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A multiple shutdown method for managing evacuation in case of major fire accidents in chemical clusters

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Abstract

This paper may be regarded as the second part of a larger article. The basic decision model developed in the first part of the article by Reniers et al. [G.L.L. Reniers, N. Pauwels, A. Audenaert, B.J.M. Ale, K. Soudan, Management of evacuation in case of fire accidents in chemical industrial areas, J. Hazard. Mater., 147 (2007) 478–487] is extended to determine both the optimal time and the optimal mode to stop the ongoing activities in case of a major fire possibly giving rise to an escalating event. 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.

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

1. Introduction

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.[2] However, precautionary evacuation can also lead to important unnecessary costs if there is no knock-on effect at all. Reniers et al. [1] solved a (simplified) two-period example of the precautionary evacuation decision problem 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. A dynamic optimal intervention strategy was determined by dealing with the precautionary evacuation decision problem as one of optimal stopping. The authors showed 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 in the simple case of an industrial company that has only a single mode to shut down the ongoing production process. This assumption allowed deriving an analytical expression for the free boundary triggering evacuation in a relatively simple setting. A numerical example demonstrated 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. Some recent studies on domino effect probability and impact assessments are carried out by Cozzani et al. [2–5].

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[2] 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 (Delvosalle [9]; Lees [10]).

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However, in reality chemical plants might have several modes to shut down their production processes, each drastically different with respect to the resulting costs, and the required time and personnel to complete the necessary shutdown operations [6–8]. The slow shutdown procedure is the procedure personnel are usually trained for in chemical plants. To the best of the authors' knowledge, there are no additional risks or costs involved in a slow evacuation procedure compared with a fast evacuation procedure. The latter procedure may only be implemented in facilities where an 'emergency shutdown' button exists. In this paper, we extend our basic decision model to determine both the *optimal time* to shut down the ongoing production processes, and the *optimal mode* to do so. Although this modification complicates the algebra to some extent, we will show in this paper that the basic ideas and previously obtained results will remain valid.

The method described in this paper can be incorporated into the different phases of emergency management (i.e., mitigation, preparedness, response and recovery) by elaborating and implementing emergency procedures at different levels (slow and fast) depending on the evolution of the estimated severity and of the uncertainty of a potential major fire incident.

As already mentioned, the original decision settings were introduced in the paper of Reniers et al. [1]. Section 2 explains the modified decision settings and discusses the various modes to shut down industrial production processes. Section 3 deals with the precautionary evacuation decision problem from the point of view of a myopic decision maker. In Section 4, the fully dynamic decision problem is solved. The obtained results are illustrated in a numerical example in Section 5. Section 6 concludes this paper.

2. Modified decision settings

Most chemical industrial companies can shut down the ongoing production processes either in a completely safe and economic justified (or slow) way, or in a 'safe only' (or fast) manner. The former procedure refers to a slow shutdown without any residual risks, nor important start-up costs due to damage of the installations; the latter shutdown procedure implies an emergency stop respecting the safety of the workers and the neighbouring population, as well as the environment, but without taking into account the economic implications of this stop. Moreover, some small residual risks may still remain (e.g., due to the presence of toxic materials in the installations).

Assuming safety management to be risk-neutral and to minimize costs, the economic costs $C_\mathrm{f}(t)$ of the decision to quickly shut down the production processes at time t can be expressed as (1). The costs $C_\mathrm{s}(t)$ induced by the decision to slowly shut down the production processes at time t are given by (2):

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

$$C_\mathrm{s}(t) = c_{\mathrm{i,s}} + \int_t^T \lambda\, \mathrm{e}^{-\lambda(u-t)} \cdot \left(\int_t^u c_\mathrm{d}\, \mathrm{e}^{-\rho(v-t)}\, \mathrm{d}v \right) \mathrm{d}u \tag{2}$$

with $c_{\mathrm{i,f}}$, immediate costs of a fast shutdown; $c_{\mathrm{i,s}}$, immediate costs of a slow shutdown; t, time variable; T, maximum anticipated duration of the threat; c_d, evacuation costs per unit of time during the shutdown period; u, time of a domino accident actually taking place; ρ, discount rate; v, random time between t and u.

It should be noticed that u is influenced by the segmentation of a plant into fire zones, the type of possible domino accident taking place, the type of protection of the equipment within the installation on fire, the quantities or characteristics of the hazardous materials which are handled within the installation, etc. Therefore, different shutdown procedures can be worked out depending on which part of the plant is affected by the fire and depending on the accident scenario parameters.

As $c_{\mathrm{i,s}} \le c_{\mathrm{i,f}}$, we have that $C_\mathrm{s}(t) \le C_\mathrm{f}(t)$. Furthermore, assume the number of workers required during a fast shutdown is only a fraction γ (with $\gamma < 1$) of the workers needed during a slow shutdown, and also that less time is required to complete a fast shutdown (L_f) than is needed for a slow stop (L_s). Then, the expected costs of the health effects, notwithstanding the initiation of a fast ($H_\mathrm{f}(x,t)$) or slow ($H_\mathrm{s}(x,t)$) evacuation, are given by

$$H_\mathrm{f}(x, t) = \int_t^{t+L_\mathrm{f}} \lambda\, \mathrm{e}^{-(\rho+\lambda)(u-t)} \cdot \alpha \cdot \gamma \cdot W \cdot \varepsilon[x(u)]\, \mathrm{d}u \tag{3}$$

$$H_\mathrm{s}(x, t) = \int_t^{t+L_\mathrm{s}} \lambda\, \mathrm{e}^{-(\rho+\lambda)(u-t)} \cdot \alpha \cdot W \cdot \varepsilon[x(u)]\, \mathrm{d}u \tag{4}$$

with $H_\mathrm{f}(x, t) \le H_\mathrm{s}(x, t)$

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

In case evacuation is initiated at time t, it will only be effective from time ($t + L_\mathrm{f}$), or time ($t + L_\mathrm{s}$) onwards, in case of a fast (Eq. (3)) and a slow (Eq. (4)) shutdown, respectively. The latter equations 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 fast or slow shutdown is completed ($t \le u \le t + L_{\mathrm{f\ or\ s}}$), weighted by the corresponding probability of a domino event actually taking place at that point in time u.

Taking into account (1) and (3), and (2) and (4), the total expected costs of a fast ($\mathrm{TC_f}(x,t)$) and a slow ($\mathrm{TC_s}(x,t)$) shutdown are given by

$$\mathrm{TC_f}(x, t) = C_\mathrm{f}(t) + H_\mathrm{f}(x, t) \tag{5}$$

$$\mathrm{TC_s}(x, t) = C_\mathrm{s}(t) + H_\mathrm{s}(x, t) \tag{6}$$

Fig. 1a and b plot the relationships between the various parameters with respect to a fast and a slow shutdown decision. A fast shutdown requires fewer workers ($\gamma \le 1$) during a smaller period of time ($L_\mathrm{f} \le L_\mathrm{s}$), and hence, results in a smaller expected costs of health effects: $H_\mathrm{f}(x,t) \le H_\mathrm{s}(x,t)$. However, this goes at the expense of the economic evacuation costs, since $C_\mathrm{s}(t) \le C_\mathrm{f}(t)$.

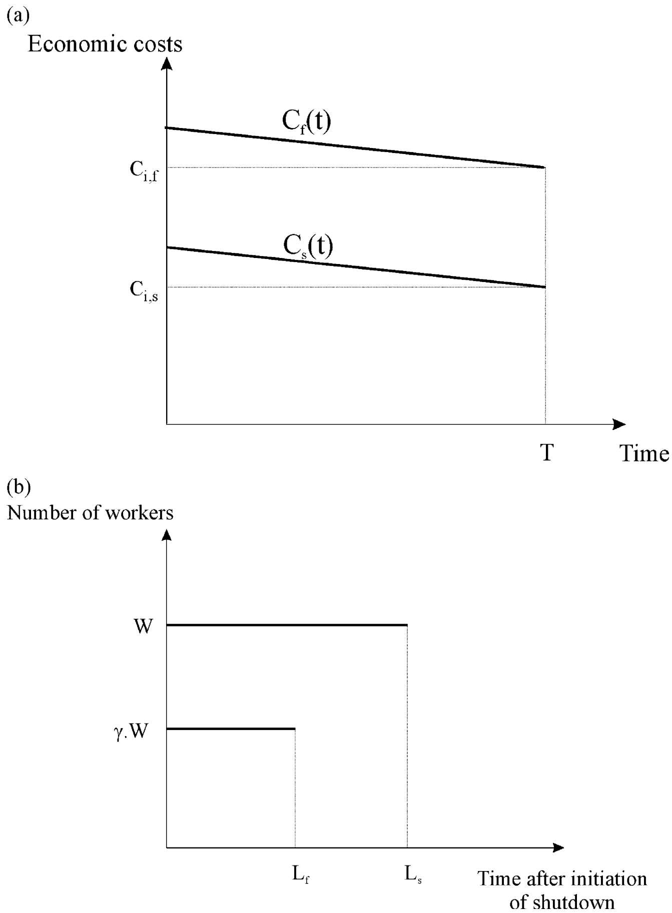

Fig. 1. (a) Economic costs of fast and slow shutdown. (b) Number of workers required during fast and slow shutdown.

3. Myopic intervention rule

A governmental decision maker who ignores the prospect of further information at later stages of the decision process or considers the precautionary evacuation as a 'now or never' question, will take the decision (i.e., fast evacuation, slow evacuation, or no protective action at all) that results in the smallest expected costs.

The total expected costs of an immediate fast ($\mathrm{TC_f}(x_0, 0)$) and slow ($\mathrm{TC_s}(x_0,0)$) evacuation are given by

$$\mathrm{TC_f}(x_0, 0) = C_\mathrm{f}(0) + H_\mathrm{f}(x_0, 0) = C_\mathrm{f}(0) + \int_0^{L_\mathrm{f}} \lambda\, \mathrm{e}^{-(\rho+\lambda)t} \cdot \alpha \cdot \gamma \cdot W \cdot \varepsilon[x(t)]\, \mathrm{d}t, \tag{7}$$

$$\mathrm{TC_s}(x_0, 0) = C_\mathrm{s}(0) + H_\mathrm{s}(x_0, 0) = C_\mathrm{s}(0) + \int_0^{L_\mathrm{s}} \lambda\, \mathrm{e}^{-(\rho+\lambda)t} \cdot \alpha \cdot W \cdot \varepsilon[x(t)]\, \mathrm{d}t, \tag{8}$$

The expected costs of the health effects in case the industrial workers are not evacuated are given by $\mathrm{TC_n}(x_0,0)$, with

$$\mathrm{TC_n}(x_0, 0) = \int_0^{T} \lambda\, \mathrm{e}^{-(\rho+\lambda)t} \cdot \alpha \cdot W \cdot \varepsilon[x(t)]\, \mathrm{d}t. \tag{9}$$

As a result, the expected costs $G(x_0,0)$ resulting from a myopic intervention rule are given by

$$G(x_0, 0) = \min\{\mathrm{TC_f}(x_0, 0); \mathrm{TC_s}(x_0, 0); \mathrm{TC_n}(x_0, 0)\} \tag{10}$$

Under the assumption of a possibly everlasting threat ($T \to \infty$),[3] Eqs. (7)–(9) reduce to

$$\mathrm{TC_f}(x) = c_{\mathrm{i,f}} + \frac{c_\mathrm{d}}{\rho+\lambda} + \frac{\alpha \cdot \lambda \cdot \gamma \cdot W \cdot (1 - \mathrm{e}^{-(\rho+\lambda)L_\mathrm{f}})}{\rho+\lambda} x \tag{11}$$

$$\mathrm{TC_s}(x) = c_{\mathrm{i,s}} + \frac{c_\mathrm{d}}{\rho+\lambda} + \frac{\alpha \cdot \lambda \cdot W \cdot (1 - \mathrm{e}^{-(\rho+\lambda)L_\mathrm{s}})}{\rho+\lambda} x \tag{12}$$

$$\mathrm{TC_n}(x) = \frac{\alpha \cdot \lambda \cdot W}{\rho+\lambda} x \tag{13}$$

Standard calculations (cf. [1]) yield that the critical severity of the potential domino effect triggering a slow ($x_{1\mathrm{s}}$) or fast ($x_{1\mathrm{f}}$) evacuation is given by

$$x_{1\mathrm{s}} = \frac{(\rho+\lambda)c_{\mathrm{i,s}} + c_\mathrm{d}}{\alpha \cdot \lambda \cdot W \cdot \mathrm{e}^{-(\rho+\lambda)L_\mathrm{s}}} \tag{14}$$

$$x_{1\mathrm{f}} = \frac{(\rho+\lambda) \cdot (c_{\mathrm{i,f}} - c_{\mathrm{i,s}})}{\alpha \cdot \lambda \cdot W \cdot (1 - \mathrm{e}^{-(\rho+\lambda)L_\mathrm{s}} - \gamma \cdot (1 - \mathrm{e}^{-(\rho+\lambda)L_\mathrm{f}}))} \tag{15}$$

in case condition

$$\frac{(\rho+\lambda)c_{\mathrm{i,s}} + c_\mathrm{d}}{(\rho+\lambda)c_{\mathrm{i,f}} + c_\mathrm{d}} < \frac{\mathrm{e}^{-(\rho+\lambda)L_\mathrm{s}}}{1 - \gamma(1 - \mathrm{e}^{-(\rho+\lambda)L_\mathrm{f}})} \tag{16}$$

is satisfied.[4] For estimates of the severity below $x_{1\mathrm{s}}$, the decision maker will decide to take no protective action at all; for estimates of the severity between $x_{1\mathrm{s}}$ and $x_{1\mathrm{f}}$, he or she will decide to slowly shut down the ongoing production processes; a fast shutdown will result in case the critical level $x_{1\mathrm{f}}$ is exceeded.

In case condition (16) is not satisfied, a slow evacuation will never be decided as it is dominated by taking no action or a fast shutdown, depending on the severity of the potential domino event. The trigger level of a fast evacuation is then given by

$$\tilde{x}_{1\mathrm{f}} = \frac{(\rho+\lambda)c_{\mathrm{i,f}} + c_\mathrm{d}}{\alpha \cdot \lambda \cdot W \cdot (1 - \gamma(1 - \mathrm{e}^{-(\rho+\lambda)L_\mathrm{f}}))} \tag{17}$$

As long as the estimate of the severity of the potential knock-on accident does not exceed $\tilde{x}_{1\mathrm{f}}$, the decision maker will decide to take no protective action; for initial estimates of the severity exceeding this trigger level, a fast evacuation will result. Both possibilities are illustrated in Fig. 2a and b. Note that in the case condition (16) is satisfied (Fig. 2a), $G(x)$ is the lower envelope of the straight lines $\mathrm{TC_n}(x)$, $\mathrm{TC_s}(x)$, and $\mathrm{TC_f}(x)$. In the opposite case (Fig. 2b), $G(x)$ is the lower envelope of $\mathrm{TC_n}(x)$ and $\mathrm{TC_f}(x)$.

[3] The latter assumption is often made in economics literature: see, e.g., the numerous examples in Dixit and Pindyck [11], or Kelly [12], Dixit [13,14], Martzoukos and Templitz-Sembitzky [15], Mauer and Triantis [16], Mauer and Ott [17], and Yin and Newman [18], Matzoukos [19].

[4] This condition states that $\mathrm{TC_s}(x_{1\mathrm{s}}) < \mathrm{TC_f}(x_{1\mathrm{s}})$.

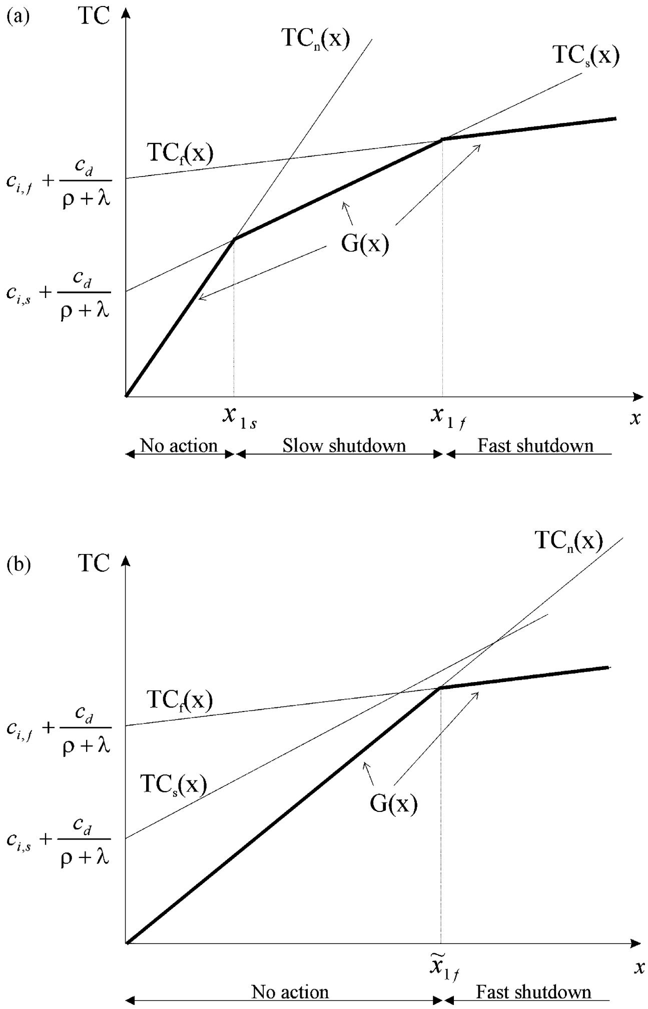

Fig. 2. (a) Myopic approach to the precautionary evacuation decision problem in case of multiple shutdown modes where $((\rho+\lambda)c_{\mathrm{i,s}}+c_{\mathrm{d}})/((\rho+\lambda)c_{\mathrm{i,f}}+c_{\mathrm{d}}) < (\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{s}}})/(1-\gamma(1-\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{f}}}))$. (b) Myopic approach to the precautionary evacuation decision problem in case of multiple shutdown modes where $((\rho+\lambda)c_{\mathrm{i,s}}+c_{\mathrm{d}})/((\rho+\lambda)c_{\mathrm{i,f}}+c_{\mathrm{d}}) > (\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{s}}})/(1-\gamma(1-\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{f}}}))$.

4. Dynamic optimal intervention rule

The precautionary evacuation decision problem has some important similarities with typical optimal stopping problems. The decision maker initially has the flexibility to defer the evacuation decision, and therefore he has to decide at every point in time whether or not to exercise this option. Moreover, using the models elaborated in this paper, in case he or she decides to evacuate, he or she will decide to do so in an optimal way, i.e., by means of a fast or a slow shutdown.

The expected costs of following a dynamic optimal intervention strategy at time t, $F(x,t)$, given that a domino event has not taken place earlier, are given by

$$F(x,t)=\min\{\psi(x,t);\lambda\,\mathrm{d}t\cdot\alpha\cdot W\cdot x+(1-\lambda\,\mathrm{d}t)\cdot(1+\rho\,\mathrm{d}t)^{-1}\varepsilon[F(x+\mathrm{d}x,t+\mathrm{d}t)|x]\} \quad (18)$$

with

$$\psi(x,t)=\min\{\mathrm{TC_s}(x,t);\mathrm{TC_f}(x,t)\} \quad (19)$$

As the waiting process can be stopped in more than one way, a two-step procedure is followed. First, $F(x,t)$ is determined, successively under the assumption that a slow and a fast shutdown is the optimal way to stop the waiting process. Secondly, it is verified which of both assumptions was correct and results in the smallest expected costs $F(x,t)$.

Under the assumption of a possibly everlasting threat (i.e., $\partial F(x,t)/\partial t=0$), calendar time t can be left out of the analysis, and the decision problem is reduced to solving the second order differential equation

$$\frac{\sigma^2x^2}{2}\frac{\partial^2F(x)}{\partial x^2}-(\rho+\lambda)F(x)+\alpha\cdot\lambda\cdot W\cdot x=0 \quad (20)$$

Taking into account the fact that $F(0)=0$,[5] we obtain

$$F(x)=\Omega\cdot x^{\beta}+\frac{\alpha\cdot\lambda\cdot W}{\rho+\lambda}x \quad (21)$$

with

$$\beta=\frac{1+\sqrt{1+(8(\rho+\lambda)/\sigma^2)}}{2}>1. \quad (22)$$

The constant Ω and the trigger level for evacuation x_2 can be determined by taking into account the ‘value matching’ and the ‘smooth pasting’ boundary conditions. These conditions are respectively given by

$$F(x_{2\mathrm{s}})=\mathrm{TC_s}(x_{2\mathrm{s}})=c_{\mathrm{i,s}}+\frac{c_{\mathrm{d}}}{\rho+\lambda}+\frac{\alpha\cdot\lambda\cdot W\cdot(1-\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{s}}})}{\rho+\lambda}x_{2\mathrm{s}} \quad (23)$$

$$\frac{\partial F(x_{2\mathrm{s}})}{\partial x_{2\mathrm{s}}}=\frac{\partial\mathrm{TC_s}(x_{2\mathrm{s}})}{\partial x_{2\mathrm{s}}}=\frac{\alpha\cdot\lambda\cdot W\cdot(1-\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{s}}})}{\rho+\lambda}, \quad (24)$$

in case it is optimal to stop the waiting process by slowly shutting down the ongoing industrial production processes. Plugging (23) and (24) into (21), and solving Ω and $x_{2\mathrm{s}}$, yields

$$\Omega_{\mathrm{s}}=\frac{-(c_{\mathrm{i,s}}+(c_{\mathrm{d}}/(\rho+\lambda)))}{((\beta/(\beta-1))\cdot((\rho+\lambda)c_{\mathrm{i,s}}+c_{\mathrm{d}})/\alpha\cdot\lambda\cdot W\cdot\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{s}}})^{\beta}\cdot(\beta-1)} \quad (25)$$

$$x_{2\mathrm{s}}=\frac{\beta}{\beta-1}\cdot\frac{(\rho+\lambda)c_{\mathrm{i,s}}+c_{\mathrm{d}}}{\alpha\cdot\lambda\cdot W\cdot\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{s}}}} \quad (26)$$

In case it is optimal to halt the waiting process by means of a fast shutdown, the value matching and smooth pasting boundary conditions become

[5] This condition implies that once the severity of the potential domino accident becomes zero, it will remain zero from then on, and the decision maker will no longer decide to evacuate the workers.

$$F(x_{2\mathrm{f}})=\mathrm{TC}_{\mathrm{f}}(x_{2\mathrm{f}})=c_{\mathrm{i,f}}+\frac{c_{\mathrm{d}}}{\rho+\lambda}+\frac{\alpha\cdot\lambda\cdot W\cdot(1-\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{s}}})}{\rho+\lambda}x_{2\mathrm{f}} \tag{27}$$

$$\frac{\partial F(x_{2\mathrm{f}})}{\partial x_{2\mathrm{f}}}=\frac{\partial \mathrm{TC}_{\mathrm{f}}(x_{2\mathrm{f}})}{\partial x_{2\mathrm{f}}}=\frac{\alpha\cdot\lambda\cdot W\cdot(1-\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{s}}})}{\rho+\lambda}, \tag{28}$$

Plugging (27) and (28) into (21), and solving for Ω and $x_{2\mathrm{f}}$, results in

$$\Omega_{\mathrm{f}}=\frac{-(c_{\mathrm{i,f}}+(c_{\mathrm{d}}/(\rho+\lambda)))}{(\beta/(\beta-1)\cdot((\rho+\lambda)c_{\mathrm{i,f}}+c_{\mathrm{d}})/(\alpha\cdot\lambda\cdot W\cdot(1-\gamma(1-\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{f}}}))))^{\beta}\cdot\beta-1} \tag{29}$$

$$x_{2\mathrm{f}}=\frac{\beta}{\beta-1}\cdot\frac{(\rho+\lambda)c_{\mathrm{i,f}}+c_{\mathrm{d}}}{\alpha\cdot\lambda\cdot W\cdot(1-\gamma(1-\mathrm{e}^{-(\rho+\lambda)L_{\mathrm{f}}}))} \tag{30}$$

As mentioned above, the stopping procedure (i.e., a slow or a fast shutdown) that results in the smallest expected costs $F(x)$ needs to be selected. This practice is simplified here, as choosing the shutdown mode that results in the smallest expected costs $F(x)$ is equivalent to choosing the shutdown mode for which the constant Ω (given by (25) and (29)) is smallest.

In case condition (16) is satisfied, and it is optimal to stop the waiting process by means of a slow shutdown ($\Omega_{\mathrm{s}}<\Omega_{\mathrm{f}}$), it can easily be shown that $x_{2\mathrm{s}}>x_{1\mathrm{s}}$ by comparing (26) to (14), and taking into account that $\beta>1$. Similarly, in case condition (16) is satisfied, but it is optimal to stop the waiting process by means of a fast shutdown ($\Omega_{\mathrm{s}}>\Omega_{\mathrm{f}}$), we have $x_{2\mathrm{f}}>x_{1\mathrm{f}}$. In case condition (16) is not satisfied (i.e., a slow shutdown is dominated by a fast shutdown, or no stop at all), a comparison of Eqs. (30) and (17) shows that $x_{2\mathrm{f}}>\tilde{x}_{1\mathrm{f}}$.

Therefore, an emergency manager who ignores the ability to defer his intervention decision to obtain further information on the severity of the threat, might wrongly decide to evacuate the workers of the installations nearby the installation on fire, for estimates of the severity within the interval $[x_{1\mathrm{s}}; x_{2\mathrm{s}}]$, $[x_{1\mathrm{s}}; x_{2\mathrm{f}}]$ or $[\tilde{x}_{1\mathrm{f}}; x_{2\mathrm{f}}]$, depending on the prevailing case.

Fig. 3a and b depict these results in case condition (16) is satisfied and it is optimal to stop the waiting process by means of a slow (Fig. 3a) and a fast (Fig. 3b) shutdown, respectively. In both cases, the expected costs $G(x)$ of a myopic intervention strategy are given by the lower envelope of the straight lines $\mathrm{TC}_{\mathrm{n}}(x)$, $\mathrm{TC}_{\mathrm{s}}(x)$, and $\mathrm{TC}_{\mathrm{f}}(x)$, as indicated in Eq. (10). The myopic trigger level for slow evacuation, $x_{1\mathrm{s}}$, is determined by the intersection of $\mathrm{TC}_{\mathrm{n}}(x)$ and $\mathrm{TC}_{\mathrm{s}}(x)$, whereas the fast evacuation trigger level, $x_{1\mathrm{f}}$, is found at the intersection of $\mathrm{TC}_{\mathrm{s}}(x)$ and $\mathrm{TC}_{\mathrm{f}}(x)$.

In case it is optimal to stop the waiting process by means of a slow shutdown (Figure 3a), $F(x)$ is tangent to $\mathrm{TC}_{\mathrm{s}}(x)$ at $x_{2\mathrm{s}}$. Note that in case the estimate of the severity of the threat x is above $x_{2\mathrm{s}}$, the decision maker should decide to evacuate immediately and choose the shutdown mode which results in smallest expected costs. For sufficiently high x, i.e., $x>x_{1\mathrm{f}}$, this could imply a fast shutdown. Furthermore, observe that suboptimal decisions may result for initial estimates of the severity in the interval $[x_{1\mathrm{s}},x_{2\mathrm{s}}]$.

In case it is optimal to stop the waiting process by means of a fast shutdown (Fig. 3b), $F(x)$ is tangent to $\mathrm{TC}_{\mathrm{f}}(x)$ at $x_{2\mathrm{f}}$. Ignoring option characteristics might then result in suboptimal intervention decisions for estimates of the severity in the interval $[x_{1\mathrm{s}},x_{2\mathrm{f}}]$.

5. Numerical example

In this paper, the same example as discussed in our previous paper [1] is considered. Numerical data based on a qualitative study performed by Pauwels et al. [20] is used. We assume that, besides the relatively slow shutdown mode, the ongoing processes of the threatened industrial company can also be stopped in a faster, yet more expensive way. Suppose, e.g., that a fast shutdown can be completed by $\gamma\cdot W=100$ workers

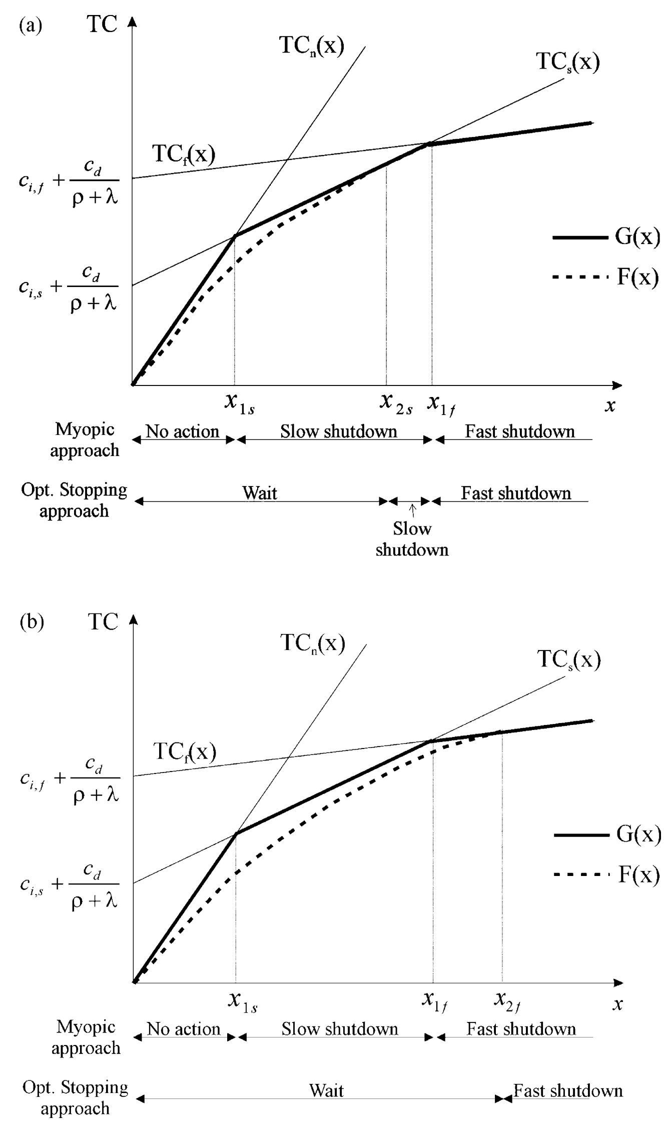

Fig. 3. (a) Myopic versus optimal stopping approach to the precautionary evacuation decision problem in case of multiple shutdowns; slow shutdown is optimal stopping action. (b) Myopic versus optimal stopping approach to the precautionary evacuation decision problem in case of multiple shutdowns; fast shutdown is optimal stopping action.

Table 1
Base case parameter values

Parameter	Value
Immediate costs of fast evacuation, $c_{i,f}$	€3,350,000
Immediate costs of slow evacuation, $c_{i,s}$	€2,500,000
Evacuation costs per unit of time in shutdown, c_d	€5000 per hour of shutdown
Required time to execute fast shutdown, L_f	2 h
Required time to execute slow shutdown, L_s	8 h
Fraction of workers required during fast shutdown, γ	0.5
Uncertainty, σ	0.15 per hour
Monetary value assigned to the severity, α	€625 per person per e2 J/s m^2
Number of industrial workers, W	200
Rate per hour at which domino event might take place, λ	0.417% per hour
Discount rate, ρ	0.0007% per hour

in $L_f = 2$ h, and is expected to result in immediate evacuation costs of €3,350,000 ($c_{i,f}$). Table 1 provides an overview of the base case parameter values.

Given these parameter values, we obtain $\Omega_s = -2.2694 \times 10^4$ and $\Omega_f = -2.2201 \times 10^4$. As a result, it is optimal to stop the waiting process by means of a slow shutdown. This is shown in Fig. 4 with $F(x)$ tangent to $TC_s(x)$ and $x_{2s} = 136.9$e2 J/sm^2. A fast evacuation decision is the optimal response to very severe potential heat radiation, i.e., for values of x exceeding $x_{2f} = x_{1f} = 237.3$e2 J/sm^2. Ignoring option characteristics might result in suboptimal intervention decisions for estimates of the severity in the interval [30.6e2 J/sm^2; 136.9e2 J/sm^2]. Note that in case the production processes could only be shut down in a fast way, the decision maker should decide to do so if the estimated severity exceeds 163.5e2 J/sm^2. As such, the existence of an additional and less costly shutdown mode, may encourage the decision maker to stop the production processes earlier, but in a less intervening (i.e., slow) manner.

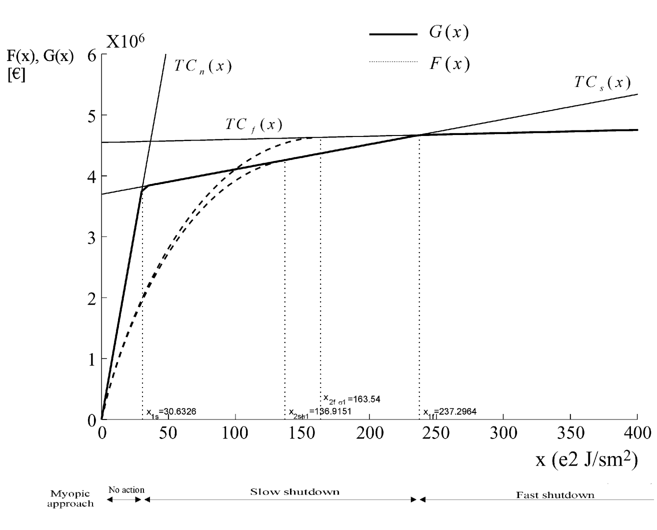

Fig. 4. Myopic versus optimal stopping approach to the precautionary evacuation decision problem in case of multiple shutdown modes ($\sigma = 0.15\,\mathrm{h}^{-1}$).

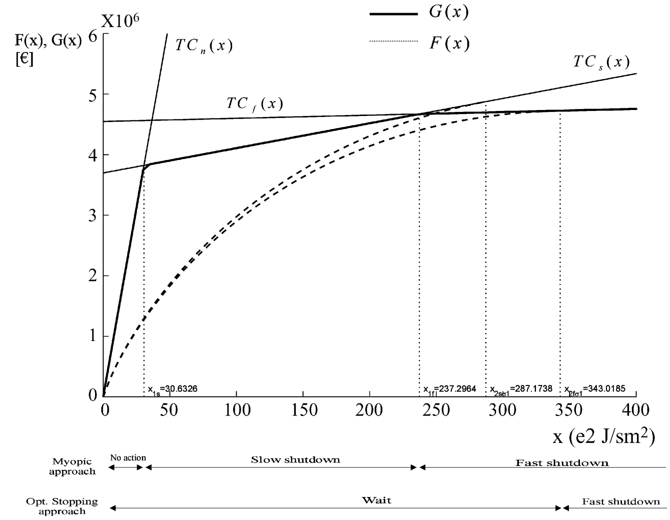

Fig. 5. Myopic versus optimal stopping approach to the precautionary evacuation decision problem in case of multiple shutdown modes ($\sigma = 0.25\,\mathrm{h}^{-1}$).

Now suppose the uncertainty with respect to the evolution of the estimated severity increases to $\sigma = 0.25\,\mathrm{h}^{-1}$. Fig. 5 depicts this situation. As we find that $\Omega_s = -5.4848 \times 10^4$ and $\Omega_f = -5.5291 \times 10^4$, it is optimal to stop the waiting process by means of a fast shutdown: $F(x)$ is tangent to $TC_f(x)$ at $x_{2f} = 334.0$e2 J/sm^2. A comparison with the situation depicted in Fig. 4 shows that increased uncertainty stimulates the decision maker to stop the production processes later, but possibly in a more intervening manner. Suboptimal decisions may result for estimates of the severity in the interval [30.6e2 J/sm^2; 343.0e2 J/sm^2], and hence, our previous conclusion that increased uncertainty increases the importance of ‘options thinking’ remains valid. Note that in this case the production processes could only be shut down in a slow way, the decision maker should decide to do so in case the estimated severity of the heat radiation exceeds 287.2e2 J/sm^2. As such, the existence of an alternative and less time-consuming shutdown mode may encourage the decision maker to stop the production processes later, but in a more intervening (i.e., fast) manner.

6. Conclusions

Industrial companies often have several modes to stop their production processes when required, e.g., in case of a major fire possibly giving rise to a domino effect. These modes differ with respect to the resulting costs, and with respect to the required time and personnel to complete the shutdown operations. In this paper, a decision model to determine the optimal time and the optimal mode to shut down the ongoing activities is discussed. 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.

In addition to the results of Reniers et al. [1] indicating that unjustified interventions may result in case of simple one-mode production process stop settings, we found that ignoring option characteristics may produce suboptimal intervention decisions in complex multiple shutdown settings as well. Moreover, 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.

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