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Nuclear incident response in industrial areas: Assessing the economic impact of the decision to evacuate.

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ABSTRACT

The economic impact of imposing countermeasures in case of a nuclear emergency is a very important aspect in both the Probabilistic Risk Assessment code COSYMA and the Real-time On-line DecisiOn Support system RODOS. Therefore, these codes make use of the economic model ECONOM.
In this paper, we will show that this economic model is not very well suited, nor designed, to predict the economic impact of evacuating a highly industrialised area in case of a nuclear emergency. Furthermore, we will indicate how recent economic investment theories can be used to deal with this decision problem in a more elaborate way.

1. INTRODUCTION

In this paper we are dealing with the decision problem whether or not to evacuate an industrial region in case of a nuclear incident from an economic point of view. For simplicity's sake, an industrial region is assumed to be a set of factories without residential population and agricultural production. An incident refers to an emergency situation in which there is a possibility of a release actually taking place in the near future. However, it is possible as well that the incident does not escalate into an accident and that hence, there will be no release at all.

Section two demonstrates the ineffectiveness of the economic model ECONOM, integrated in both the Probabilistic Risk Assessment (PRA) code COSYMA [4] and the Real-time On-line DecisiOn Support system RODOS [8, 11], to assess the economic impact of evacuating an industrial area. Strongly related to this problem, we show in the third section that the traditional Net Present Value decision criterion will give rise to wrong decisions in our specific settings. Recent economic investment theories, however, offer large opportunities to deal with our evacuation problem in a more elaborate way. The fourth section summarises the major conclusions.

NOMIC IMPACT OF EVACUATING AN INDUSTRIAL AREA

NOM model calculates both the cost of countermeasures (evacuation, relocation, ng, food restrictions and decontamination) and the cost of health effects in the exposed ion. As far as the countermeasures are concerned, we focus our discussion on the tion cost. This countermeasure has to be decided on in the early phase of an accident; ver, it may cause large distortions in industrial production [12]. The assessment of the of health effects has already been the subject of a large number of papers; we refer to [16,] for an interesting overview of possible evaluation methods.

2.1 Assessment of the evacuation cost using ECONOM

In the ECONOM model [9, 14] three types of evacuation costs are considered: transport costs, accommodation costs and loss-of-income costs.

Transport costs include the direct expenditures that are necessary to move people away from, and back to the evacuation area, either by private cars or by public transport means. In case of evacuating an industrial area, workers will return to their own houses. As they would have done so in normal circumstances as well, transport costs must not be taken into account.

Evacuation will generally cause accommodation costs as people cannot use their own houses in the evacuated zone and additional accommodation will have to be provided elsewhere. Again, costs will be zero in industrial areas as no inhabitants are assumed in these regions. The workers will return to their own houses outside the evacuated area.

If the evacuated people are unable to reach their respective workplaces, the contribution they would have made to the economy will be lost. The calculation of this loss-of-income cost was originally based on the number of inhabitants of the affected area and the mean Gross Domestic Product (GDP) per inhabitant. This approach largely underestimates loss-of-income costs in industrial regions where generally a lot of added value is created in a thinly populated area. Therefore, the extended version of ECONOM [10] makes it possible to use the number of employees evacuated and the sectoral added value per employee, which certainly is a much better approach to reality.

2.2 Major shortcomings of this approach

In the previous part we indicated that the only cost that ECONOM will take into account in case of evacuating an industrial area is the added value that will be foregone in this area during the evacuation. However, reality is more complicated.

First, ECONOM assumes that the evacuated area is economically independent. In reality, however, this will rarely be the case and the evacuation of a certain region may cause large indirect effects outside this area [19, 21]. Due to the shut-down of factories in industrial regions, there will not only be temporarily no raw materials for customers, no sales potential for suppliers, but also new opportunities for competitors and substitute products, ... A similar situation may occur if important transport facilities (airport, harbour) are situated in the affected zone. The economic technique of input-output modelling has recently been used successfully as a supplement to the ECONOM model, in order to take into account indirect implications as well [15].

Secondly, the abrupt shut-down of certain industries may involve severe secondary (explosions, toxic releases, ...) and losses (product-in-process, ...) [12], which are not with in ECONOM. Clearly these costs are highly time-dependent, as they can be reduced to large extent by notifying the factories as soon as possible of the eventuality of a nucle accident. In this way they can start preparing for a possible emergency stop.

As far as the effective implementation of evacuation is concerned, the situation is more ambiguous. On the one hand, high costs caused by radiation induced health effects may result when this countermeasure is not taken in time. On the other hand, carrying out too hastily a countermeasure which proves to be unjustified afterwards, may cause high losses as well. One could raise the objection that this is also the case in residential areas. Although this is true to a certain extent, it has to be stressed that the irreversibility of the decision to evacuate will be much larger in industrial areas. Once a production process has been stopped, it can take days before the factory will be fully operational again. The cost of this production distortion is sunk, once the initial decision to evacuate has been taken. In the case of a residential population, the decision maker (DM) can revoke quite easily his decision to evacuate, with only small sunk costs.

The last two shortcomings are closely related to the problem of determining the optimal point in time to take the evacuation decision. We will explore this issue in more detail in the following section.

3. POSSIBLE CONTRIBUTION OF ECONOMIC INVESTMENT THEORIES

The decision to evacuate an industrial region is very similar to the decision to invest in financial markets. We show that the use of the traditional Net Present Value (NPV)-rule, however, is not appropriate in our specific decision context. Therefore, the option approach to investment decisions is introduced as a possible way of dealing with our evacuation problem more elaborately.

3.1 The NPV-decision rule

Suppose an investment project requires initially spending an amount of money C_0 in order to obtain a cash flow CF_t at time t, during n periods of time. If r is the opportunity cost of money, the NPV of this investment can be calculated as:

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - C_0 \qquad (1)$$

The NPV-rule then says that you should invest in this project only if its NPV is strictly positive [2].

The striking correspondence between the decision to evacuate an industrial region in case of a nuclear accident and the decision to invest in government bonds is shown in table 1.

	Decision to invest in government bonds	Decision to evacuate in case of an accident
C_0	Issue price	Evacuation cost, C
CF_t	Periodic interests Nominal (par, face) value at maturity	Avoided health effects, AH

Table 1. Analogy between the decision to invest in bonds and the decision to evacuate in case of an accident

Hence, the emergency manager will decide to evacuate the industrial region if this decision has a strict positive NPV, i.e., if the present value of the cash flows (avoided health effects) is strictly larger than the initial evacuation cost.

$$NPV = AH - C > 0 \Leftrightarrow AH > C \qquad (2)$$

Note that the use of equation (2) requires the determination of the monetary value of the avoided health effects, so that they can be compared directly with the initial evacuation cost. This can be side-stepped by using Multi-Attribute Utility Theories (MAUT) in which a general utility is assigned to the combination of a number of health effects and an evacuation cost. This utility thinking, furthermore, allows to distinguish a health cost of 1 million BEF from an evacuation cost of 1 million BEF, by assigning them a different utility. For reasons of clarity, we restrict ourselves here to the first approach. We refer the reader for a description of MAUT and some interesting examples, to [1, 17].

In case of a nuclear incident, the pay-offs of the decision to evacuate an industrial area will depend on the further course of the alarm, which, however, is unknown at the time of the decision. This situation can be compared with the uncertainty faced when investing in shares. Table 2 explains what is meant.

	Decision to invest in shares	Decision to evacuate in case of an incident
C_0	Issue price	Evacuation cost, C
CF_t	Uncertain pay-offs due to: - uncertainty in dividends - fluctuations on stock-market	Avoided health effects depend on evolution of the incident: - escalation into accident: $AH > 0$ - no accident: $AH = 0$

Table 2. Analogy between the decision to invest in shares and the decision to evacuate in case of an incident

The problem of our DM is represented by the decision tree in figure 1. In this tree, decision nodes, where the DM is in control, are indicated by squares; chance nodes, where chance is in control, by circles [22]. Given the information i of a nuclear emergency, the DM assesses that the incident will escalate to an accident (event s_1) with probability $p(s_1|i)$. In this case, it may be optimal to evacuate the industrial region, i.e., when $AH>C$. In the same way, the DM assumes that, with a complementary probability $1-p(s_1|i)$, the incident will not escalate (event s_2). Then, it would be better of course not to evacuate.

The probability of occurrence of event s_1, given information i is denoted by $p(s_1|i)$. It is the probability that an accident will take place, given the information that there has been a nuclear alarm. By applying Bayes' Theorem, $p(s_1|i)$ can be calculated as [18]:

$$p(s_1|i) = \frac{p(i|s_1) \cdot p(s_1)}{p(i|s_1) \cdot p(s_1) + p(i|s_2) \cdot p(s_2)} \qquad (3)$$

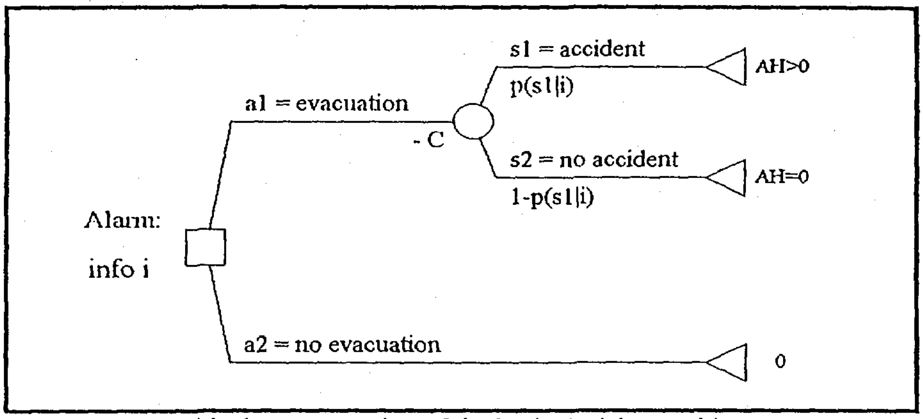


Figure 1. Graphical representation of the basic decision problem

The decision problem can now be solved by what Raiffa [22] calls "averaging out and folding back". The expected NPV of every chance node is determined by "averaging out" the possible outcomes of this node. In the 'evacuation' branch we get:

$$E\left[NPV(a_1)\right] = -C + p(s_1|\,i) \cdot AH + \left[1 - p(s_1|\,i)\right] \cdot 0 = -C + p(s_1|\,i) \cdot AH \qquad (4)$$

At every decision node, the DM chooses that action that will lead to the chance node with the highest E[NPV]. This process starts from the decision nodes at the right-hand side of the figure, and therefore, it is called "folding back".

By following this procedure of averaging out and folding back, the optimal decision can be identified, i.e., the decision with the highest expected return, taking into account the uncertainty about the actual state (accident versus no accident) that will occur. The DM will opt for action a_1 and evacuate the industrial region, if and only if:

$$E\left[NPV(a_1)\right] > 0 \Leftrightarrow p(s_1|\,i) \cdot AH > C \qquad (5)$$

3.2 Option theory

As was stated in the introduction of this section, the decision to evacuate is very similar to the decision to invest in an uncertain project. Pindyck [20] and Dixit and Pindyck [6, 7], however, state that the traditional NPV-rule for investment decisions is incorrect, when investments are irreversible and decisions to invest can be postponed.

As we have already said in section 2, the decision to evacuate an industrial area will produce irreversible effects. Furthermore, there will generally be a certain course of time between the initial nuclear alarm and the actual radioactive release [13], allowing to postpone the decision for a certain time. As both conditions of irreversibility and the possibility to delay are fulfilled, the traditional NPV-decision criterion expressed by inequality (5) is not appropriate according to Pindyck and Dixit. In the following, we will explain what is meant, and how this affects our basic decision problem from figure 1.

The possibility of a DM to postpone an evacuation decision, is very much like the privilege that belongs to the holder of a financial call option. A call option is a contract giving its owner the right to buy a fixed number of shares at a fixed price before a given date [5]. Clearly, such call option has a certain value as it gives the investor the flexibility to wait and observe the evolution of stock prices. When the holder of the option finally decides to buy the shares, he makes an irreversible investment expenditure. He "kills" the option and gives up the possibility of waiting for new information to arrive that might affect the desirability or timing of the expenditures. The value of the option that is lost, has to be taken into account. Therefore, the traditional NPV-rule has to be changed from E[NPV]>0 to E[NPV]>K, where K is the opportunity cost of killing the option.

Knowing this, the problem of the DM is no longer whether he should evacuate the industrial region or not, but rather, whether he should decide immediately to evacuate, or whether he should wait for further information on the course of the alarm and preserve the flexibility to evacuate, when the obtained information points in the direction of a real accident. This situation is shown in figure 2.

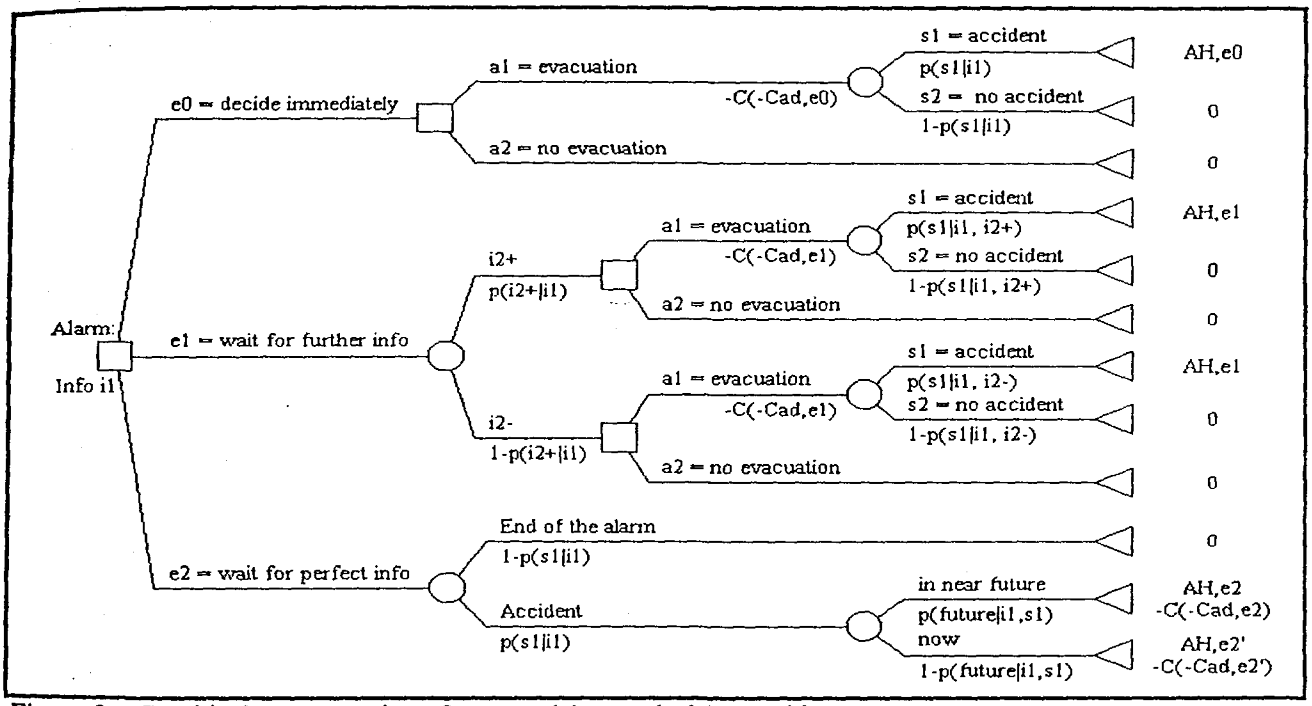


Figure 2. Graphical representation of a more elaborate decision problem

Branch e_0 represents our basic decision problem, i.e., the situation in which the DM decides to evacuate (or not), as soon as he receives the information i_1 of a nuclear alarm. The initial evacuation cost $C_{0(e0,\ a1)}$ depends on both the time that is available to evacuate the industrial region, t_{av}, and the time that is necessary to do so, t_n. The available time t_{av} is defined as the time course between the decision to evacuate and the arrival of the release at the industrial region. The necessary time t_n can be further diversified in t_{n1}, the time necessary to evacuate with minimal economic losses, t_{n2}, the time necessary to evacuate with loss of product-in-process, etc.

When the available time exceeds or equals the necessary time, the total cost of evacuation will be C. However, when the available time is not sufficient, i.e., smaller than the necessary time, an additional cost $C_{ad,\ e0}$ will occur. Hence, we get:

$$C_{0(e_0,a_1)} = \begin{cases} C & if\, t_{av} \geq t_n \\ C + C_{ad,e_0} & if\, t_{av} < t_n \end{cases} \qquad (6)$$

As we have stated already in the previous section, these time aspects are particularly important in industrial regions, where certain processes can not be stopped immediately in a safe and economic manner, and hence produce large t_n values.

In branch e_1, the DM decides to wait for further information on the course of the alarm. The new information may either reinforce the initial information of the emergency (i_{2+}) or weaken it (i_{2-}). It is obvious that by using this additional information (i_{2+} or i_{2-}), the DM will be able to better assess the probability of the accident actually taking place. Note that:

$$p(s_1|i_1,i_{2+}) \geq p(s_1|i_1) \geq p(s_1|i_1,i_{2-}) \qquad (7)$$

Hence, the chance grows that the DM takes the right decision. On the other hand, the available time to evacuate will be smaller, possibly resulting in higher additional costs $C_{ad,\,e1}$. Moreover, t_{av} may be no longer sufficient to evacuate all people. If this is the case, the value of the health effects avoided by evacuation in case of an accident will be lower than in the e_0 branch, i.e., $AH_{e1} \leq AH_{e0}$.

The extreme case, in which the DM waits until he receives perfect information is shown in branch e_2. This information can either indicate the end of the alarm, or the true release of radioactive material to the atmosphere, now or in the very near future. Mind that, in order to be consistent, the probabilities assigned to these possible states (end of alarm versus accident), have to be the same as those in the e_0-branch. By receiving perfect information, the chance of taking the wrong decision, is reduced to zero. However, there may be large additional costs $C_{ad,\,e2}$ and $C_{ad,\,e2'}$ ($\geq C_{ad,\,e2}$) in case of a release starting in the near future or now, respectively. Moreover, the health effects that still can be avoided by this 'late' evacuation may be substantially smaller than in the e_0- and e_1-branch, i.e., $AH_{e2'} \leq AH_{e2} \leq AH_{e1}$.

In this more elaborate decision problem, the DM will immediately decide to evacuate, if and only if:

$$\mathrm{E}\left[NPV(e_0,a_1)\right] > MAX\left\{0, \mathrm{E}\left[NPV(e_1)\right], \mathrm{E}\left[NPV(e_2)\right]\right\} \qquad (8)$$

Note that (8) implies:

$$\mathrm{E}\left[NPV(e_0,a_1)\right] > 0,$$

i.e., condition (5).

Influence diagrams (ID) [3] can be used to clarify the decision branches from figure 2. In such diagrams, rectangles represent decision nodes, ovals represent chance nodes and rounded rectangles represent consequence nodes. These nodes are connected by arrows, either indicating sequence when they end in a decision node, or relevance in all other cases.

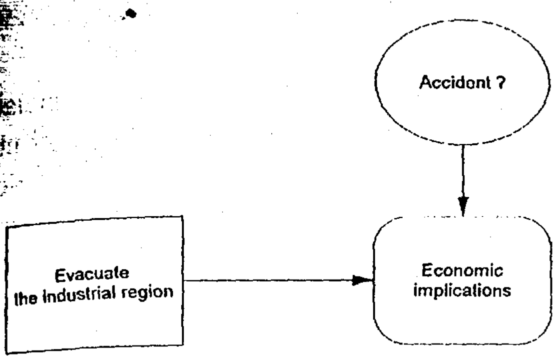
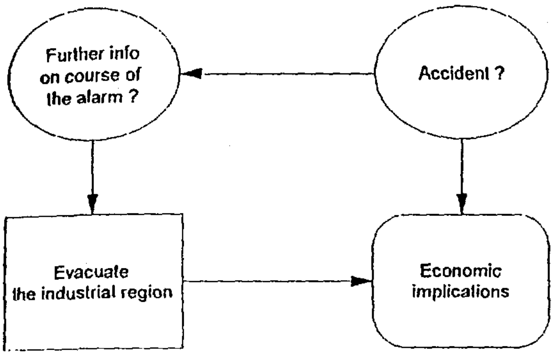
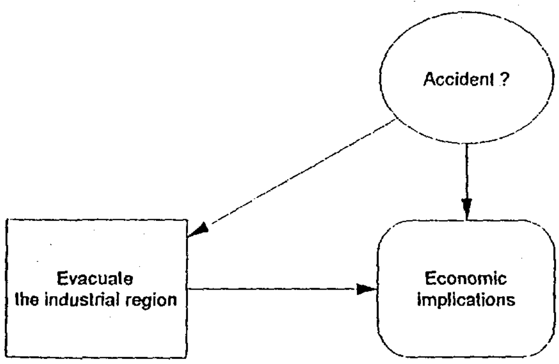
ID representation	Meaning
	**Branch e_0: no information** Both arrows represent relevance: the economic implications depend on the decision (evacuation or not) that is taken and the event (accident or not) that finally occurs. There is no arrow from the chance node to the decision node: the decision is made without the DM knowing whether there is going to be an actual release or not.
	**Branch e_1: imperfect information** The DM receives further (but imperfect) information on the course of the alarm before he decides (sequence arrow) whether to evacuate or not. The information he receives, depends on the chance that an accident will actually occur or not (relevance arrow). The more an accident is likely, the more likely will the received information point in the direction of an accident (and vice versa). The decision is made without the DM exactly knowing whether there is going to be an actual release or not.
	**Branch e_2: perfect information** As in branch e_0, the arrows from the chance node and the decision node to the consequence node represent relevance: the economic implications depend on the decision (evacuation or not) that is taken and the event (accident or not) that finally occurs. There is, however, a sequence arrow from the chance node to the decision node: the decision is only made when the DM has perfect information on the outcome of the chance node, i.e., end of the alarm or actual release.

Table 3. ID for branches e_0, e_1 and e_2 of figure 2.

CONCLUSION

In this paper, we have shown that the ECONOM model is not very well suited to determine the cost of evacuating an industrial area in case of a nuclear emergency as time aspects of the decision are ignored. The decision to evacuate an industrial region can produce large irreversible effects. Hence, it is important not to carry out countermeasures too hastily, which prove to be unjustified afterwards. On the other hand, it is evident that taking countermeasures too late is not optimal either, as the abrupt shut-down of certain industries may involve severe secondary risks (explosions, toxic releases, ...) and losses (product-in-process, ...).

Recent economic investment theories can be used to deal with this decision problem in a more elaborate way. The options approach to the evacuation decision indicated that the "real" problem of the DM is not whether to evacuate the industrial region in case of a nucl emergency or not, but rather, whether he should decide immediately to evacuate or whether should wait for further information on the course of the alarm.

We considered the decision to evacuate as an "all or nothing" decision, i.e., evacuate t complete area, or not evacuate at all. However, the DM could proceed in steps and make sequence of smaller decisions: evacuate certain factories, but wait on further information fo other firms; let certain factories prepare themselves for a possible emergency stop; evacuate a number of workers that are not necessary to keep production going ... Every such action, will not only affect the set of possible future actions, but will also change their respective pay-offs. Further research will focus on these problems.

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