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Empirical validation of a real options theory based method for optimizing evacuation decisions within chemical plants

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ABSTRACT

This article empirically assesses and validates a methodology to make evacuation decisions in case of major fire accidents in chemical clusters. In this paper, a number of empirical results are presented, processed and discussed with respect to the implications and management of evacuation decisions in chemical companies. It has been shown in this article that in realistic industrial settings, suboptimal interventions may result in case the prospect to obtain additional information at later stages of the decision process is ignored. Empirical results also show that implications of interventions, as well as the required time and workforce to complete particular shutdown activities, may be very different from one company to another. Therefore, to be optimal from an economic viewpoint, it is essential that precautionary evacuation decisions are tailor-made per company.

1. Introduction

Evacuation management and evacuation decision modeling have been the subject of an important amount of academic and industrial research. In fact, computer-based egress models are an essential alternative to evacuation drills to confidently evaluate evacuation effectiveness. Egress models have been developed on the basis of human movement and behavior studies, and are able to simulate evacuation from buildings and other types of structures. An important review of building evacuation models has been carried out by Kuligowski and Peacock [1]. The authors thoroughly discuss 30 computer-automated models which can provide evacuation information from buildings. Kuligowski and Peacock typify the models as either behavioral models, or movement models, or partial behavior models. Such models may take a variety of parameters into account for performing calculations, for example number and geometry of exits, walking speed (for example of the slowest evacuee), stairway features, fatigue and physical exertion of evacuees, fire behavior, movement capabilities of a cross-section of society, occupants' behaviors before, during and after evacuation, risk perception and its impact on judgment and interaction between individuals and groups, etc. More recent academic research on evacuation theories was for example carried out by Yuan et al. [2], Hanea and Ale [3], Tavares and Galea [4], Gwynne et al. [5], Kuligowski and Mileti [6], Thompson and Bank [7], and Karagiannis et al. [8]. The reader interested in evacuation models and theories is referred to these important research articles. This current paper does not present and/or discuss a type of before mentioned evacuation model or theory; the present article actually investigates whether in a real setting of chemical plants, it is possible to optimize, from an economic perspective, the time at which the decision to evacuate a chemical installation, which is situated nearby chemical installation on fire, is taken.

Emergency preparedness and evacuation management for chemical hazards have been studied and modeled for decades. For example, Sorensen [9] examines the frequency and cause of evacuations associated with chemical accidents from 1980 through 1984. Glickman and Ujihara [10] and Sorensen et al. [11] compare two protective action options (that is, in-place protection and evacuation) in case of hazardous chemical release emergencies and describe a decision aid to this end. Contini et al. [12] discuss the use of GIS in major accident risk management and emergency management. Lindell [13] describes the process by which protective action recommendations are developed in nuclear power plant emergency exercises and provides recommendations from research on emergency response in other types of natural and technological hazards. Georgiadou et al. [14] present a methodology for multi-

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objective optimization of emergency response planning in case of a major accident.

In chemical industrial areas, efficient and effective evacuation management may thus be crucial to avoid mass casualties. For example, in case of a large-scale fire in one of the facilities chemical installations nearby may need to be evacuated. In such case, precautionary evacuation decision problems in chemical industrial areas can be seen from the point of view of a risk-neutral decision maker seeking to minimize costs. In this regard, trade-offs between economic and safety arguments exist in the operation of chemical installations, should fire accidents occur: a sudden installation shutdown might result in substantial economic losses, but may be needed to ensure safety. To address this issue from a real options theory perspective, Reniers et al. [15] initially developed a one-mode approach to calculate the economic gains and/or losses linked to the decision problem whether or not, and when, to evacuate chemical installation(s) threatened by possible so-called fire-induced risks. A fire-induced risk is a risk which originates from another chemical installation on major fire, which is located nearby the facility for which an optimal evacuation decision has to be taken. A major fire may be caused by a variety of reasons and the industrial activities of the chemical installation on fire are not important in this regard. In this paper, only the heat radiation caused by the major fire is taken into account as an essential factor for the decision to evacuate or not the installation nearby.

Reniers et al. [15] conclude from their study that suboptimal interventions may indeed result if option characteristics are overlooked, that is, if the ability to initially defer evacuation and to adjust subsequent decisions to the obtained information is not explicitly taken into account. In theory, unjustified interventions might thus result if the ability to temporarily defer evacuation is ignored. This appeared certainly to be the case when the severity of the potential accident is very uncertain, while the probability of the unwanted event actually taking place is small.

Furthermore, in real industrial settings, chemical plants have multiple modes to stop their production processes, differing with respect to the resulting costs, and with respect to the required time and personnel to complete the shutdown operations. The existence of an additional and more economic (but slower) shutdown mode might encourage the decision maker to stop the production processes earlier, in a less intervening manner, whereas the availability of an additional faster (but less economic) shutdown procedure might stimulate the decision maker to stop the production processes later, in a more intervening manner. Cowing et al. [16] indicate that industrial operations may be interrupted for several reasons such as scheduled maintenance, maintenance on demand, response to warnings, subsystem failure, or a catastrophic accident. In their paper, Cowing et al. use decision analysis to support the management of the short-term trade-offs between productivity and safety in order to maximize long-term performance. The model presented by Cowing et al. actually provides a framework for the evaluation of alternative risk management strategies based on the predicted operating performance of a critical system in term of short-term productivity and failure risks. The authors illustrate their suggested model by the case of planned (or slow) and unplanned (or fast) shutdowns in nuclear power plants. The Cowing et al. article thus indicates the existence and the possibility of a slow and a fast shutdown mode in real industrial settings. The model does not present an evacuation decision model.

To address this more realistic perspective of a possible fast (or unplanned) shutdown and a slow (or planned) shutdown, Reniers et al. [17] refined their original one-mode real options based decision model to a two-mode model. Results from theoretically applying this refined model indicate that ignoring option characteristics may produce suboptimal intervention decisions in complex multiple shutdown settings as well. Greater uncertainty with respect to the evolution of the estimated severity of the threat may give rise to stopping the production processes later, but possibly in a more intervening manner. Whereas the existence of an additional and more economic (but slower) mode might encourage the decision maker to stop the production processes earlier, in a less intervening manner, the availability of an additional and faster (but less economic) shutdown procedure might stimulate the decision maker to stop the production processes later, in a more intervening manner.

Reniers et al. [18] further elaborated the real options based model in a way that precautionary evacuation decision problems can be tackled in a more real-life way. The suggested model allows dealing with the precautionary evacuation decision problem in the (more realistic) case of a major fire accident threat with finite anticipated duration.

Although Reniers et al. [15–18] used realistic figures for presenting numerical examples to illustrate the succeeding (ever more refined) versions of their real options based model, no actual case-study with real data from several existing chemical plants, was presented. Multi-company realistic information should however be used to assess and to validate the model. The goal of this article is therefore to obtain a more profound insight in the real-life scale and the relative importance of the several economic costs and the practical difficulties that may arise when precautionary protective actions (such as evacuation decisions) are imposed on industrial companies.

2. Methodology

The required data were collected by means of semi-structured interviews [19–20]. This data collection method shows three important advantages compared with gathering data via a postal survey or an electronic survey. First, the person-to-person contact between the interviewer and the interviewee can stimulate the latter to ‘confide’ quite delicate information. Second, it allows to ask additional questions for clarification whenever necessary, and to collect qualitative information more easily. Third, semi-structured interviews also allow avoiding possible misinterpretation of questions. The interviews were conducted with either the Head of the plant’s Safety, Health and Environment Department, or with one of its members being knowledgeable of safety measures, industrial production processes, human resources and evacuation management, at each major chemical enterprise. These prevention managers were regarded as experts in the field and considered information-rich people who would probably provide the researchers with a great deal of general background information about the chemical plant as well as about the existing safety and evacuation practices. Based on academic and professional literature and in close collaboration with a questionnaire expert and a company evacuation manager, an exploratory interview guide was developed and used during the interviews to ensure that relevant questions were raised, to maintain some extend of scope and direction, and to guarantee the possibility of objective comparison. The interview guide consisted of a 10-page questionnaire divided into 5 main sections: (i) general company information, (ii) safety and precautionary measures of the company, (iii) evacuation implications, (iv) shelter implications, and (v) the emergency decision process. The questions were drafted in such a way (and in collaboration with experts, as already mentioned) as to minimize the possibility of poly-interpretation.

The interviews lasted for 1–3 h and were carried out at the informants’ workplaces. The interviews started with information about the purpose of the study and how the results from the interviews would be used. All participants were informed of the confidentiality of the interviews and the fact that they were being used for research

Table 1
Required workforce and time to complete a slow shutdown.

Company	Required number of workers	Shutdown activities in open air	Duration to complete the shutdown
1	10–29	>80%	15 min
2	<10	40–60%	72 h
3	<10	20–40%	36 h
4	6–10	50–80%	4–5 h
5	40	<20%	48 h
6	<10	40–60%	36 h

purposes. The questionnaires were filled in by the interviewer during the interviews and based on the interviewees' responses and comments. As the number of interviews was limited (one or two per company), the main drawbacks of semi-structured interviews, that is, that they are costly and time-consuming, were of minor importance. The prevention advisors of nine industrial facilities in the Antwerp port area were asked for information. However, only six of these interviews provided satisfactory detailed information which could be used in our empirical analysis.

The authors anticipate that although the interviews were conducted in 1998, the authors suspect that the gathered data and the results are still valid today.

3. Survey results

The prevention advisors of the industrial companies in the Antwerp harbour region were asked for their opinion of several emergency preparedness and response matters, in a number of semi-structured interviews. The participating companies are active in the field of chemistry, oil refinement, and energy production. All companies have (a majority of) continuous production processes. The results with respect to the implications of the precautionary decision to shutdown the production processes of the participating companies and to evacuate their workforce, are summarized in Sections 3.1 and 3.2, respectively discussing a slow shutdown mode and a fast shutdown mode. Section 3.3 offers a comparative overview of both modes.

The small number of factories cannot cover the whole spectrum of industrial activities. In addition, some of the obtained answers may reflect the individual opinion of the interviewed prevention advisors, having a specific educational background and professional experience. Both drawbacks should be taken into account when interpreting the obtained results.

3.1. *Slow Shutdown*

Table 1 offers an overview of the workforce and time that are required to complete a slow shutdown, that is, a completely safe and economic justified stop. This shutdown procedure refers thus to a shutdown without any residual risks, nor important start-up costs due to damage to the installations.

First, note that company 1 can almost instantaneously shutdown its activities. Stopping the other companies' production processes may require some hours (4) to several days (2, 3, 5, 6). This considerable shutdown period is needed, for example to pump the products-in-process into the tanks, and to wash the reactors and pipelines subsequently in order to prevent any remaining products from coagulating. The shutdown activities are automated to a certain extent, and as a result, the workforce required during this period ranges from a relatively limited number of 6–10 workers (in case of company 4) to a rather extensive number of 40 workers (in case of company 5). A distinction is made between indoor and outdoor shutdown activities. Outdoor shutdown activities typically require workers to manually closing valves, stopping pumps, repairing breakdowns, etc. and have an impact on the duration to shutdown, and hence the costs associated with the shutdown. This financial distinction may for example be crucial to decide between a slow and a fast shutdown. When shutting down the production processes in a slow manner, the workers of company 5 can mainly remain indoors, whereas those of company 1 mainly have to carry out activities in open air; the shutdown of the other factories requires indoor and outdoor activities in more or less the same measure.

The most important costs resulting from a slow shutdown are the losses of the added value during the period of shutdown (that is, opportunity losses). Table 2 presents an overview of estimated financial losses due to a slow shutdown.

Table 2 indicates that the costs are relatively small for companies 1 and 6, but may amount to 187,500 € per day for plant 3. The duration of this unproductive period is determined by the duration of the evacuation itself, and by the time required to restart the production processes afterwards. Companies 1 and 5 can become operational again in a couple of hours (or less); companies 2, 3, 4, and 6 need considerably more time to restart their activities, that is, some days to almost a week.

As the products-in-process are pumped into the tanks, the damage to the installations, as well as the losses of reaction products and reagents, remain moderate. In general, no damage will be caused to the environment as no toxic materials are being released, nor will there be fire or explosion risks.

All companies work on the basis of long term contracts committing them to permanently deliver products or to deliver products at well-specified points in time. As a consequence, an unexpected and unplanned shutdown of the production processes may invoke severe secondary effects for their industrial customers. Moreover, it may result in the temporary or even permanent loss of market share.

3.2. *Fast shutdown*

Table 3 shows the required workforce and time to complete a fast, that is, a 'safe only' shutdown. Such a shutdown refers to an emergency shutdown respecting the safety of the workers and the neighbouring population, as well as the environment, without taking into account the economic implications of this stop. Moreover, some small residual risks may still exist, for example, due to the presence of dangerous materials in the installations.

Companies 1, 4, and 5 can stop the production in a fast manner in 1 h or less; some hours are required to shutdown the production

Table 2
Estimated cost implications of a slow shutdown.

Company	Loss of added value (€ per day)	Loss of products (€)	Costs to installations (€)	Start-up costs (h)	Loss of market share	Secondary costs	Environ-mental damage
1	75,000	0	0	1	Yes	Yes	No
2	150,000	0	0	96	Yes	Yes	No
3	187,500	16,250	0	24	Yes	Yes	No
4	100,000	0	0	24	Yes	Yes	No
5	175,000	0	0	0	Yes	Yes	No
6	65,000	0	12,500	144	Yes	Yes	No

Table 3
Required workforce and time to complete a fast shutdown.

Company	Required number of workers	Shutdown activities in open air	Duration to complete the shutdown
1	10–29	>80%	15 min
2	<10	40–60%	4 h
3	<10	<20%	8 h
4	6–10	50–80%	1 h
5	25	20–40%	1 h
6	<10	40–60%	2–3 h

Table 5
Comparative overview of a slow versus a fast shutdown.

	Slow shutdown mode	Fast shutdown mode
Worker exposure		
•Duration of shutdown	15 min → 72 h	5 min → 8 h
•Number of workers	6 → 40	6 → 29
•Activities in open air	<20% → >80%	<20% → >80%
Economic impact		
•Loss of added value	65,000–187,500 € per day	65,000–187,500 € per day
•Duration of start-up phase	0–6 days	1 h–30 days
•Costs to installations	0–12,500 €	0–1,250,000 €
•Loss of reaction products	0–16,250 €	0–156,250 €
•Loss of market share	Yes	Yes (much more than in case of a slow shutdown mode)
•Secondary costs	Yes	Yes (considerably more than in case of s slow shutdown mode)
•Environmental damage	No	Moderate

processes of companies 2, 3, and 6. A considerable amount of time is gained compared to a slow shutdown: the products-in-process are no longer pumped into the reservoirs, but remain in the reactors or are partly burned off. Furthermore, less workers are needed during the shutdown period for company 5, while the percentage of the workforce that has to perform outdoor activities is smaller for company 3.

Table 4 summarizes the possible financial implications of a fast shutdown.

Table 4 indicates that most companies need (considerably) more time (3–6) or at least as much time (1) to restart their activities, compared to the situation following a slow stop. Only company 2 can restart in a faster way as its reactors are not completely cooled down in case of a fast shutdown. Furthermore, important costs to the installations may result due to the products-in-process sticking to the reactors. In a particular case, reaction products and reagents may be released deliberately in case of company 2. As the design capacity of the flame may be exceeded, some moderate environmental damage may be incurred. The unplanned shutdown of the activities may again result in important secondary effects for the industrial customers. Due to the longer start-up period, both the probability and the extent of the loss of market share increase.

3.3. *Comparative overview*

A comparative overview of the implications resulting from both shutdown modes can be found in Table 5.

Table 5 illustrates that the potential worker exposure will be smaller in case of a fast shutdown as both the time needed to complete the shutdown and the required workforce in open air are smaller than in case of a slow stop. Furthermore, a fast shutdown may result in a much longer start-up phase once the evacuation has been terminated. This does not only imply an increased immediate loss of added value, but also a potentially considerable loss of market share (having a prolonged negative effects on the company's results) and important secondary losses. Moreover, this shutdown procedure may severely damage the installations and result in larger losses of reagents and reaction products. The occurrence of environmental pollution cannot be excluded in advance, but the implications remain moderate in general.

After the production processes have been halted, either in a slow or in a fast way, most companies need one or more workers to safeguard their territories. The goal is to maintain plant safety (for example, to fight the spontaneous combustion of particular products), rather than to protect the site for economic reasons (for example, to prevent theft).

In case the time to shutdown the production processes (which is actually available) is smaller than the time needed for a fast emergency stop, important escalation risks (for example, large-scale fire or a release of toxic materials) may result. These secondary risks should be avoided and are of major importance for those companies that require a considerable amount of time to be safely shutdown.

4. Analysis of empirical data

This section combines the finite difference approximation to the extended precautionary evacuation decision model [15–18], and the empirical results discussed in the previous section, to analyse the importance of options thinking in the precautionary evacuation decision process for a number of industrial companies participating to the study, situated within the second largest chemical cluster worldwide, and some realistic emergency scenarios.

4.1. *Model background information*

In this Subsection some background information from previous articles is summed up and is provided for increasing the understanding and the legibility of the next sections. Reniers et al. [15] describe a simple case of an industrial company that has a single mode to shutdown the ongoing production processes. In these simplified settings, the authors derive an analytical solution for the free boundary triggering immediate evacuation in the particular case of a threat with possibly infinite duration. The analysis was then broadened [17] to industrial companies having several modes to stop their production processes, differing with respect to the resulting costs, and with respect to the required time and

Table 4
Estimated cost implications of a fast shutdown.

Company	Loss of added value (€ per day)	Loss of products (€)	Costs to installations (€)	Start-up costs (h)	Loss of market share	Secondary costs	Environ-mental damage
1	75,000	0	0	1	Yes	Yes	No
2	150,000	0	0	48	Yes	Yes	CO-release
3	187,500	42,500	0	72	Yes	Yes	No
4	100,000	0	0	168	Yes	Yes	No
5	175,000	156,250	250,000	120	Yes	Yes	No
6	65,000	0	1,250,000	720	Yes	Yes	No

personnel to complete the shutdown operations. The basic decision model was thus extended to determine the optimal time and the optimal mode to shutdown ongoing activities in industrial settings. A continuous-time optimal stopping model was developed to support the precautionary evacuation decision problem.

The authors found that greater uncertainty with respect to the evolution of the estimated severity of the threat may give rise to stopping the production processes later, but possibly in a more intervening manner. Whereas the existence of an additional and more economic (but slower) shutdown mode might encourage the decision maker to stop the production processes earlier, in a less intervening manner, the availability of an additional and faster (but less economic) shutdown procedure might stimulate the decision maker to stop the production processes later, in a more intervening manner.

The probability of an accident actually taking place between the time of notification ($t = 0$) and the maximum anticipated duration of the threat ($t = T$) is given by a Poisson arrival rate λ,

$$\begin{cases} \lambda(t) = \lambda, \forall t < T \\ \lambda(t) = 0, \forall t \geq T \end{cases}$$

At any time t, if a (major) accident has not occurred before, there is a probability λdt that it will occur during the next short interval of time dt. In case an accident scenario has not occurred by time T, it can be assumed the emergency situation is again under control and there will be no major accident at all. The corresponding probability density function of an accident actually taking place at time t is $\lambda e^{-\lambda t}$.

Furthermore, the severity of the potential accident is initially assessed to be $x(0) = x_0$. This severity represents the worker risk[1] in case an accident actually takes place and no precautionary evacuation decision has been made.

The evolution of this estimated severity over time, however, is stochastic and depends on the information that safety management will have obtained by the actual time of the decision. The estimated severity of the threat is assumed to follow a geometric Brownian motion without drift, that is, $dx = \sigma x dz$, with σ the variance and dz the increment of a Wiener process. This geometric Brownian motion is a Markov process with independent increments. Moreover, percentage changes in x, that is $\Delta x/x$, are normally distributed with mean 0 and variance $\sigma^2 dt$, indicating no reason exists to a priori assume the estimated severity of the potential accident will deviate (positively or negatively) from its initial estimate x_0.

Table 6
Emergency scenarios.

Scenario	Duration of threat, T (h) (%/h)	Accident arrival rate, λ	Probability of accident $1 - e^{-\lambda T}$ (%)
A	24	0.930	20
B	48	0.465	20
C	72	0.310	20

In order to obtain an analytical, closed-form solution for the severity of the threat triggering immediate evacuation, x_2, and for the expected resulting costs, $F(x)$, the duration of the threat was assumed by Reniers et al. [17] to be possibly everlasting[2]. Reniers et al. [17] further indicate that if the maximum duration of the threat is finite and given by T, a dynamic optimal intervention strategy can be determined by solving the partial differential equation

$$\frac{\sigma^2 x^2}{2}\frac{\partial^2 F(x,t)}{\partial x^2} + \frac{\partial F(x,t)}{\partial t} - (\rho + \lambda) F(x,t) + \alpha \lambda W x = 0 \qquad (1)$$

$$\text{with}: \begin{cases} \alpha = \text{the monetary value assigned to the unit of worker risk for the worst} - \text{case scenario} \\ \text{W} = \text{the number of industrial workers required during shutdown operations} \\ \rho = \text{discount rate} \end{cases}$$

subject to a number of boundary conditions, depending on the assumptions made with respect to the feasible shutdown modes. In a sequel article, Reniers et al. [18] discuss a numerical procedure allowing obtaining a discrete-time approximate solution to (1) without having to assume a possibly everlasting threat. The authors derive an analytical closed-form solution for x_2 and $F(x)$ for this particular case.

By implementing the proposed mathematical model, precautionary evacuation decisions can be tackled in a realistic manner, that is allowing for major accident threats with limited duration.

4.2. Emergency scenarios

Consider three possible emergency scenarios, characterized by an increasing duration of the threat ($T = 24$, 48, and 72 h) and a decreasing Poisson arrival rate λ ($\lambda = 0.930$%/h, 0.465%/h, and 0.310%/h). Table 6 presents the three distinct emergency scenarios.

The overall probability of a major fire actually taking place is equal to 20% in each emergency scenario. This is shown more directly in Fig. 1: the surface below the probability density function for the time of such an accident happening is the same for all emergency scenarios.

As far as the estimated severity x of the potential heat radiation is concerned, based on a literature review [21–28], the following heat radiation figures (in e2 J/sm^2) should be kept in mind: (i) $x = 3$: at high levels of exercise, work duration limitations appear (for emergency responders); (ii) $x = 10$: the maximal duration of heat exposure is further limited (for emergency responders) for high levels of exercise; (iii) $x = 15$: at moderately high levels of exercise, work duration limitations (for emergency responders) appear and they need to be monitored; (iv): $x = 20$: the advantage of wearing protective clothing becomes apparent; risks on burn injuries on unprotected skin arise when exposed to heat radiation; (v) $x = 30$: protective clothing is necessary; work duration (for emergency responders) is limited to 20 min; (vi) $x = 50$: exposure to this level longer than 30 s causes second degree burns over the exposed skin; (vii) $x = 80$: possible failure of unprotected atmospheric vessels, unprotected cryogenic tanks, and unprotected pressurized tanks when exposed a short period of time (30 min); (viii) $x = 320$: possible failure of protected atmospheric vessels, protected cryogenic tanks, and protected pressurized tanks.

It should be noted that the heat radiation exposure figures are highly dependent on the time of exposure to heat, the level of protection for humans and/or equipment, the level of exercise (light work/heavy work) humans have to carry out and/or the type of installation (dangerousness of substances present). Although no concrete figures are discussed/accepted in available literature for very long durations (24 h and more) of heat exposure, when a longer

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[1] The worker risk is the worst-case risk that would result for an average installation operator of the installation under consideration.

[2] As long as the estimated severity of the potential major accident remains below the trigger level x_2, it is optimal to defer the evacuation decision and obtain additional information on the severity of the threat. When the estimate of the severity x equals the threshold x_2, immediate evacuation will result. The expected costs of a dynamic optimal intervention strategy, assuming that the duration of the threat can be everlasting, and provided that a major accident has not taken place earlier, is noted by $F(x)$.

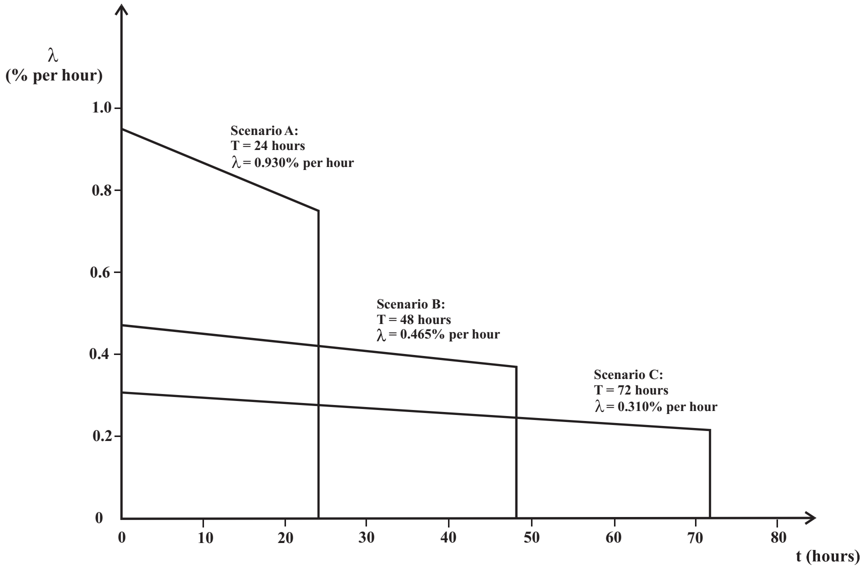

Fig. 1. Probability density functions for the time of a major fire event in each emergency scenario.

duration of heat radiation exposure is envisioned (such as in the case of the three suggested scenarios in this article), heat radiation limits (indicating dangerousness for humans and equipment) decrease sharply.

4.3. Parameter values

This section determines the values of the parameters used in the discrete-time approximation to the extended precautionary evacuation decision model. Taking into account the empirical results with respect to the implications of a slow and fast shutdown, the corresponding parameter values are obtained.

The immediate costs resulting from a slow ($c_{i,s}$) or fast ($c_{i,f}$) shutdown are obtained by adding the costs resulting from the loss of products, the damage sustained to the installations, and the start-up costs. In determining the latter, the loss of added value is assumed to continue during the start-up period. The costs c_d per hour of shutdown are determined by the loss of added value. As far as the number of workers required during slow (W) or fast ($W.\gamma$, with γ = the fraction of workers required during fast shutdown) shutdown activities is concerned, we make the conservative assumption that both the upper limit of the required workforce and the upper limit of the percentage of activities in open air (and thus subject to the heat radiation) prevail. The time needed to complete a slow (L_s) or fast (L_f) shutdown is obtained directly from Tables 1 and 3, respectively. The loss of market share, the secondary losses, and the potential environmental damage are not considered here, as we have not obtained quantitative estimates of their importance in the interviews. Table 7 summarizes the parameter values.

Note that company 1 has only one mode to stop its production: the implications of a slow and fast shutdown are exactly alike. Company *2* will never decide to shutdown the production processes in a slow way as a fast stop results in both smaller costs and a smaller potential worker exposure. Companies *3*, *4*, *5*, and *6* show more ‘typical’ patterns implying that a trade-off has to be made between costs and potential worker exposure when deciding on the shutdown mode.

A mathematical model of an explicit finite difference approximation was developed by Reniers et al. [18]. The general idea underlying finite difference methods is to simplify the differential Eq. (1) by transforming the continuous variables x and t into discrete variables, and by replacing the partial derivatives $\partial^2F(x, t)/\partial x^2$ and $\partial F(x, t)/\partial t$ by finite differences. Therefore, a finite difference mesh is constructed by dividing the maximum duration of the threat into M equally spaced intervals of time Δt. Furthermore, at every discrete point in time $m\Delta t$, with $0 \le m \le M$, $(N+1)$ possible estimates of the severity $n\Delta x$ are considered, with $0 \le n \le N$. The resulting set of difference equations are solved iteratively, starting at the end of the mesh and stepping back through time: $t = T \to t = (T - \Delta t) \to t = (T - 2\Delta t) \to \ldots \to t = 0$. Using this underlying concept, Reniers et al. [18] constructed a finite difference grid by dividing the time horizon T into M equally spaced intervals of time Δt, and the considered interval for values of y up into discrete intervals of equal length Δy. Reniers et al. [18] restrict their attention to values of y in the interval $-N_1\,\Delta y \le y \le N_2\,\Delta y$. By doing so, the infinite mesh is truncated at $y = -N_1\,\Delta y$ and at $y = N_2\,\Delta y$. This truncation introduces an error in the analysis. However, by taking N_1 and N_2 sufficiently large, these errors will not be significant, as the boundary values for large y and large negative y will be very close to the boundary conditions at infinity [18].

As far as the parameters defining the finite difference grid are concerned, we set $\Delta y = 0.05$, $N_2 = 380$, and $N_1 = 20$ (see Reniers et al. [18] for more info). From [18], the length of the time intervals, Δt, and hence, the number of time intervals considered, M, depend on the uncertainty σ[3]. Table 8 provides an overview of the resulting values for Δt and M in each of the considered emergency scenarios if $\sigma = 0.15$, 0.20, and 0.25 h^{-1}. We further assume (see also [15–18]) that the monetary value assigned to the severity $\alpha = 625$ € per person per e2 J/sm^2, while the discount rate $\rho = 0.0007\%$/h.

5. Dynamic optimal versus myopic intervention decisions

The decision maker’s ability to defer an intervention decision in order to obtain additional information on its desirability or optimal timing in case a chemical installation is on fire, has been discussed in the papers on precautionary intervention decision making by Reniers et al. [15–18]. A distinction was made between a myopic decision maker who ignores the prospect of further information

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[3] σ denotes the uncertainty with respect to the evolution of the initially estimated severity of the threat, expressed in h^{-1}. This type of uncertainty is an important contribution to the field of real options analysis research, and recognizes the concept of the ‘option to defer’.

Table 7
Parameter values with respect to the implications of a slow and fast shutdown.

	Company					
	1	2	3	4	5	6
$c_{i,f}$ (in 10^3 €)	3.125	300	605	700	1,281.25	3,200
$c_{i,s}$ (in 10^3 €)	3.125	600	203.75	100	–	402.5
c_d (in 10^3 €/h of shutdown)	3.125	6.25	7.812	4.167	7.292	2.707
L_f (h)	0.25	4	8	1	1	3
L_s (h)	0.25	72	36	5	48	36
W	29	10	10	10	40	10
γ	1	1	1	1	0.625	1

Table 8
Parameter values with respect to the finite difference grid.

Scenario	Uncertainty		
	$\sigma = 0.15\ \mathrm{h}^{-1}$	$\sigma = 0.20\ \mathrm{h}^{-1}$	$\sigma = 0.25\ \mathrm{h}^{-1}$
A	$\Delta t = 0.037037$ $M = 648$	$\Delta t = 0.020833 M = 1152$	$\Delta t = 0.013333 M = 1800$
B	$\Delta t = 0.037037 M = 1296$	$\Delta t = 0.020833 M = 2304$	$\Delta t = 0.013333 M = 3600$
C	$\Delta t = 0.037037 M = 1944$	$\Delta t = 0.020833 M = 3456$	$\Delta t = 0.013333 M = 5400$

(and considers evacuation as a 'now or never' question), and a decision maker who recognizes the option to defer the evacuation decision, and solving the fully dynamic decision problem.

In this section, the dynamic optimal intervention strategies are compared to the intervention decisions resulting from a myopic decision rule for each of the considered companies, in the various emergency scenarios. As Reniers et al. introduce in [18], the relative length of the interval where ignoring option characteristics may result in suboptimal decisions, is expressed as φ. Hence, the more φ exceeds the value 1.0, the more that ignoring the prospect of further information at later stages of the decision process may result in suboptimal decisions.

First, assume that the uncertainty σ with respect to the evolution of the severity of the accident is given by $\sigma = 0.15\ \mathrm{h}^{-1}$. Table 9 shows the myopic and dynamic optimal evacuation trigger levels resulting for the considered companies in each of the emergency scenarios.

Table 9 shows that the dynamic optimal evacuation trigger levels may differ by several orders of magnitude from one company to another. In case of emergency scenario A, the production of company *4* will be stopped in a slow way whenever the estimated severity of the accident exceeds 1.412 e2 J/sm^2. The production processes of company *6* will be shutdown in a fast way for an estimated severity of the accident above 36.41 e2 J/sm^2 only. This is due to the fact that a slow shutdown is quite easy and inexpensive in company *4*, whereas a fast shutdown of the production processes in company *6* is a very intervening and costly decision (as also shown in Table 7).

Table 9
Myopic (x_{1s}, x_{1f}) and dynamic optimal (x_{2s}, x_{2f}) evacuation trigger levels in e2 J/sm^2, in the considered emergency scenarios ($\sigma = 0.15\ \mathrm{h}^{-1}$).

	Company					
	1	2	3	4	5	6
Scenario A						
x_{2s}	0.049	–	–	1.412	–	–
x_{2f}	0.049	3.838	8.978	26.54	3.303	36.41
x_{1s}	0.030	–	–	1.156	–	–
x_{1f}	0.030	3.142	8.214	26.54	2.704	29.81
φ	1.65	1.22	1.09	1.22	1.22	1.22
Scenario B						
x_{2s}	0.110	–	–	1.640	–	16.36
x_{2f}	0.110	4.241	8.978	52.34	4.034	31.91
x_{1s}	0.049	–	–	1.099	–	14.80
x_{1f}	0.049	2.989	6.327	52.34	2.704	31.91
φ	2.23	1.42	1.42	1.49	1.49	1.10
Scenario C						
x_{2s}	0.182	–	–	2.003	–	9.923
x_{2f}	0.182	5.180	9.923	78.14	4.687	46.47
x_{1s}	0.070	–	4.459	1.156	–	7.351
x_{1f}	0.070	2.989	8.124	78.14	2.843	46.47
φ	2.58	1.73	2.23	1.73	1.64	1.25

In every emergency scenario, the multiple φ exceeds unity for every plant, ranging from $\varphi = 1.09$ (company *3*, scenario A) to $\varphi = 2.58$ (company 1, scenario C). Therefore, suboptimal intervention decisions may result in case the prospect of further information at later stages of the decision process is not explicitly taken into account. For organizations 1–5, the multiple φ increases as the duration of the threat T increases and the major fire accident arrival rate λ decreases. This is in agreement with earlier results by Reniers et al. [15–18]. Note that the multiple φ decreases for company 6 when going from emergency scenario A to B. The latter can be explained as follows. In case of company 6, $L_s = 36$ h are required to stop the production processes in a slow way (see Table 7). As a result, a slow shutdown is not a practical option in emergency scenario A. In the second and the third emergency scenario (with an anticipated duration of the threat $T = 48$ and 72 h, respectively), a slow stop enters the set of feasible actions. It was shown in [17] that in this case the multiple φ may indeed decrease.

Tables 10 and 11 show the resulting evacuation trigger levels in case the uncertainty σ with respect to the evolution of the severity of the threat rises to $\sigma = 0.20$ and $\sigma = 0.25\ \mathrm{h}^{-1}$, respectively.

A comparison of the results shows that for every company, in every emergency scenario, the dynamic optimal evacuation trigger level increases as the uncertainty σ increases. As a consequence – note that the myopic evacuation trigger level does not depend on σ – also φ increases when the evolution of the severity of the threat becomes more uncertain. In order to illustrate, consider the situation of company 2 in case of emergency scenario B. The fast evacuation trigger level increases from 4.241 e2 J/sm^2 ($\sigma = 0.15\ \mathrm{h}^{-1}$) to 5.180 e2 J/sm^2 ($\sigma = 0.20\ \mathrm{h}^{-1}$) and 6.327 e2 J/sm^2 ($\sigma = 0.25\ \mathrm{h}^{-1}$), while the multiple φ rises from 1.42 ($\sigma = 0.15\ \mathrm{h}^{-1}$) to 1.73 ($\sigma = 0.20\ \mathrm{h}^{-1}$) and 2.12 ($\sigma = 0.25\ \mathrm{h}^{-1}$). The previously obtained results (in case $\sigma = 0.15\ \mathrm{h}^{-1}$) remain valid. Furthermore, the analysis is but partial as it ignores the loss of market share, the secondary losses, as well as the potential environmental damage. Also the potentially severe financial secondary and higher order risks resulting from an abrupt shutdown are not taken into account here. In situations where these effects are important, the implications from taking a too intervening decision too conservatively may be very significant.

Table 10
Myopic (x_{1s}, x_{1f}) and dynamic optimal (x_{2s}, x_{2f}) evacuation trigger levels in e2 J/sm^2, in the considered emergency scenarios ($\sigma = 0.20\ h^{-1}$).

	Company					
	1	2	3	4	5	6
Scenario A						
x_{2s}	0.057	–	–	1.560	–	–
x_{2f}	0.057	4.241	9.923	26.54	3.837	40.24
x_{1s}	0.030	–	–	1.156	–	–
x_{1f}	0.030	3.142	8.214	26.54	2.704	29.81
φ	1.92	1.35	1.22	1.35	1.42	1.35
Scenario B						
x_{2s}	0.128	–	–	2.003	–	–
x_{2f}	0.128	5.180	10.97	52.34	4.927	49.15
x_{1s}	0.049	–	–	1.099	–	14.80
x_{1f}	0.049	2.989	63.27	52.34	2.704	31.91
φ	2.59	1.73	1.73	1.82	1.82	3.32
Scenario C						
x_{2s}	0.222	–	–	2.572	–	11.53
x_{2f}	0.222	6.651	12.74	78.14	6.018	46.47
x_{1s}	0.070	–	4.459	1.156	–	7.351
x_{1f}	0.070	2.989	8.124	78.14	2.843	46.47
φ	3.16	2.23	2.86	2.23	2.12	1.57

Table 11
Myopic (x_{1s}, x_{1f}) and dynamic optimal (x_{2s}, x_{2f}) evacuation trigger levels in e2 J/sm^2, in the considered emergency scenarios ($\sigma = 0.25\ h^{-1}$).

	Company					
	1	2	3	4	5	6
Scenario A						
x_{2s}	0.067	–	–	1.813	–	–
x_{2f}	0.067	4.928	11.53	26.54	4.459	46.75
x_{1s}	0.030	–	–	1.156	–	–
x_{1f}	0.030	3.142	8.214	26.54	2.704	29.81
φ	2.23	1.57	1.42	1.57	1.65	1.57
Scenario B						
x_{2s}	0.156	–	–	2.447	–	–
x_{2f}	0.156	6.327	12.74	52.34	6.018	60.03
x_{1s}	0.049	–	–	1.099	–	14.80
x_{1f}	0.049	2.989	6.327	52.34	2.704	31.91
φ	3.16	2.12	2.01	2.23	2.23	4.06
Scenario C						
x_{2s}	0.271	–	–	3.303	–	14.80
x_{2f}	0.271	8.541	16.36	78.14	7.728	46.47
x_{1s}	0.070	–	4.459	1.156	–	7.351
x_{1f}	0.070	2.989	8.124	78.14	2.843	46.47
φ	3.86	2.86	3.67	2.86	2.72	2.01

It should be noted that the ‘gains’ from following a dynamic optimal intervention strategy are largest for intermediate values of the estimated severity (that is, heat radiation) of the threat. In case of a very severe threat, the decision maker probably will decide to shutdown the production processes, irrespective of the decision rule that is followed. Similarly, in case of a very small threat, the decision maker will decide to take no action, irrespective of the applied decision strategy.

6. Conclusions

This article describes the testing of a real options based model which was developed and described in earlier papers by the same authors. Some important conclusions with respect to the possible implications of precautionary evacuations in chemical industrial areas can be drawn using this model validation based on real industrial companies' data and information.

A distinction was made between the implications resulting from a ‘completely safe and economic justified’ (or slow) shutdown of the production processes, and those following a ‘safe only’ (or fast) emergency stop. The analysis of the obtained data shows that the potential worker exposure to the consequences of a large fire incident will be smaller in case of a fast shutdown as both the time needed to complete the necessary operations and the required workforce are smaller than in case of a slow stop. However, a fast shutdown is expected to result in a much longer start-up phase once the evacuation has been terminated, implying an increased immediate loss of added value, a potentially considerable loss of market share, and important secondary losses. Moreover, a fast stop may cause severe damage to the installations, and may result in larger losses of reagents and reaction products. In case the available time to halt the production processes is smaller than the time needed for a fast emergency stop, important knock-on risks may result.

For six plants participating in our empirical study, the myopic and dynamic optimal intervention strategies were determined. The dynamic optimal evacuation trigger level was found to differ significantly from one company to another. A comparison between the myopic and the dynamic optimal intervention rules showed that suboptimal interventions may result if the ability to defer evacuation to obtain additional information on the severity of the threat is not explicitly taken into account. The importance of solving the fully dynamic decision problem (instead of its myopic counterpart) was found to increase as the uncertainty with respect to the evolution of the severity of the threat increases, and as the duration of the threat increases, while the major fire accident arrival rate decreases (at least, if an increase in the anticipated duration of the threat does not enlarge the set of feasible actions).

7. Suggestions for further research

Future research could be directed toward applying and extending the decision method in various new directions. Some examples are given hereunder.

The method considered the case where additional information on the severity of the threat may be obtained as time passes by. In real emergencies, the probability of the domino effect actually taking place or the anticipated duration of the threat may be repeatedly updated as well. The inclusion of additional stochastic processes for these parameter values, taking into account the possible correlation between them, would further increase the realism of the decision models (at the expense of increased complexity).

The decision model assumed that the decision maker is a cost minimiser. However, it would be interesting to verify in a number of experiments which decision criterion is (implicitly) used by a decision maker who has to decide on precautionary interventions. Is it expected value, expected utility, one of the ‘safety first’ criteria, or still another decision rule?

The methodology of ‘options thinking’ was used to deal with the precautionary evacuation of a chemical installation's workforce in case there is a risk of an internal domino effect from an installation on fire nearby. It would be interesting to verify whether, and how, this method could be transferred towards other alarm situations. As chemical plants typically are grouped in industrial zones or chemical clusters, an alarm situation (for example, an increased explosion risk, a potential release of toxic pollutants, etc.) in one chemical plant may threaten the workforce of another and nearby chemical company.

The rather complex model may be translated into a user-friendly software package which can be employed by companies and emergency responders for making uncertain decisions quickly in a stressful environment. Based on a combination of a priori gathered information on the one hand, and real-time data on the other hand, the computer-automated tool might provide its user with continuously updated optimized evacuation information in highly stressful situations.

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