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Management of evacuation in case of fire accidents in chemical industrial areas

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Abstract

Trade-offs between economic and safety arguments exist in the operation of chemical installations, should knock-on calamities induced by fire accidents occur: a sudden installation shutdown might result in substantial economic losses, but may be needed to ensure safety. Due to the very rare nature of domino effect risks induced decision problems an adequate evacuation decision aid model to be used by plant safety management does, to the best of the authors' knowledge, not exist. This paper develops a tentative 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 domino effect risks. The proposed model is illustrated by a case-study based on empirical data.

Keywords: Optimal stopping; Intervention decisions; Evacuation decisions; Domino effect risks; Precautionary evacuation; Knock-on prevention; Fire evacuation management

1. Introduction

Accidents resulting from domino effects in a chemical industrial area are defined as those in which a chemical accident becomes the initiating event of one or more accidents, increasing the severity of the original accident [1]. Statistical analysis of such complex domino effect phenomena has been performed by Fievez [2] who investigated a sample of 41 accidents involving escalation effects between 1944 and 1994. Research results indicate approximately 80% of the physical effects produced by the primary accident in domino effects (leading to secondary effects) to be of thermal nature. Hence, eight out of ten major escalation accidents in chemical industrial areas result from a (large-scale) fire incident.

However, some time may be needed to obtain such a major fire accident, for example in the case of lagging fires which arise when certain materials are spilt and soak into lagging or insulation. In such circumstances, a slow reaction continues but the heat generated is unable to get away, leading to a temperature above the auto-ignition point. As a result, a fire arises, possibly aggravating over time. For more examples, the interested reader is e.g. referred to Wells [3] or Lees [4].

Therefore, during a fire it is very important for safety management, economically as well as socially, to be able to decide whether to precautionary evacuate or not, based on rational arguments. The decision problem of preventively evacuating the workers of one or more chemical installations in a chemical plant in case one of these installations (which is on fire) is threatened to initiate a domino effect with a particular probability, can be treated as one of optimal stopping. Company safety management initially holds a call option enabling it to postpone the evacuation decision and obtain further information on the course of the alarm situation of the installation on fire (IoF).[1] As such, safety management has to decide on the optimal point in time to 'exercise' the option, i.e., to take the irreversible decision to evacuate the threatened industrial workers from the IoF itself and – if necessary – from nearby installations.

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[1] The Installation on Fire refers to a chemical installation subject to such adverse conditions (i.e., a fire) that they have the potential to lead to an initiating domino event.

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The time-horizon of this decision problem is finite: within a reasonable period of time, either a domino event effectively takes place, or either the fire alarm is ended as the situation in the Installation on Fire is again under control. Moreover, the call option is American as it can be exercised at every single point in time (and not only at maturity). As such, an analytical closed-form solution cannot be obtained [5,6]. Nonetheless, a continuous-time optimal stopping approach to model the research problem at hand can be developed.

The remainder of the paper proceeds as follows. Section 2 discusses the potentially far-reaching cost implications that might result from imposing evacuation precautions on a chemical industrial installation. Section 3 discusses the research objectives. Section 4 deals with setting forth a continuous-time optimal stopping mode to deal with the precautionary evacuation decision problem. Section 5 discusses a case-study based on empirical data while section 6 draws the conclusions.

2. Evacuation intervention costs in industrial areas

A chemical installation on fire will normally be forced to shut down the ongoing production processes when (part of) its workforce has to be evacuated or relocated. Moreover, the neighbouring chemical installation(s) being threatened by the IoF also might have to be evacuated (and shut down). Evacuation costs traditionally considered in the derivation of the intervention levels and/or in economic precautions include time-independent costs (e.g. transportation costs), time-dependent costs (e.g. loss of income, capital depreciation) and health effects (e.g. human injuries, non-monetary effects) [7–9].

Besides these customary costs due to implementing evacuation measures in general, other costs and potential secondary risks specifically in case of evacuations (and shutdowns) in chemical industrial areas can be conceived [10–12]:

- A considerable part of the products-in-process at the moment of the shutdown might be lost. This will be the case when these products have to be permanently mixed or heated in order to prevent them from coagulating, when particular gasses are burned off deliberately in order to reduce explosion risks, etc. Moreover, important damage may be caused to the installations due to the poisoning of catalysts, products sticking to the reactors, inappropriate cooling down of ovens, etc.
- Costs are not limited to the affected company itself, as they may be essential elements in a production chain, composed of many units located elsewhere. The geographic propagation of the economic implications therefore has to be assessed and appropriately taken into account. These costs are not limited to the duration of the evacuation measure either. It can take days or even weeks before a chemical installation will be fully operational again, once its production processes have been halted. Some important customers might be lost temporarily or forever.
- The magnitude of the incurred losses will strongly depend on the shutdown mode: industrial production processes can be halted either in a completely safe and economic justified way, or in a 'safe only' manner. The former shutdown procedure refers to a shutdown without any residual risks or important start-up costs due to damage to the installations. The latter implies 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 might remain (e.g., due to the presence of toxic materials in the installations). When deciding on the shutdown mode, a trade-off has to be made as the costs of a completely safe and economic shutdown procedure will be smaller, but the required time and personnel to complete the stop will be larger.
- In case the time required to complete a safe emergency shutdown is not available (or respected), and the production processes have to be stopped abruptly, risks may result boosting the costs described above.

The implications of evacuation may differ considerably from plant to plant. Whereas some companies will have the possibility to shut down the production processes, others may not or may have completely different evacuation timings. To keep the problem at hand relatively simple, in this research the shutdown is assumed to be carried out in a 'safe only' way.

3. Research objectives

Precautionary evacuation interventions have to be decided at the moment there is a threat (but far from a certainty) of an imminent escalation event. As such, with a particular probability, an actual domino effect may result subsequently, while with a complementary probability, there will be no domino event at all (e.g. due to appropriate safety engineering actions). The duration of this pre-domino event period may vary from half an hour to several hours and even longer.

The implications of evacuation interventions in chemical industrial areas in case of a *threatening* domino accident have received but marginal attention. The focus of previous research, however the topic is rarely addressed, has been on evacuation interventions *during* an actual (domino) event and in the later phase of a domino accident. Nonetheless, as already mentioned, there may be several hours' warning between an initiating (at first eventually non-domino threatening) fire event and a domino event actually taking place or not. During this pre-domino event phase, there is an increased probability (but no certainty) of a domino event actually taking place in the near future, and the problem faced by the decision maker consists in whether to take precautionary protective actions immediately, later, or not at all. The research objective can be described as:

> Whether or not, when, and under what circumstances to evacuate the workers and operators of the nearby installations threatened by a possible cascade event induced by a chemical installation on fire.

The following aspects will be explicitly taken into account: (i) irreversibility, (ii) ability to defer, and (iii) opportunity costs of evacuation deferral.

Irreversibility. Once a shutdown decision has been made, it is no longer possible to revise this decision without the (prolonged) losses being incurred. The considerable secondary risks for the workers that may result from an abrupt shutdown are not integrated in the analysis due to the lack of quantitative data.

Ability to defer. The evacuation decision can be postponed deliberately. As time passes by, the decision maker may obtain additional information on the severity of the potential domino event, possibly affecting the desirability or optimal timing of the evacuation decision.

Opportunity costs of evacuation deferral. The possibility of a domino event actually occurring while the decision maker is awaiting further information on the severity of the threat does exist. In this case, considerable costs of health effects may result.

In this research, the decision problem is viewed upon from a normative point of view. A single, rational and risk-neutral decision-maker (belonging to the plant safety management), who seeks to minimize costs, is assumed.

4. Continuous-time decision model

4.1. Decision settings

Suppose an installation X operator alerts plant safety management at time $t=0$ that an initiating fire event has taken place that might possibly escalate into a large-scale accident in the near future. This alarm situation threatens the workers and the operators of installation X (i.e., the Installation on Fire) as well as other installations in the surroundings of the IoF. As such, plant safety management has to decide whether or not to evacuate the workers and operators of the adjacent installations on a precautionary basis.

It can be assessed that the probability of escalation 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:

$$\lambda(t) = \lambda, \quad \forall\, t < T, \qquad \lambda(t) = 0, \quad \forall\, t \geq T.$$

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

Furthermore, the severity of the potential knock-on accident is initially assessed to be $x(0)=x_0$. 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, i.e.

$$\mathrm{d}x = \sigma x\,\mathrm{d}z$$

with σ the variance and $\mathrm{d}z$ the increment of a Wiener process. This geometric Brownian motion is a Markov process with independent increments. Moreover, percentage changes in x, i.e. $\Delta x/x$, are normally distributed with mean 0 and variance $\sigma^2\,\mathrm{d}t$, indicating no reason exists to a priori assume the estimated severity of the potential domino event will deviate (positively or negatively) from its initial estimate x_0. Concerning the geometric Brownian motion and its properties, the interested reader is referred to Dixit and Pindyck [6], Hull [5], Neftci [13], and Ohnishi [14].

Assuming safety management to be risk-neutral and to minimize costs, the economic costs resulting from a precautionary evacuation decision at time t can be expressed as [15]:

$$C(t) = c_i + \int_t^T \lambda\,\mathrm{e}^{-\lambda(u-t)} \left(\int_t^u c_\mathrm{d}\,\mathrm{e}^{-\rho(v-t)}\,\mathrm{d}v \right) \mathrm{d}u \tag{1}$$

with c_i is the evacuation immediate costs, t the time variable, T the maximum anticipate duration of the threat, c_d evacuation costs per unit of time during shutdown the period, u the time of a domino accident actually taking place, ρ the discount rate and v is the random time between t and u.

Assume a period of time L is required in order to shut down the industrial production processes and evacuate the workers. Hence, in case evacuation is initiated at time t, it will only be effective from time $(t+L)$ onwards. Therefore, notwithstanding the evacuation decision, some health effects might still be incurred due to the possibility of a domino event actually taking place between the initiation of the evacuation at time t and its termination at time $(t+L)$. As such, the costs of the expected health effects $H(x,t)$ in case evacuation is initiated at time t are given by Pauwels [25]:

$$H(x,t) = \int_t^{t+L} \lambda\,\mathrm{e}^{-(\rho+\lambda)(u-t)} \alpha W \varepsilon[x(u)]\,\mathrm{d}u \tag{2}$$

with α is the monetary value assigned to the severity, W the number of industrial workers required during shutdown operations and ε is the expectation operator.

The latter equation expresses that the costs of the health effects expected to be incurred notwithstanding the shutdown initiation at time t are given by the sum of the present values at time t of the expected health effects costs in case a domino event actually occurs at time u before the shutdown is completed ($t \leq u \leq t+L$), weighted by the corresponding probability of a domino event actually taking place at that point in time u.

It has been suggested that all indirect costs coming from the responsibility of fatalities (e.g. due to a lack or a delay in evacuation) might be up to four times the direct costs, but in practice it seems extremely difficult to estimate this ratio [9,16]. However, it is not required that equation (2) includes these implicit costs, since such costs can be expressed as a multiplication result of the direct costs, implying there is no impact on eventual evacuation decisions based on (2).

4.2. Continuous-time optimal stopping mode

In this section, the intervention decisions taken by a myopic decision maker who ignores the prospect of further information or considers evacuation as a 'now or never' question, are compared to the intervention strategy followed by a decision maker recognizing option characteristics and solving the fully dynamic decision problem.

4.2.1. Myopic intervention rule

A myopic decision maker being part of safety management will decide to evacuate the workers in a chemical industrial environment if the total expected costs of evacuation $TC(x_0,0)$ are smaller than the total expected costs of taking no protective action $TC_n(x_0,0)$. The total expected costs of immediate evacuation are given by

$$TC(x_0, 0) = C(0) + H(x_0, 0) = C(0) + \int_0^L \lambda\, e^{-(\rho+\lambda)t} \alpha W \varepsilon[x(t)]\, dt, \quad (3)$$

whereas the total expected costs of the health effects in case the industrial workers are not evacuated, are

$$TC_n(x_0, 0) = \int_0^T \lambda\, e^{-(\rho+\lambda)t} \alpha W \varepsilon[x(t)]\, dt. \quad (4)$$

Therefore, assuming that $L < T$, condition $TC(x_0,0) \leq TC_n(x_0,0)$ implies:

$$x_0 \geq x_1 = \frac{\rho+\lambda}{\alpha W \lambda} \frac{1}{e^{-(\rho+\lambda)L} - e^{-(\rho+\lambda)T}} C(0). \quad (5)$$

The severity x_1 represents the estimated consequences at which (myopic) safety management will decide to evacuate immediately at the time of the initial alarm, if it is exceeded. Hence, if the initial severity estimate is below this critical level x_1, (myopic) safety management will decide not to evacuate the industrial workers.

Assuming that the duration of the threat can be everlasting, the myopic decision rule expressed in (5) is reduced to (see Appendix A, Section 7):

$$x_1 = \frac{(\rho+\lambda)c_i + c_d}{\alpha \lambda W\, e^{-(\rho+\lambda)L}}. \quad (6)$$

The latter assumption is often made in economics literature: see, e.g., the numerous examples in Dixit and Pindyck [6], or Kelly [17], Dixit [18], Dixit [19], Martzoukos and Teplitz-Sembitsky [20], Mauer and Triantis [21], Mauer and Ott [22], Yin and Newman [23], and Martzoukos [24].

4.2.2. Dynamic optimal intervention rule

As discussed in the introduction, the precautionary evacuation decision problem has some important similarities with typical optimal stopping problems. The decision maker initially has the option to defer the evacuation decision. At every point in time he is offered a binary choice: exercising his option at total evacuation costs, or waiting one more time period dt to observe the evolution of the estimated severity of the potential domino event before taking a decision. In the latter case, however, there is a probability $\lambda\, dt$ a domino event occurs while the decision maker is waiting for further information, resulting in the costs of health effects $\alpha W x$. The expected costs at time t of a dynamic optimal intervention strategy, $F(x, t)$, provided that a domino event has not taken place earlier, are therefore given by

$$F(x, t) = \min\{TC(x, t);\ \lambda\, dt\, \alpha W x + (1 - \lambda\, dt)(1 + \rho\, dt)^{-1} \times \varepsilon[F(x + dx,\ t + dt)|\, x]\}. \quad (7)$$

Note that the costs of deferring the evacuation decision at time t during an infinitesimal period of time dt are given by the probability of a domino event actually taking place in that period of time $\lambda\, dt$, times the resulting costs of health effects $\alpha W x$, added with the complementary probability of a domino event not taking place in that period of time $(1 - \lambda\, dt)$, times the discounted costs of continuing to follow a dynamic optimal intervention strategy at time $t + dt$ (thus $(1 + \rho\, dt)^{-1}\, \varepsilon[F(x + dx, t + dt|x])$. The latter costs are unknown at time t as they depend on the evolution of the severity of the threat dx (and hence, the expectation operator).

At every point in time t, there will be a critical severity $x_2(t)$, whereby evacuation is optimal for $x(t) > x_2(t)$, and waiting is optimal for $x(t) < x_2(t)$. In the latter case, costs of keeping the option 'alive' one more time period are given by

$$F(x, t) = \lambda\, dt\, \alpha W x + (1 - \lambda\, dt)(1 + \rho\, dt)^{-1} \times \varepsilon[F(x + dx,\ \ t + dt)|\, x]. \quad (8)$$

Using Ito's Lemma [6], Pauwels [15] shows that $F(x, t)$ must satisfy the second order partial differential equation:

$$\frac{\sigma^2 x^2}{2} \frac{\partial^2 F(x, t)}{\partial x^2} + \frac{\partial F(x, t)}{\partial t} - (\rho + \lambda) F(x, t) + \alpha \lambda W x = 0, \quad (9)$$

subject to the boundary conditions:

$$F(x_2, t) = TC(x_2, t) = C(t) + \frac{\alpha \lambda W (1 - e^{-(\rho+\lambda)L})}{\rho + \lambda} x_2,$$

$$\frac{\partial F(x_2, t)}{\partial x_2} = \frac{\partial TC(x_2, t)}{\partial x_2} = \frac{\alpha \lambda W (1 - e^{-(\rho+\lambda)L})}{\rho + \lambda},$$

$$F(x, T) = 0, \qquad F(0, t) = 0.$$

The first 'value matching' condition states that at the critical severity $x_2(t)$ the decision maker is indifferent between immediate evacuation and deferring his decision during an additional period of time. The second 'smooth pasting' condition indicates that the total costs of evacuation and the costs of waiting one more time period tangentially meet at the boundary value $x_2(t)$. Both conditions guarantee a smooth, continuous transition between values of x where respectively 'waiting' and 'evacuation' is the optimal decision. Furthermore, the maximum duration of the alarm T is given by the third condition. The final condition implies that once the severity of the potential domino event becomes zero, it will remain zero from then on, and the decision maker will no longer decide to evacuate the industrial workers. This can be interpreted as the end of the alarm before its initially anticipated duration.

An analytical closed-form solution for $F(x, t)$ and for the free boundary $x_2(t)$ triggering evacuation is derived in the particular case that the duration of the threat can be everlasting, implying $\partial F(x, t)/\partial t = 0$. Making the proposed assumption, calendar time t can be left out of the analysis, and the decision problem is reduced to solving the second order differential equation:

$$\frac{\sigma^2 x^2}{2}\frac{d^2 F}{dx^2} - (\rho + \lambda)F + \alpha\lambda W x = 0, \tag{10}$$

subject to the boundary conditions:

$$F(x_2) = TC(x_2) = c_i + \frac{c_d}{\rho+\lambda} + \frac{\alpha\lambda W(1 - e^{-(\rho+\lambda)L})}{\rho+\lambda}x_2,$$

$$\frac{dF(x_2)}{dx_2} = \frac{dTC(x_2)}{dx_2} = \frac{\alpha\lambda W(1 - e^{-(\rho+\lambda)L})}{\rho+\lambda}, \qquad F(0) = 0.$$

Calculation results of (10) offer the analytical solution, i.e.

$$F(x) = \frac{-(c_i + c_d/\rho+\lambda)}{\left[\beta/(\beta-1)(\rho+\lambda)c_i + c_d/\alpha\lambda W e^{-(\rho+\lambda)L}\right]^{\beta}(\beta-1)}x^{\beta} + \frac{\alpha\lambda W}{\rho+\lambda}x, \tag{11}$$

where

$$\beta = \frac{1 + \sqrt{1 + 8(\rho+\lambda)/\sigma^2}}{2} > 1, \tag{12}$$

whereas the free boundary triggering immediate evacuation, x_2, is given by

$$x_2 = \frac{\beta}{\beta-1}\frac{(\rho+\lambda)c_i + c_d}{\alpha\lambda W e^{-(\rho+\lambda)L}}. \tag{13}$$

As long as the estimated severity of the potential knock-on event remains below this 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 following general remarks can be drawn with respect to the influence of the most important parameters on the dynamic optimal evacuation trigger level x_2:

(a) Higher evacuation costs increase the trigger level x_2, and hence, stimulate the decision maker to wait longer before taking the evacuation decision. The evacuation trigger x_2 also increases as more time (L) is required to complete the shutdown. Finally, the more uncertain the evolution of the estimated severity (σ) of the potential domino event is, the higher x_2 will be.
(b) Larger costs of deferring evacuation, due to more workers W being present in the industrial area or higher monetary values α being assigned to the worker risk, lower x_2. As such, the decision maker is encouraged to evacuate sooner.
(c) When an escalation event becomes more probable (λ rises), x_2 decreases.
(d) The larger the uncertainty σ with respect to the evolution of the severity of the threat is, the larger will be the interval where ignoring option characteristics may result in suboptimal intervention decisions.

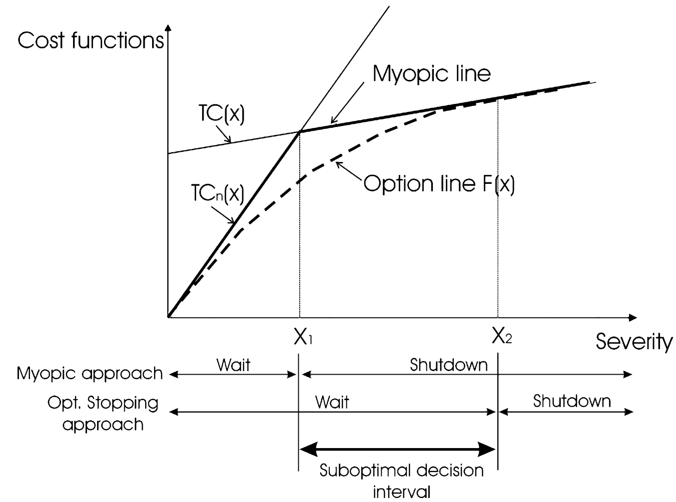

Fig. 1. Myopic versus optimal stopping approach to the precautionary evacuation decision problem.

4.3. Comparison of both decision rules

Comparing (6)–(13), it can be derived that (since $\beta > 1$) $x_2 > x_1$. Fig. 1 illustrates the latter finding. The expected costs in case a myopic decision criterion is followed, are given by the lower envelope of the straight lines $TC(x)$ and $TC_n(x)$; the myopic trigger level is situated at the intersection of both lines. The expected costs in case option characteristics are explicitly recognized, $F(x)$, are an increasing and concave function of x (the ‘option line’); the tangency point of the myopic line with the option line indicates the dynamic optimal evacuation trigger x_2.

Fig. 1 depicts a safety management decision maker ignoring the prospect of further information at later stages of the decision process possibly taking suboptimal intervention decisions. More in particular, he might decide with no justification to evacuate the industrial workers for estimates of the severity of the domino event within the interval $[x_1, x_2]$. The relative length of the suboptimal decision interval (and hence the relative importance of explicitly taking into account the value of future information) is given by $x_2/x_1 = \beta/(\beta - 1)$. The influence of three parameters on this relative importance of postponing the decision can be discussed in this regard. On the one hand, the increase of the uncertainty σ with respect to the evolution of the severity of the threat leads to a larger relative interval length and thus increases the importance of waiting for future information. On the other hand, the value of future decision flexibility decreases when a domino event becomes more probable (λ), or in case less weight (ρ) is assigned to future costs.

5. Empirical case-study

An empirical study with respect to the possible implications of interventions such as evacuation and sheltering in chemical industrial areas was carried out by Pauwels et al. [25]. The results

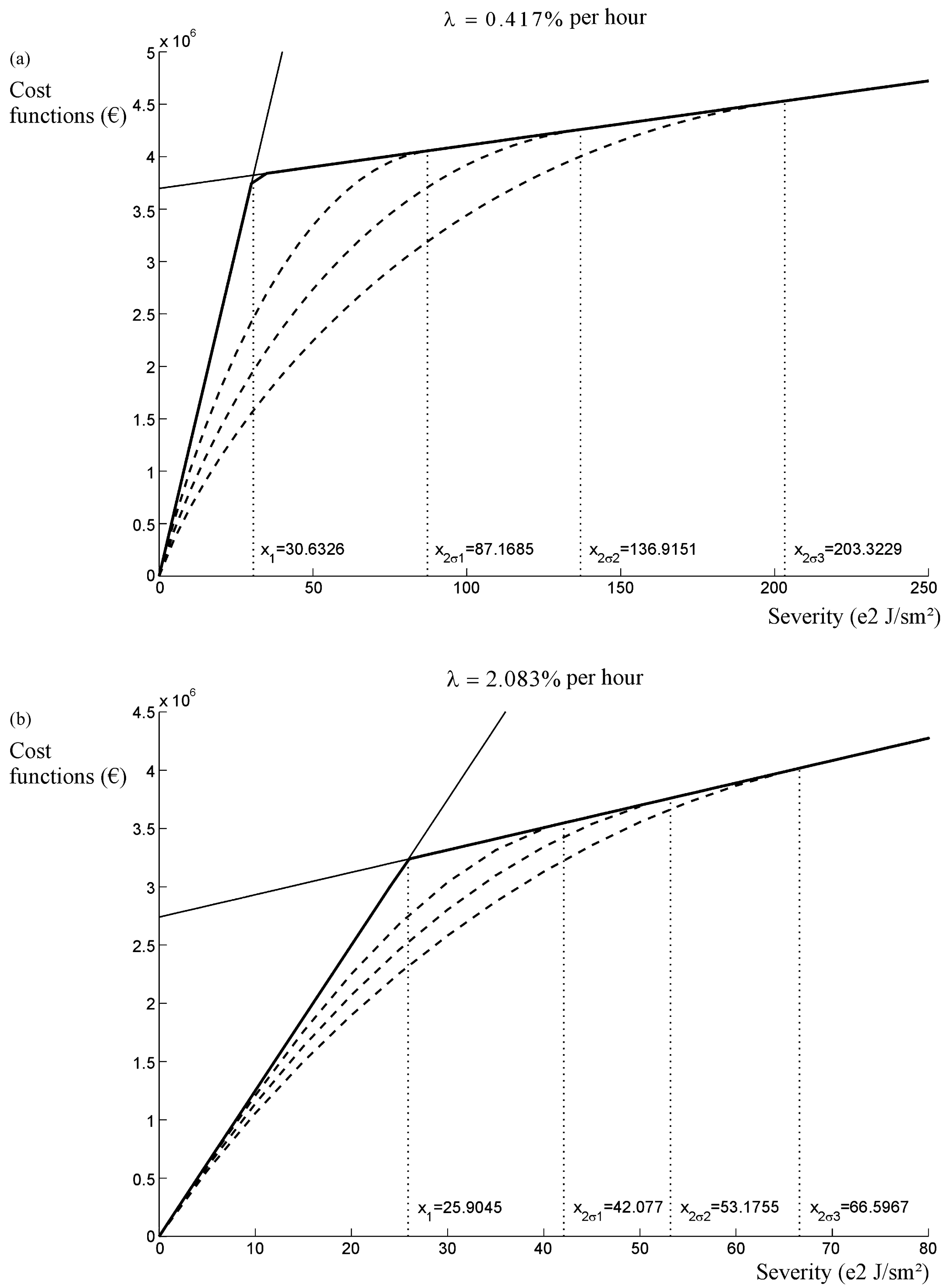

Fig. 2. (a) Expected costs of a myopic and a dynamic optimal intervention strategy, for $\sigma = 0$ (myopic), and $\sigma_1 = 0.10$, $\sigma_2 = 0.15$ and $\sigma_3 = 0.20$ per hour (optimal stopping) in case $\lambda = 0.417\%$ per hour. (b) Expected costs of a myopic and a dynamic optimal intervention strategy, for $\sigma = 0$ (myopic), and $\sigma_1 = 0.10$, $\sigma_2 = 0.15$ and $\sigma_3 = 0.20$ per hour (optimal stopping) in case $\lambda = 2.083\%$ per hour.

were obtained by interviewing the prevention advisors of nine chemical companies in the Antwerp harbour region, which is the second largest chemical cluster worldwide. Taking into account the empirical outcomes, realistic parameter values were derived for W, L, c_i, c_d, α and ρ (see Table 1). These parameters are based on average quantitative estimates for a general emergency scenario.

Given these parameter values, Fig. 2a and b show simulation experiments for different values of both the uncertainty with respect to the evolution of the initially estimated severity of the

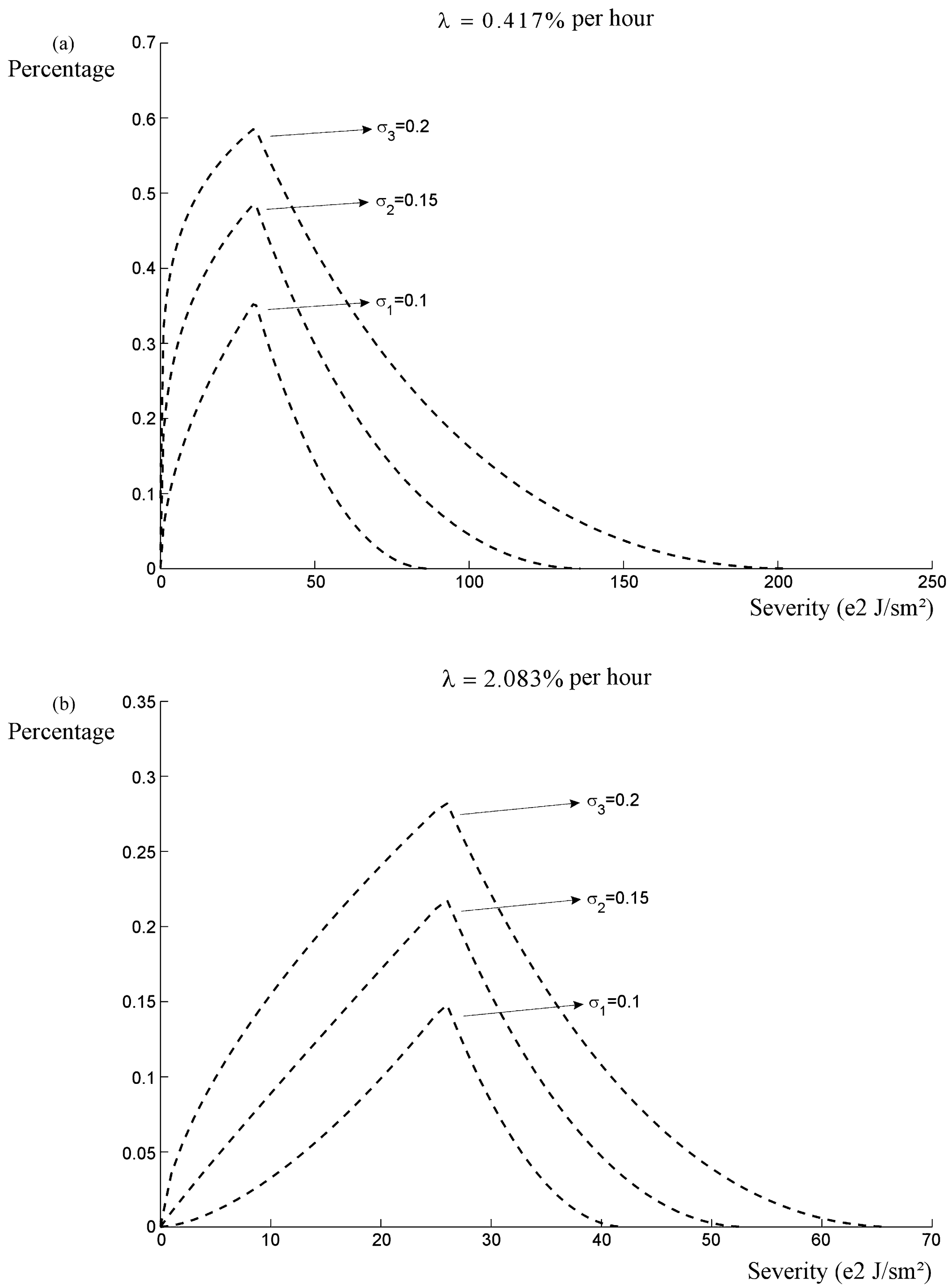

Fig. 3. (a) Relative gains from following a dynamic optimal instead of a myopic intervention strategy for $\lambda = 0.417\%$ per hour. (b) Relative gains from following a dynamic optimal instead of a myopic intervention strategy for $\lambda = 2.083\%$ per hour.

domino event, i.e. σ, and the rate per hour λ at which a domino event might take place.[2]

The costs that are expected to result from a dynamic optimal (dotted lines) and a myopic (straight line) intervention strategy are plotted as a function of the initial estimate of the severity of the potential domino event, x. The tangency points of intervention strategy lines indicate the estimate of the severity of the potential domino event x_2 that will trigger immediate evacuation. For values of x in the interval $[x_1, x_2]$, suboptimal decisions might result if option characteristics are ignored.

The myopic intervention decision criterion, stating that evacuation should be initiated as soon as the expected costs resulting from this decision are smaller than the expected costs of taking no evacuation actions, is gravely erroneous: for the

[2] A rate of e.g. 0.417% per hour corresponds to a domino event actually taking place within the next 24 h with a probability of approximately 10%; if $\lambda = 2.083\%$, there is a fifty-fifty percent chance of a domino event taking place within the next 24 h.

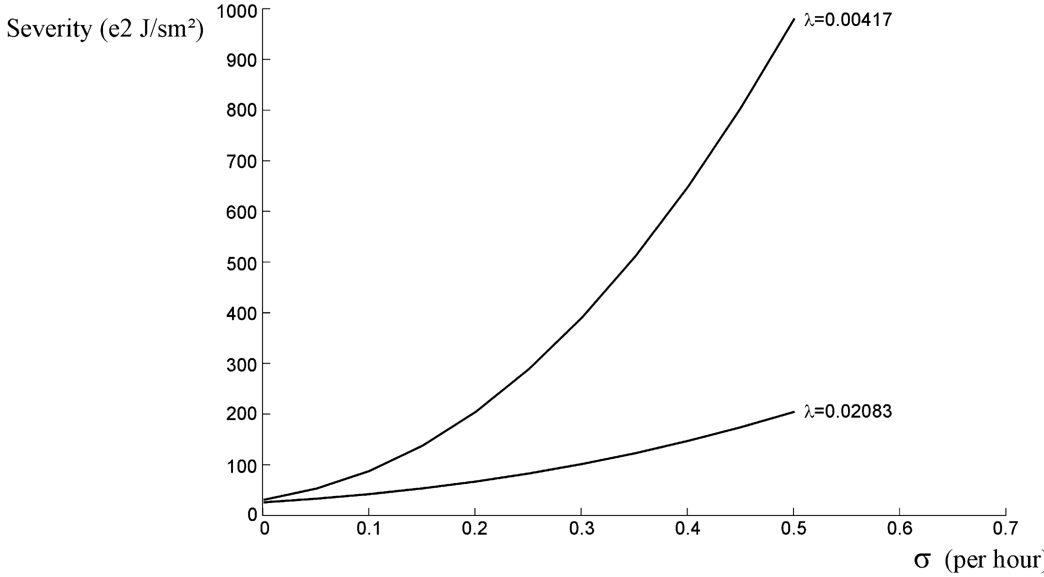

Fig. 4. Dynamic optimal evacuation trigger level x_2 as a function of σ, for λ = 2.083% per hour and λ = 0.417% per hour.

Table 1
Case-study parameter values

Parameter	Value
W	200 workers
L	8 h
c_i	2.5 million €
c_d	5000€ per hour of shutdown
α	625€ per person per E2 J/sm^2
ρ	0.0007% per hour[a]

Source: Ref. [25].
[a] ρ = 0.0007% per hour corresponds to roughly 6% on a yearly basis.

least uncertain situations ($\sigma_1 = 0.10$), the estimated severity of the potential domino event must be approximately 2.8 times (case λ = 0.417) or 1.6 times (case λ = 2.083) as high as this myopic trigger level, before safety management should decide to evacuate. For situations in which the uncertainty is higher, even much larger discrepancies between myopic- and optimal stopping levels are observed.

Fig. 2a and b also illustrate the suboptimal character of evacuation decisions (a) decreasing with increasing domino event probability and (b) increasing with higher uncertainty about the evolution of the severity of the domino event.

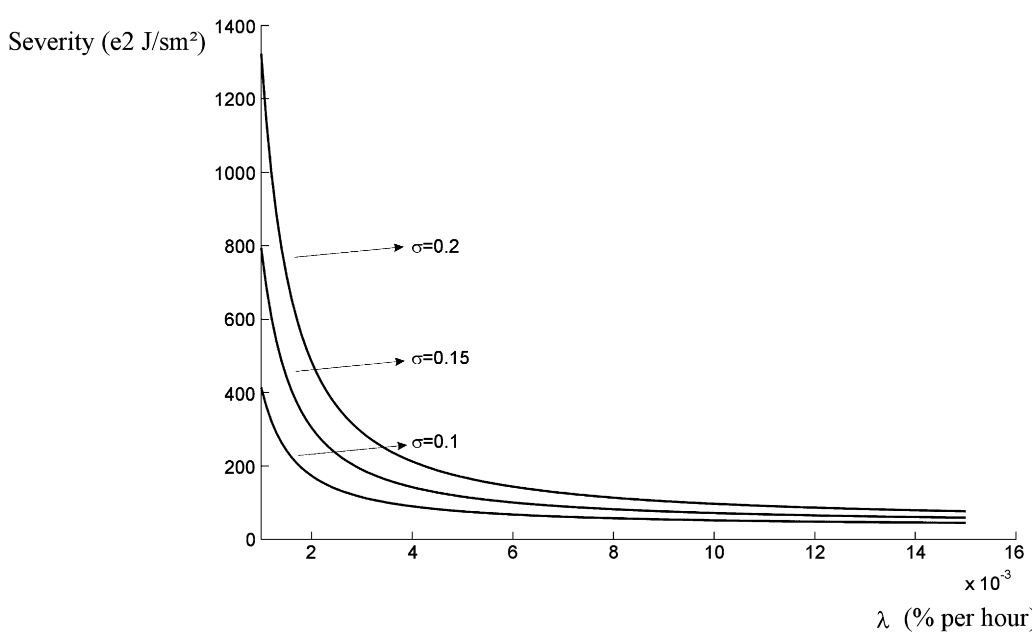

Fig. 5. Dynamic optimal evacuation trigger level x_2 as a function of λ, for $\sigma_1 = 0.10$, $\sigma_2 = 0.15$ and $\sigma_3 = 0.20$ per hour.

Fig. 3a and b depict the fraction of the costs (in percentage) resulting from a myopic intervention strategy expected to be avoided by explicitly taking into account the ability to defer the evacuation decision. Note that for values of x in the interval [0, x_1] following a dynamic optimal intervention strategy instead of a myopic decision rule may result in a reduction of the expected intervention costs, only if a myopic decision maker who initially decides not to evacuate the workers is assumed never to revise his decision afterwards (which is very unlikely). For values of x above x_2, the resulting costs under a myopic and a dynamic optimal intervention rule are equal as the decision maker will immediately decide to evacuate the workers in both cases.

The dependency of x_2 on σ is shown in Fig. 4 for the different values of λ. The lower the probability of a domino event actually taking place, the more sharply x_2 will rise with σ.

Fig. 5 shows the dependency of the free boundary x_2 on λ, for increasing levels of uncertainty. The larger the uncertainty with respect to the evolution of the severity of the threat, σ, the more sharply x_2 rises when λ declines.

In summary, Figs. 2–5, based on empirical data, show the advantages and the potential gains that could be derived in chemical companies from making evacuation decisions which have to be taken in consequence of fire events possibly leading to escalation effects, more rational.

6. Conclusions

A fire may take time to develop. During that time interval evacuation decisions of the installation on fire as well as of other installations in its neighbourhood continuously have to be evaluated. Precautionary evacuating installations' staff can be of crucial importance for saving lives in case the fire leads to a major domino accident. However, precautionary evacuating can also lead to important unnecessary costs if there is no knock-on effect at all. In this paper, a (simplified) two-period example of the precautionary evacuation decision problem was first solved from the point of view of a myopic decision maker considering evacuation as a 'now or never' question, or ignoring the prospect of further information. Second, a dynamic optimal intervention strategy was determined by dealing with the precautionary evacuation decision problem as one of optimal stopping, a specific category of dynamic programming problems. A comparison of both decision rules shows that suboptimal interventions may result if option characteristics are overlooked, i.e., if the ability to initially defer evacuation and to adjust subsequent decisions to the obtained information is not explicitly taken into account. This important insight is mathematically analyzed in a continuous-time optimal-stopping framework. A numerical example demonstrates that unjustified interventions might result if the ability to temporarily defer evacuation is ignored. This is definitely the case when the severity of the potential domino event is very uncertain, while the probability of the escalation event actually taking place is small. A tentative model is proposed that allows calculating the expected costs of the optimal intervention strategy, i.e., a strategy that minimizes both the immediate costs and the expected future costs knowing that subsequent decisions will be taken optimally too, contingent on the state of nature that is revealed at that time.

Appendix A

This appendix shows how the myopic decision rule in case the anticipated duration of the threat T is infinite:

$$x_1 = \frac{(\rho+\lambda)c_i + c_\mathrm{d}}{\alpha\lambda W\,\mathrm{e}^{-(\rho+\lambda)L}},$$

can be derived from:

$$x_0 \geq x_1 = \frac{\rho+\lambda}{\alpha W\lambda}\frac{1}{\mathrm{e}^{-(\rho+\lambda)L} - \mathrm{e}^{-(\rho+\lambda)T}}C(0).$$

Under the assumption that $T=\infty$ and taking into account (1), Eq. (5) can be rewritten as

$$x_1 = \frac{\rho+\lambda}{\alpha W\lambda\,\mathrm{e}^{-(\rho+\lambda)L}}\left[c_i + \int_0^\infty \lambda\,\mathrm{e}^{-\lambda u}\left(\int_0^u c_\mathrm{d}\,\mathrm{e}^{-\rho v}\,\mathrm{d}v\right)\mathrm{d}u\right]. \tag{14}$$

Standard calculations yield:

$$x_1 = \frac{\rho+\lambda}{\alpha\lambda W\mathrm{e}^{-(\rho+\lambda)L}}\left[c_i + \frac{c_\mathrm{d}}{\rho+\lambda}\right], \tag{15}$$

or

$$x_1 = \frac{(\rho+\lambda)c_i + c_\mathrm{d}}{\alpha\lambda W\,\mathrm{e}^{-(\rho+\lambda)L}}.$$

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