control the effects of a major accident. The value of the index component can vary from 0 to 10 as follows:

- The value is 0 if the accident affects the lives of the population in a fatal way instantly; for example, an unexpected, unforeseen high-power explosion causes total destruction in the settlement.
- The value is 1–5 if there are only a few options to eliminate the consequences of an accident for the public due to the limited time available; for example, after a rapid malfunction with instantaneous emission, a cloud containing toxic or combustible gases reaches the settlement almost instantly.
- The value is 6–8 if it is possible to eliminate the consequences of the accident for the public due to the time available; for example, after a shorter or longer period of disruption, a cloud of toxic or combustible gases with continuous emissions slowly develops an emergency in the settlement.
- The value is 9–10 if all options are available to eliminate the consequences of the accident for the public due to the time available, where the public is alerted in a timely manner, and sufficient time is available for the application of the full spectrum of population protection after the release of the dangerous substances.

The K_3 index component is used to take the implementation conditions of emergency plan into account. The value of the index component can vary from 0 to 10 as follows:

- The value is 1 if the conditions for the population protection measures (individual and collective protection, evacuation) set out in the external emergency plan are currently fulfilled; for example, external emergency system and a plan for their allocation is available, and the population is prepared for the implementation of the elements for the plan.
- The value is 2–5 if the conditions for the protection of the population (individual and collective protection, evacuation) as set out in the external emergency plan are mostly met. There are shortcomings in the implementation of conditions described in preceding paragraph, but the conditions are given.
- The value is 6–8 if the conditions for the application of population protection measures (individual and collective protection, evacuation) as set out in the external emergency plan are mostly absent.
- The value is 9–10 when the conditions for the application of population protection measures (individual and collective protection, evacuation) set out in the external emergency plan are completely absent or there is not an approved plan yet.

The K_4 index component takes into account the complexity of the vulnerability. That means that the settlement (part of the settlement) is endangered by one or more vulnerability factors. The value of the index component can vary from 0 to 10 as follows:

- The value is 1 if the settlement is threatened by a major accident at a dangerous establishment.
- The value is 2–5 if the settlement is threatened by major accidents at several dangerous establishments.
- The value is 6–8 if the settlement is threatened by multiple types of vulnerability sources.
- The value is 9–10 if it concerns the county centres or a capital city.

The K_5 index component takes into account the cost efficiency of installing the chemical monitoring system. The value of the index component can vary from 0 to 10 as follows:

- The value is 1 if one measuring station serves fewer than 200 protected people.
- The value is 2–5 if one measuring station serves 200–600 protected people.
- The value is 6–8 if one measuring station serves 600–800 protected people.
- The value is 9–10 if one measuring station serves more than 800 protected people.

The K_6 index component takes into account the cost efficiency of the public alarm information system. The value of the index component can vary from 0 to 10 as follows:

- The value is 1 if one monitoring station serves fewer than 100 protected people.
- The value is 2–5 if one monitoring station serves 100–300 protected people.
- The value is 6–8 if one monitoring station serves 300–400 protected people.
- The value is 9–10 if one monitoring station serves more than 400 protected people.

The K_7 index component takes into consideration the technically feasibility of the monitoring stations.

The value of the index component can vary from 0 to 10 as follows:

- The value is 0 if continuous probing of the dangerous substance considered cannot be technically ensured, such probes are not provided by the plant, or the cost of probing is unacceptable.
- The value is 1–5 if, although it is technically ensured that the dangerous substance can be continuously probed, the cost of probing is high, and the measuring stations are difficult to fit into the monitoring system of the dangerous establishment.
- The value is 6–8 if continuous probing of the dangerous substance can be technically ensured, the cost aspects of probing are acceptable, and the measuring stations can be inserted into the plant system.
- The value is 9–10 if continuous probing of the dangerous substance is technically easy and inexpensive, the measuring stations can be easily inserted into the monitoring system of the plant, and their joint technical service can be well ensured.

The K_8 index component comprises cofactors that take into account the involvement of the settlement, and the value of the index component can vary from 0 to 2 as follows:

- The value is 0 if the settlement (part of the settlement) is not in the danger zone, and the effects of a deterministically calculated major accident do not affect the settlement (part of the settlement).
- The value is 1 if the settlement (part of the settlement) is not in the danger zone, but the effects of a deterministically calculated major accident reaches the settlement (part of the settlement) or the settlement (part of the settlement) is in the prevailing (or near probability) wind direction.
- The value is 2 if the settlement (part of the settlement) is in the danger zone or the effects of the deterministically calculated major accident reaches the settlement (part of the settlement).

K can be used to determine the resulting index to set a relative ranking of dangerous establishments, noting that, if the difference in the resulting index (K) does not exceed 10%, it may be considered professionally equal for the installation of a chemical monitoring and

public alarm system for dangerous establishments. The minimum condition for installing the system is as follows:

$$M = K_1 \times K_2 \times K_3 \times K_4 \times K_5 \times K_6 \times K_7 \times K_8 > 0. \tag{6}$$

4. Results and Discussion

4.1. Presentation of Calculation Results for the Determination of Places for Deployment of Chemical Monitoring and Public Alarm System

The applicability of the location determination methodology was checked in the framework of research project supervised by the Hungarian Competent Authority responsible for the implementation of the Seveso Directive. In this project, a total of 215 dangerous establishments involving dangerous substances were examined using the methodology in detail described in the previous section of this study.

As a first step in the course of the analyses of safety documentations (safety reports and external emergency plans) of dangerous establishments, the assessed consequences to the public (K1) of major accidents in a dangerous establishment were evaluated. According to results of the examination of safety documentations, in the case of 49 dangerous establishments, a major accident with disastrous consequences may occur that could endanger the public in the territory of surrounding settlements. In the case of other establishments, the impact of the accident remains within the fence of the dangerous establishment, which is why K1 = 0. It can be assumed that no life in the territory of the settlement or part of the settlement could be endangered as a result of a major accident. In this case,

$$M = K_1 (= 0) \times K_2 \times K_3 \times K_4 \times K_5 \times K_6 \times K_7 \times K_8 = 0. \tag{7}$$

In this case, we can note that the minimum installation conditions were not met.

After the index components K_2, K_3, K_4, K_5, K_6, K_7, and K_8 have been determined, the K originating index may be calculated. The results are a K dangerous establishment chart, as illustrated in Figure 3. In the figure, the dangerous establishments selected for the installation of the chemical monitoring and public alarm system are marked in red, while the facilities where the location of the system is not justified are marked in yellow.
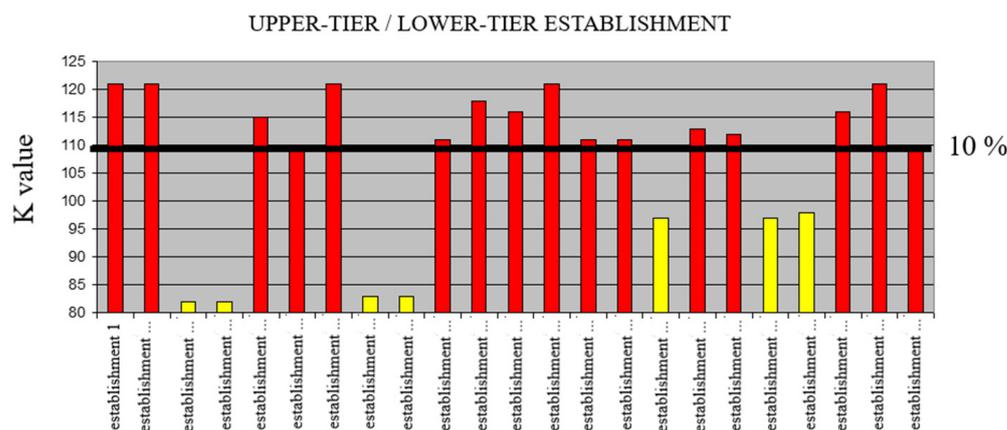

Figure 3. Calculation of K index for upper-tier and lower-tier establishments. Source: own research.

In the example diagram above, the most ideal establishment score for an installation is 121 (highest score); therefore, 16 dangerous establishments with a score above 109 were selected, which are within the 10% derogation.

In reality, because of safety considerations, the system was built in the environment of 20 dangerous establishments.

4.2. Installation and Operational Experience of the System

The main technical information related to the purpose, installation, and use of the system [33] was analysed and evaluated by the authors in this chapter.

The chemical monitoring and public alarm system to be installed in the territory of dangerous establishments ensures the timely detection of dangerous substances released in the event of a possibly major accident, the identification of data on spread of dangerous substances, the display of data for decision-makers, early alarm of the affected population, and activation of the external emergency plans.

The system consists of three main system components: a meteorological and chemical monitoring system, a public alarm and information system, and a communication and IT data transmission system.

The defining element of the system is a meteorological and chemical monitoring subsystem, which measures the weather factors influencing the concentration of gases released into the open air during the event of a major accident and the spread of the generated gas cloud in the immediate vicinity of dangerous establishments and in the surrounding residential area.

The metrological and chemical monitoring systems were installed in the area of the dangerous establishment (in the endangered directions) and on the border of the endangered settlements. An average of four meteorological stations and gas sensors were installed per dangerous establishments, as well as 14 measuring points equipped exclusively with gas sensors.

The measuring equipment of the meteorological and chemical monitoring subsystem to be placed in the residential area shows the appearance and dilution of the gas cloud already indicated by the system at the fence of the dangerous establishment in the residential area. Its main purpose is to provide data for the timely introduction of municipal external population protection measures.

The elements of the public alarm subsystem (siren endpoints) are responsible for informing the public about the emergency situation and what to do in the event of an emergency with signal tones and human speech. The system ensures the continuous operational readiness of the siren endpoints, and it is able to inform the population in the event of a major accident, both remotely controlled and locally; it is suitable for live and stored speech and transmission of predetermined signals, also in addition to being able to perform a silent test.

The communication and IT data transmission subsystem ensures that the data provided by the sensors of a meteorological and chemical monitoring system is properly processed and accessible to all decision-making and emergency response organizations involved. The system has a three-level (local, regional, and national) system of data management and control.

Chemical monitoring and public alarm system deployment is a necessary but not sufficient condition for an effective emergency planning. Effective protection against major accidents involving dangerous substances can be ensured by providing adequately preparation for the effected population.

In order to maintain and monitor the continuous operational safety of the chemical monitoring and public alarm system, the maintenance of the monitoring station is regular, and population alarm stations are tested at specified times, once a month, under reduced operation conditions.

There were no extraordinary incidents related to the operation of the chemical monitoring and public alarm system.

The system can be operated not only in connection with dangerous establishments. It is also possible to install monitoring endpoints at other hazardous facilities, such as in the vicinity of nuclear installations or at the dams of water reservoirs and mining landfill sites. It may be suitable, among other things, for ambient air monitoring, for monitoring of water quality at the entry points of border rivers, or for detecting the effects of flash

floods for small rivers. Endpoints can be tailored to each type and features of natural or manmade disasters.

The emergency services of the decision-making disaster management bodies can decide in real time on the introduction of population protection measures. The monitoring system can significantly reduce or eliminate human loss and property damage.

5. Conclusions

5.1. Contributions to Theory

In recent years, the experiences of major accidents involving dangerous substances demonstrated that a risk level of '0' does not exist. In order to minimise the possible damages, in addition to prevention, proper attention should be paid to external emergency planning, especially to the introduction of population protection measures. Population protection is a complex process and can only be effective if the major accident event is detected on time and the protection measures are implemented in a timely and effective manner. In the case of many types of disasters, such as meteorological events and nuclear accidents, systems are already in place to detect the event and then provide the population with early warning and accident information.

In the event of major accidents involving dangerous substances, response time also plays a key role in the application of population protection measures, especially in the evacuation process. If the event is detected, public alerts are made in a short period of time; consequently, the potential damages of major accidents can be minimised. Unfortunately, there is no uniform methodology used for the protection of the general public in the event of major accidents involving dangerous substances. This is one of the reasons why the mortality rate of the population in the event of major accidents involving dangerous substances may be relatively high.

The other reason is connected with land-use planning matters. As a result of urbanization, the surrounding area of many dangerous establishments has been densely populated. External emergency planning would be inconceivable without adequate technical support and operation of chemical monitoring and population alert systems.

5.2. Contributions to Practitioners

The installation and operation of monitoring and population alert systems, due to the relatively complex technology and equipment, is considered a relatively costly prevention measure. Therefore, the determination of the installation sites for the system is a complex process that requires an appropriate scientific-based selection methodology for location. Therefore, in Hungary, the professional disaster management body has installed a chemical monitoring and public alarm system in the environment of densely populated and high-risk dangerous establishments involving dangerous substances. The system is an integral part of the implementation of Seveso Directive's national regulation on the prevention of major industrial accidents involving dangerous substances. The system provides a basis for timely implementation of internal and external emergency plans, which can significantly reduce the consequences in the event of a major accident.

In this article, the authors presented the application of the Hungarian selection methodology for the determination of installation places of the chemical monitoring stations. This selection methodology is intended to apply a preliminary risk analysis procedure to individual external safety circumstances. To select the dangerous establishments and settlements, the authors developed a methodology based on relative ranking methodology, which consists of eight independent index components. Accurate data were available in the safety reports and emergency plans prepared by the operators and authorities to determine the index components for the methodology. At the time of application of our methodology, it was possible to identify and prioritise dangerous activities with the highest risk of major accidents. The development and the application of this methodology have provided significant practical experience for professionals working for dangerous establishments and disaster management organizations.

5.3. Limitations and Suggestions for Future Research

With the help of the installation and the application of the monitoring and population alert system, the time for decision making is reduced and the subjectivity in decision making on the implementation of population protection measures is eliminated. This means that, if a major incident involving the release of a dangerous substance occurs in the territory of selected dangerous establishment that could affect the population, the disaster management organisation in line with the external emergency plan will detect the dangerous substances immediately after the event, determine an affected area, and alert the population concerned within a short period of time.

According to the authors' experience, in the near future, the operators of dangerous establishments will continue to apply appropriate prevention and consequence reduction measures. However, even with the introduction of the best available technology and safety management system as a preventive measure, major accidents can easily occur. Therefore, the means to reduce the possible consequences of major accidents cannot be avoided.

In our opinion, following the introduction of population protection measures based on the early detection of harmful effects, decision making is based on proper online technical data and the time needed to alert the effected population. This conclusion is particularly true for existing activities with already formed internal and external safety circumstances and land-use planning situations.

On the other hand, these safety aspects can be fully taken into account in the course of designing new dangerous establishments. In this case, cost-effective internal prevention, land-use, and internal emergency planning measures in the field of fire prevention, loss prevention, and process control must be sufficiently effective to eliminate external harmful effects completely. In this situation, there is no need to apply costly external protection measures such as monitoring and early warning systems.

Lastly, we can state that the system can be used for the purposes of any type of rapidly developing natural and manmade disasters. This could be especially useful for the early warning of flash-flood events. Another vital area of use is environment monitoring.

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