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Consequences of a Nuclear Accident: An economic and radiological Approach

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Text not available

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FACTORS AFFECTING REAL-TIME SOURCE TERM RECONSTRUCTION

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Keywords: Real-time, source term estimation, RODOS system, accidental releases.

1. Abstract

The main objective is to develop a generic source term reconstruction methodology, based on off site observations, which will form part of the analysis sub-system ASY-module of the real-time on-line decision support system (RODOS). The need for a generic source term module obeys to the fact that RODOS will be implemented in different countries and under a wide variety of circumstances. This work summarizes some of the current developments, and points out some factors that affect real-time source term estimations and basic considerations that will be needed during the implementation of the RODOS system.

2.Introduction

The RODOS system (Ehrhardt et a1.,1993) has been tailored to provide decision makers with advise throughout the different stages of a nuclear accident, extending from early warning to both release and post release phases. Included in the RODOS system are several atmospheric dispersion-deposition models. These models are intended to provide an overview of the potential contamination fields as well as a quick assessment of the projected doses downwind. Regardless of the complexity of the model used, the knowledge about a number of parameters and data remains a condition *sine qua non* to guarantee reasonable and realistic model predictions. However, this type of information will be *a priori* unknown or subject to large uncertainties, which in turn leads to an attempt to solve the problem based upon a list of possible scenarios.

There are a number of reports in the literature (Robeau and Oishi, 1989; Edwards et al., 1989; Van

Camp et al., 1993 and Golubenkov et al., 1996) devoted to reconstruct the source term based upon field monitoring data. However, all these data were generated during tracer experiments, and therefore under extremely controlled circumstances, which do not correspond to those prevailing during a nuclear accident.

This work describes a method to estimate the source term that combines model predictions with field observations and it is also intended to clarify some ideas concerning the elaboration of a generic source term reconstruction procedure.

3. Basic considerations

As it was mentioned above, a minimum of information is required for a model to run, and the most logic place to start with is the instrument console at the nuclear facility. Here information regarding core status, possible pathway(s), hold-up period, use of filters, sprays and release height among others is thought to be available, although its accuracy can be questioned, specially under a severe accident where a great deal of stress and faulty readings are to be expected. Furthermore, it is also assumed that burn-up and reactor thermal-power data are available so that the core inventory is known with a certain degree of detail, since short lived nuclides could be responsible for a considerable fraction of the total dose.

Reconstructing the source term based on off site measurements implies that a number of considerations regarding monitoring systems and positioning must be thought of with a great deal of care. More details on current monitoring strategies in Europe can be found elsewhere (Sohier et al., 1996). For instance, it is widely accepted that the only way of getting a real-time flow of information should an accident occur is by using at least a set of detectors around the nuclear power plant, often called fence monitoring. As it will be shown below, the positioning of the array of detectors is crucial, considering both angular resolution as well as the relative distance to the source. It is also known that the only tvpe of information that could lead to an estimate of the magnitude of the source term, during the early phase of the accident, consists of gamma dose rates.

Should the release be through a monitored pathway (stack release), the source term will be more or less known and practically 100 % of the projected doses will be due to noble gases. In case of an unmonitored release, e.g. containment building rupture or bypass, neither the composition nor the rate with which material becomes airborne will be known. It is here that fence monitoring must prove its usefulness in estimating the extent of the accident. It is obvious that a better picture on the composition of the release will only be available after performing e.g. γ-spectrometry on air filters and determining the concentration of the different forms of iodine, but this will take time. Therefore, data assimilation techniques (French, 1996) could only be used after some delay.

If the release height is unknown, the analysis of the detector response could help estimate it (ApSimon, 1986), but there are large uncertainties to be considered when the detector is relative close to the source, i.e. if one takes into account the mean-free-path of gamma photons in air which is about 100 m, drastic variations of the gamma dose are to be expected with the distance downwind. On the other hand, positioning detectors close to the source implies that building shine and wake-effects should be taken into consideration as well.

4. Source term reconstruction methodology, the ideal case.

The methodology discussed below is based upon a number of premises:

- the core inventory is known.
- the effective release height is known or soundly guessed.
- there is a fence monitoring featured by a ring of 72 gamma detectors positioned every 5 degrees and at a given distance from the source.
- meteorological data averaged either every 10 or 30 min time steps.
- Access to an atmospheric dispersion - deposition model.

It might be thought that such a dense network of gamma detectors does not appear to be realistic in terms of installation and maintenance costs. However, the aim here is to establish a bottom line of what can be expected should the best monitoring conditions be met.

Under the assumption that during the first half hour after the beginning of the release, the source term consisted only of 50% of the core inventory of noble gases, and that neither wind direction nor wind speed have changed at such a short distance from the source (1000 m), the detector response can be plotted against the angle theta associated with each detector, as shown in Figure 1.

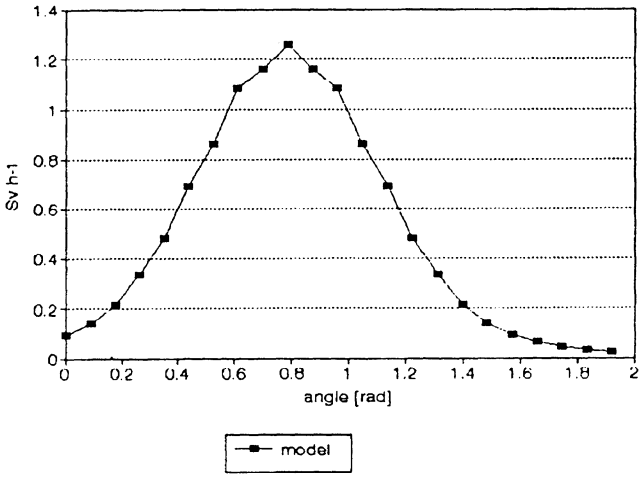

Figure 1. Gamma dose rate distribution for an ideal detector configuration.

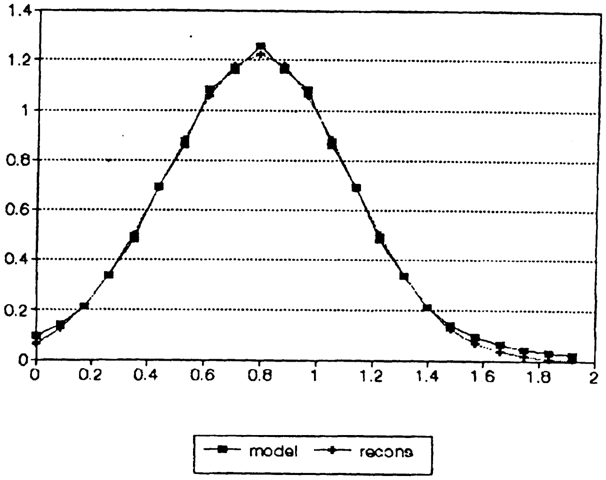

Figure 2. Fitted gamma dose rate angular distribution.

Thus, the problem of estimating the source term is reduced to obtaining the best fit of the above curve,

$$D = k.e^{[-(\theta-b)^2/c]}$$

which in this case can be best approximated by a function of the type:
where D and θ are the gamma dose rate and polar coordinate of each detector, respectively.
The coefficients k, b and c can be determined by linear least-squares, i.e. by minimizing the square of the difference between predictions and observations. These coefficients must be determined for each atmospheric stability class, which will affect the width of the plume. It is worthy to mention that, due to the symmetry of the detector array, this method does not depend on the wind direction, and there will always be the same number of detectors involved.
In Figure 2 below appear plotted the modeled gamma dose rate due to Kr-88, together with the one obtained after fitting the detector response as a function of the angle θ.

The source term reconstruction can then be done by using the set of parameters that correspond to a given atmospheric stability class, and can be achieved by computing the area under the curve and then comparing the results with those corresponding to a know release fraction of the core inventory during the first time step. In this way, it is perfectly possible to keep track on the evolution of the accident and satisfy the condition of being real-time.

5. Source term reconstruction, the real case.

Due to a number of reasons, such a dense detector network is not feasible, and therefore the number of detectors in question must be reduced, which under no circumstances should be less that one detector every 15 degrees. Using a 15° angular spacing will result, e.g. that for a D stability class there will be a decrease of a factor of 4 in detector response for two neighbouring detectors. On the other hand, the above mentioned procedure assumes that the plume's centerline passes right over one detector, which will not always be the case. This situation is depicted in Figure 3, where the wind direction forces the plume to pass between two detectors located 15° away from each other. It is obvious that, in this case one must resort to either extra measurements to account for the missing value under the plume's centerline or use an interpolation algorithm.

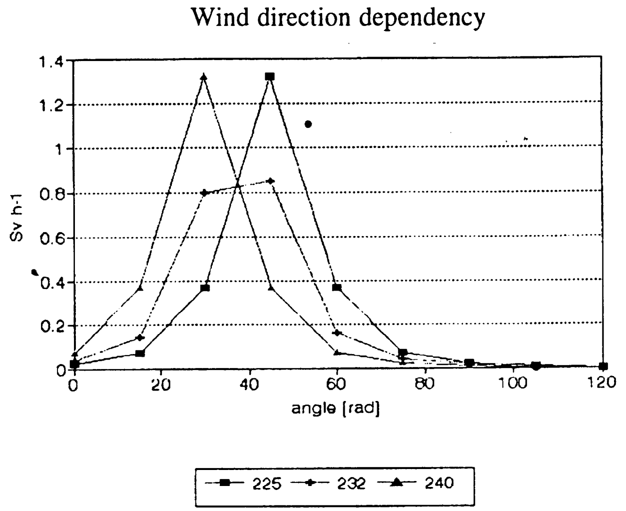

Figure 3. Variation of the detector response as a function of the prevailing wind direction.

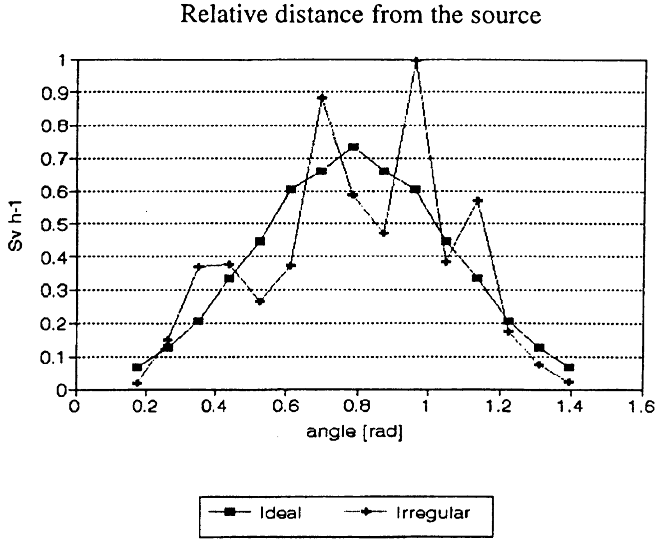

Figure 4. The ideal detector response versus one obtained using a realistic detector configuration.

Another issue that deserves attention is the detector positioning, in other words, it is not realistic to think that all 24 detectors (in case of using 15°) will be located in a perfect radius from the source. Figure 4 shows the case in which the detector response has been plotted for detectors located equidistant from the source, versus that given by detectors irregularly positioned as they often are, i.e. positioned taking into account the perimeter of the facility, risk of vandalism if they are placed off site, the topography, ease of access for maintenance, etc.

It is thought that many of the difficulties associated with the real-time reconstruction of the source term can be overcome by an adequate and efficient monitoring strategy that combines both fence and mobile monitoring stations. Indeed, the use of vehicles and a predefined sampling route would enable one to locate the plume centerline under those less favourable weather conditions, provided that the effective doses to the crew members are within safety regulations.

6. Conclusions

The conclusions can be summarized in several points namely:

- The source term can be reconstructed on a real-time basis, provided vital information such as a rough or more accurate (if available) estimation of the release height comes from the plant operator or the in-plant source term estimation procedure.

- Gamma monitoring constitutes the most efficient tool to assess the magnitude or extent of the accident, at least during its early phase.

- The number of detectors used is crucial and under no circumstances should be less than 24, i.e. one detector every 15 degrees.

- The method chosen to reconstruct the source term has proven to be simple, powerful, allows to follow the temporal evolution of the accident, and most importantly, it does not depend on a particular atmospheric dispersion-deposition model.

- This methodology requires a thorough calibration procedure, implying that the RODOS user will have to: follow some general guidelines, adapt these guidelines to his(her) site specific situation, i.e. detector positioning, identification of potential sources and calibrate the detector response taking into account the actual geometry of the fence monitoring.

It is thought that this procedure, coupled with some extra observations carried out at specific and pre-determined points, constitutes a quick and reliable tool to solve the problem of estimating the source term using off site observations.

7. Acknowledgements

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8. References

Apsimon, H.M. *Computer oriented techniques and assessment of environmental consequences within emergency procedures for nuclear accidents.* (1986) Report to the Commission of the European Communities.

Edwards, L., Harvey, T. and Pitovranov, S. *Real-time regression schemes for integrating measurements with emergency response predictions.* (1989) Proceedings of the 2nd International Workshop on Real-time Computing of the Environmental Consequences of an Accidental Release to the Atmosphere from a Nuclear Installation
2 pp 52-74

Ehrhardt, J., Päsler-Sauer, J., Schüle, 0., Benz, J., Rafat, M. and Richter, J. *Development of RODOS, a comprehensive decision support system for nuclear emergencies in Europe - an overview.* (1993). Radiat. Prot. Dosim. 50 (2-4) pp 195-203

French, S. *Uncertainty modelling, data assirnilation and decision support for management of* *off-site nuclear ernergencies.* (1996) Proceedings of the 4th International Workshop on: Real-time Computing of the Environmental Consequences of an Accidental Release from a Nuclear Installation. Aronsborg, Sweden.

Golubenkov, A., Borodin, R., Sohier, A. and Rojas-Palma, C. *Data Assimilation and Source Term Estimation During the Early Phase of a Nuclear Accident.* (1996) Report BLG 707, SCK-CEN.

Robeau, D. and Oishi, S. *Method to be used to work back to the source term and for an optimum control of parameters used in atmospheric transfer calculations*. (1989) Proceedings of the 2nd REM Workshop - Real time Radioactivity Monitoring and its Interface with Predictive Atmospheric Transport Modelling, Ispra, Italy.

Sohier, A., Rojas-Palma, C. and Liu, X. *Towards a monitoring framework for the source term estimation during the early phase of an accidental release at a nuclear power plant.* (1996) Proceedings of the 4th International Workshop on: Real-time Computing of the Environmental Consequences of an Accidental Release from a Nuclear Installation. Aronsborg, Sweden.

Van Camp, M., Ruan, D., Sohier, A. and Govaerts, P. *The use of fuzzy set theory to reduce uncertainties for nuclear emergency decision aiding systems.* (1993) Proceedings of Mathematical Methods and Supercomputing in Nuclear Applications, Karlsruhe, Germany. pp 432-442.

Résumé

L'objectif principal est de développer un méthodologie de reconstruction du terme source qui soit d'application générale et basée sur des observations hors site, qui fera partie du module d'analyse du sous-système ASY du système de soutien de décision en temps réel(RODOS).Le besoin d'un module générique pour le terme source découle du fait que RODOS sera mis en oeuvre dans des circonstances et des pays différents. Ce travail résume les progrès récents et met l'accent sur certains facteurs qui influencent les estimations en temps réel du terme source et sur les considérations de base à respecter lors de l'utilisation deRODOS.

Samenvatting

Hoofddoel is de ontwikkeling van een methodologie op basis van off-site metingen die algemeen toepasbaar is om de bronterm te reconstrueren en die deel zal uitmaken van het ASY module van het RODOS systeem. De noodzaak van een generisch model ligt in het feit dat RODOS in verschillende landen en onder uiteenlopende omstandigheden zal gebruikt worden. Hier worden recente ontwikkelingen samengevat en wordt de nadruk gelegd op een aantal faktoren die de ".real time source term" bepalingen beïnvloeden en op wat moet in acht genomen worden bij het gebruiken van RODOS.

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ASSESSING THE ECONOMIC IMPACT OF THE DECISION TO EVACUATE AN INDUSTRIAL AREA: DO THE EXISTING MODELS APPLY ?

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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 show that this economic model is not suited, nor designed, to predict the economic impact of evacuating an highly industrialised area in case of a nuclear emergency. Furthermore, we indicate how ongoing and future economic research at the Belgian Nuclear Research Centre SCK•CEN, can contribute to overcome the stated shortcomings.

1. INTRODUCTION

In case of a nuclear emergency, the decision maker will have to decide on the optimal scale and duration of the countermeasures that are required to reduce the number of health effects in the possibly affected population. In order to go through this optimisation process, it is essential to assess the economic costs associated to both health effects and countermeasures. The ECONOM model is one of the most elaborate economic models so far that can be used for this purpose in Western European countries. This model has been integrated in the Probabilistic Risk Assessment (PRA) code COSYMA and in the Real-time On-line DecisiOn Support system RODOS.

However, in our paper we demonstrate that this ECONOM model is too general to be used in determining the economic impact of the decision to evacuate an industrial region in case of a nuclear alarm. It is important to note that we deal with a nuclear incident situation, which means that there is a possibility of a release actually taking place in the near future. This is totally different from an accident situation where the release has already occurred. Moreover, we show how ongoing and future economic research at the Belgian Nuclear Research Centre SCK•CEN can provide possible solutions to the mentioned shortcomings.

In the following section we analyse how using ECONOM the cost of evacuating a certain area is assessed.
Section 3 enumerates the main shortcomings of this assessment for industrial regions.
In section 4 we demonstrate that recent economic investment theories offer an opportunity to deal with the problem of evacuating an industrial region in a more elaborate way.
Finally, in a last section, we summarise the major conclusions of our paper.

2. THE ECONOM-MODEL

As the ECONOM-model is part of the COSYMA and RODOS code, the main features of these programs will first briefly be described. Afterwards, more attention will be given to the analysis of the economic model itself, focusing on the calculation of the evacuation costs.

2.1 ECONOM: the economic model in COSYMA and RODOS

Both COSYMA and RODOS are tools that can be used to assess the off-site consequences of accidental releases of radioactive material to the atmosphere.

The COSYMA computer code is a PRA code. This means that it can be used to assess the consequences of potential accidental releases, taking into account the range of conditions which may prevail at the time of the accident, and the associated probability of these conditions. Probability may also be associated with the actual occurrence of a particular release [12]. The RODOS program is a real-time on-line decision support system. The actual source term and the atmospheric conditions, during and immediately following a radiological release to the atmosphere, are no longer defined by the user in a probabilistic way. On the contrary, they are assessed by the system itself on a real-time base.

Table 1 summarises the main characteristics of both programs. A more in-depth discussion on the philosophy, the features and the use of COSYMA and RODOS, can be found in [2] and [5] respectively.

	COSYMA	RODOS
Institution	Mainly FZK + NRPB	FZK + other Eur. Union institutions
Operational	First mainframe version 90/1 1990 Latest mainframe version 95/1 1995 PC version 1.0 1993 PC version 2.0 1995	Intended to be fully operational by the end of 1999. (Prototype already exists)
Type	Probabilistic Risk Analysis	Decision Support System (Real-time, On-line)
Use	• Risk assessment of a nuclear site • Risk reduction potential of possible plant modifications • Emergency planning • Siting studies	• Accident management

Table 1. Main characteristics of the COSYMA and RODOS program.

2.2 ECONOM: calculation of evacuation costs

The ECONOM model [6, 11] calculates both the cost of countermeasures (evacuation, relocation, sheltering, food restrictions and decontamination) and the cost of health effects in the exposed population.

The remainder of this paper deals with the decision problem, whether or not to impose countermeasures on an industrial region in case of a nuclear alarm. For simplicity's sake, an industrial region is assumed to be a set of factories without residential population and agricultural production, unless explicitly stated otherwise. It has been motivated by Govaerts et al. [9] that in this case the discussion has to focus on the evacuation countermeasure. This countermeasure has to be decided on in the early phase of an accident, and may cause large distortions in industrial production. The distortion effect of sheltering will generally be rather small and relocation and decontamination are typically long-term countermeasures, that are not considered in the initial decision-making process. No agricultural production is assumed in industrial regions and hence, there will be no food restrictions. Calculating the cost of health effects has already been the subject of a large number of papers; we refer to [14; 26] for some interesting views on this topic.

ECONOM considers three cost categories that will occur in case of an evacuation: transport costs, accommodation costs and loss-of-income costs.

2.2.1 Transport costs

The transport cost includes 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. This cost is calculated as follows:

$$TC = N_{EV} \cdot \left[\left(F_{PR} \cdot UC_{PR} \right) + \left(\left(1 - F_{PR} \right) \cdot UC_{PU} \right) \right] \cdot 2 \qquad (1)$$

where:
TC = Transport cost away from, and back to (factor 2) the evacuation area (monetary unit)
N_{EV} = Number of persons evacuated (caput)
F_{PR} = Fraction of population using private transport means (-)
UC_{PR} = Unit cost of private transport (monetary unit per caput)
UC_{PU} = Unit cost of public transport (monetary unit per caput)

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. Equation (1) uses the number of inhabitants that has to be evacuated, and hence it will correctly assess transport costs in industrial regions as being equal to zero.

2.2.2 Accommodation costs

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. Two approaches can be followed to calculate this cost. On the one hand, the direct expenditures of the evacuated people in the destination area can be taken into account. This means:

$$AC = N_{EV} \cdot UC_{AC} \cdot D_{EV} \qquad (2)$$

where:
AC = Accommodation cost (monetary unit)
UC_{AC} = Unit cost of accommodation (monetary unit per caput and per day)
D_{EV} = Duration of evacuation (days)
and the other parameters already explained above

On the other hand, the houses in the evacuation zone can be considered as capital goods. Due to the evacuation, these houses will temporarily not be used, and hence an opportunity cost arises as the capital value they represent, could have been (but is not) invested at interest rate *I*. Moreover, depreciation of the value of these houses at depreciation rate *D* has to be taken into account, as depreciation is a function of time rather than of use. The value of houses can be very different in different regions and therefore, regional values have to be used.

$$\mathrm{AC} = \sum_{\mathrm{NR}=1}^{\mathrm{NRE}} \mathrm{N}_{\mathrm{EVNR}} \cdot \mathrm{VH}_{\mathrm{NR}} \cdot (\mathrm{I} + \mathrm{D}) \cdot (\mathrm{D}_{\mathrm{EV}} / 365) \qquad (3)$$

where:
NRE = Number of economic regions (-)
N_{EVNR} = Number of persons evacuated in region NR (caput)
VH_{NR} = Value of housing in region NR (monetary unit per caput)
I = Interest rate (% per year)
D = Depreciation rate on housing (% per year)
and the other parameters already explained above

As far as industrial regions are concerned, formulae (2) and (3) correctly assess accommodation costs, i.e., equal to zero, as no inhabitants are assumed in these regions. The workers will return to their own houses, and hence no extra costs will arise.

2.2.3 Loss-of-income cost

If the evacuated people are unable to reach their respective workplaces, the contribution they would have made to the economy will be lost. The added value of the goods and services, produced within a country during one year, is measured by the country's Gross Domestic Product (GDP). This measure is used in a number of different calculation methods for the loss-of-income costs.

First, the loss-of-income cost can be determined, using the number of inhabitants of the affected area and the mean Gross Domestic Product per inhabitant. Hence:

$$LOIC = N_{EV} \cdot \left(GDP \,/\, N_{POP} \right) \cdot \left(D_{EV} \,/\, 365 \right) \qquad (4)$$

where:
$LOIC$ = Loss-of-income cost (monetary unit)
GDP = GDP (monetary unit)
N_{POP} = Number of inhabitants (caput)
and the other parameters already explained above

If there appear to be large differences in the productivity of several regions, the basic formula can be refined by using regional GDP-values, as follows:

$$LOIC = \sum_{NR=1}^{NRE} N_{EVNR} \cdot \left(GDP_{NR} \,/\, N_{POPNR} \right) \cdot \left(D_{EV} \,/\, 365 \right) \qquad (5)$$

where:
GDP_{NR} = GDP of region NR (monetary unit)
N_{POPNR} = Number of inhabitants of region NR (caput)
and the other parameters already explained above

Both formulae, however, largely underestimate the loss-of-income costs when applied to industrial regions, where a lot of added value is created in a thinly populated area.

The extended version of the ECONOM model [7] makes use of both the number of employees evacuated and the sectoral added value per employee, which is certainly a much better approach to reality in industrial areas.

$$LOIC = \sum_{NS=1}^{NES} N_{WEVNS} \cdot \left(GDP_{NS} \,/\, N_{WNS} \right) \cdot \left(D_{EV} \,/\, 365 \right) \qquad (6)$$

where:
N_{WEVNS} = Number of evacuated employees in economic sector NS (caput)
NES = Number of economic sectors (-)
GDP_{NS} = GDP of economic sector NS (monetary unit)
N_{WNS} = Number of employees in economic sector NS (caput)
and the other parameters already explained above

An exact estimation of the loss-of-income cost due to evacuation, can only be obtained by adding the contribution to GDP of the different areas in the evacuation zone. This is shown in equation (7).

$$LOIC = GDP_{EVA} \cdot \left(D_{EV} \ / \ 365\right) \qquad (7)$$

where: GDP_{EVA} = GDP of the evacuated area (monetary unit)
and the other parameters already explained above

However, the very detailed information that is required in this equation, is generally not available in national statistics.

We will now demonstrate the different calculation methods discussed above, in a small example. Suppose a situation where four zones A, B, C and D can be distinguished in the area that has to be evacuated. Zones A, B and D are strongly industrialised areas, situated in the province of Antwerp; zone C, however, is a residential area in the province of East Flanders. Purely fictive information on these zones can be found in table 2. Table 3 contains the necessary statistical information.

Zone	**Inhabitants (10^3)**	**Chemical industry workers (10^3)**	**Paper industry workers (10^3)**
A	-	3	-
B	-	1,5	1
C	18	-	-
D	7,5	-	2

Table 2. Demographic and industrial -fictive- information on zones A, B, C and D.

Geographic region	**Gross Domestic Product (10^9 BEF)**	**Inhabitants (10^3)**
Belgium	7.626	10.000
Antwerp province	1.348	1.625
East Flanders province	950 (*)	1.337
Economic sector	**Added Value (10^9 BEF)**	**Employees (10^3)**
Chemical industry	235	59
Paper industry	96	15

Table 3. Statistical information on the 1994 Belgian demographic and industrial situation [17; 18; 19; 20].

(*) This value is derived from the 1988 value.

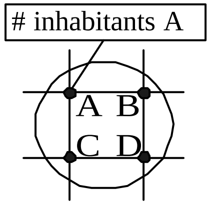
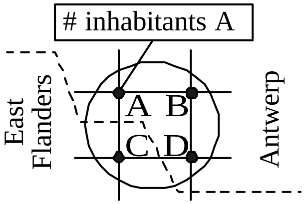
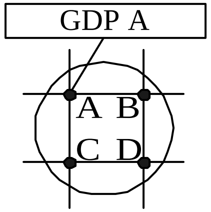
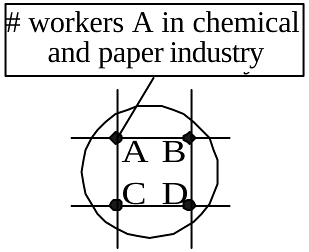
Formula	Schematic representation	Calculation	Result
4		$(18\cdot10^3+7{,}5\cdot10^3)\cdot\frac{7.626\cdot10^9}{10.000\cdot10^3}\cdot365^{-1}$	***53.277.534***
5		$\left[7{,}5\cdot10^3\cdot\frac{1.348\cdot10^9}{1.625\cdot10^3}+18\cdot10^3\cdot\frac{950\cdot10^9}{1.337\cdot10^3}\right]\cdot365^{-1}$	***52.085.935***
6		The necessary information is not available !	
7		$\left[(3\cdot10^3+1{,}5\cdot10^3)\cdot\frac{235\cdot10^9}{59\cdot10^3}+(1\cdot10^3+2\cdot10^3)\cdot\frac{96\cdot10^9}{15\cdot10^3}\right]\cdot365^{-1}$	***101.708.846***

Figure 1. Overview of the four calculation methods for the loss-of-income cost (BEF) in case of a one day evacuation of areas A, B, C and D.

Figure 1 shows the results of the different calculation methods for the loss-of-income cost due to a one day evacuation. Formulae 4 and 5 give rise to quite similar estimations; the daily regional GDP per inhabitant is almost the same in the province of Antwerp (2.273 BEF) and the province of East Flanders (1.947 BEF). However, the difference with the result of equation 7 is striking. While formulae 4 and 5 take into account the residential function of the evacuated area, but neglect the presence of some industrial activities, applying equation 7 implies exactly the opposite. Hence, reality will be best approximated by a combination of both approaches, bearing in mind, however, that simply adding up will result in an overestimation as some people may not only work in the evacuated area but also live there.

3. SHORTCOMINGS OF ECONOM FOR USE IN INDUSTRIAL AREAS

In the previous section, we indicated that loss-of-income costs are the only costs that ECONOM will take into account in case of evacuating an industrial area, i.e., the added value that will be foregone in this area during the evacuation. However, reality is more complicated than this.

Firstly, 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 [21, 23]. 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 these indirect implications as well. As an in-depth discussion on the use of input-output models can be found in [13], we refer the interested reader to this work.

Secondly, the abrupt shut-down of certain industries may involve severe secondary risks (explosions, toxic releases, ...) and losses (product-in-process, ...) [9], which are not dealt with in ECONOM. Clearly these costs are highly time-dependent, as they can be reduced to a large extent, by notifying the factories as soon as possible of the eventuality of a nuclear accident, so that they can start preparing for a possible emergency stop.

As far as the effective implementation of an 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 extend, 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 can revoke quite easily his decision to evacuate, with only small sunk costs.

Recent economic investment theories offer large opportunities to deal with the evacuation problem in an industrial environment in a more elaborate way. In the next section, ongoing research at the Belgian Nuclear Research Centre in these topics will be introduced.

4. POSSIBLE CONTRIBUTION OF ECONOMIC INVESTMENT THEORIES

The decision to evacuate an industrial region in case of a nuclear emergency, can be compared with the decision to invest in a risky project. These decisions both require the spending of money, while their pay-offs remain uncertain. The analogy between the evacuation decision and the decision to invest for instance in shares, is shown in table 4.

	Decision to invest in shares	Decision to evacuate
Cost	Purchase price of shares	Evacuation cost
Pay-off uncertainty	Fluctuations on the stock-market Uncertain dividends	Evolution of the incident (accident versus no accident)

Table 4. Analogies between the decision to invest and the decision to evacuate

Given this similarity, we will firstly show how decision trees, often used in investment theories, can be applied as well to graphically represent our evacuation decision problem. In the second part of this section, the options approach to investment decisions will be introduced as a possible way of dealing with our evacuation problem more appropriately. Finally, a last part of this section is kept for discussion.

4.1 Decision trees

In case of a nuclear emergency, the decision maker has to decide whether or not to evacuate an industrial area. Given the information *i* of a nuclear emergency, he assesses that the incident will escalate to an accident (event s_1) with probability $p(s_1 | i)$. In this case, it will be optimal to evacuate the industrial region. In the same way, he 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 consequences $c(a_i, s_j)$ of his decision, therefore, depend both on the action a_i (evacuation versus no evacuation) that is chosen and the event s_j (accident versus no accident) that finally takes place. How does the decision maker has to proceed in order to take an optimal decision?

The problem of our decision maker is shown in the decision tree of figure 2. In this tree, decision nodes, where the decision maker is in control, are represented by squares; chance nodes, where chance is in control, by circles [24].

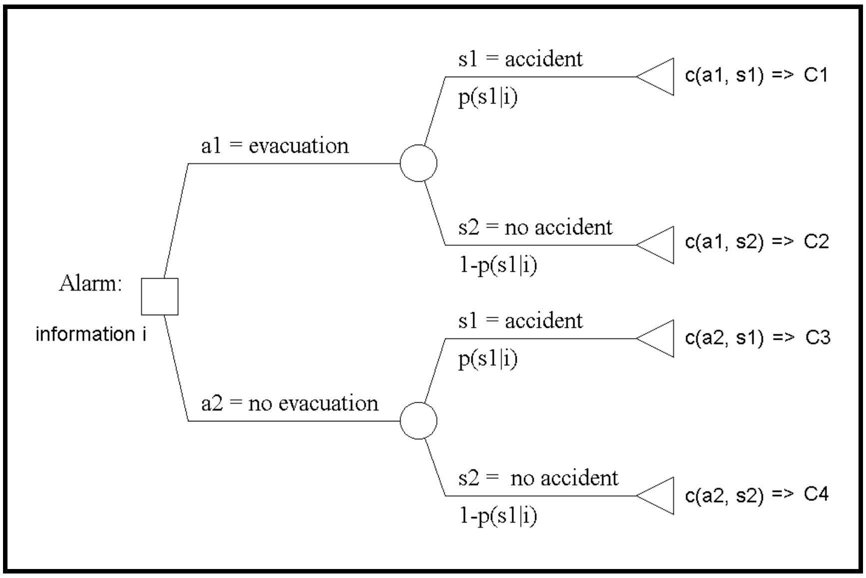


Figure 2. Graphical representation of the basic decision problem

The endpoint c(a_i, s_j) of a particular branch, will consist of a number of health effects, on the one hand, and a certain evacuation cost, on the other hand. However, in order to compare the different end-points with each other, it is necessary to express each of them in one figure. This can be achieved by determining the monetary cost of the health effects, so that they can be added directly to the evacuation cost, resulting in a total cost C_k (table 5). A direct monetary assessment of health effects, however, can be avoided by using Multi-Attribute Utility Theories (MAUT). In such theories, one 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 the work of Keeney and Raiffa [15] and that of Bana e Costa [1]. For the use of MAUT in a nuclear context, see Van de Walle [25].

Consequence	Health effect Cost (1)	Evacuation Costs (2)	Total cost (1+2)
c(a1, s1)	medium	large	C_1
c(a1, s2)	none	large	C_2
c(a2, s1)	severe	none	C_3
c(a2, s2)	none	none	$C_4 = 0$

Table 5. Composition of the total cost in different scenario's

$p(s_1 \mid i)$ is the probability of occurrence of event s_1, given information 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, $p(s_1 \mid i)$ can be calculated as [16]:

$$p(s_1|i) = \frac{p(i|s_1).\,p(s_1)}{p(i|s_1).\,p(s_1) + p(i|s_2).\,p(s_2)} \qquad (8)$$

The decision problem can now be solved by what Raiffa [24] calls "averaging out and folding back". The expected monetary value (EMV) of every chance node[1] is determined by "averaging out" the possible outcomes of this node. For instance, the expected monetary value of the chance node in the 'evacuation' branch, can be determined as:

$$EMV(a_1) = p(s_1|i) \cdot C_1 + (1 - p(s_1|i)) \cdot C_2 \qquad (9)$$

Likewise, we become for the chance node in the 'no-evacuation' branch:

$$EMV(a_2) = p(s_1|i) \cdot C_3 \qquad (10)$$

At every decision node, the decision maker chooses that action that will lead to the chance node with the lowest expected monetary value, as these monetary values are costs. 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 lowest expected cost, taking into account the uncertainty about the actual state (accident versus no accident) that will occur. The decision maker will opt for action a_1 and evacuate the industrial region, if and only if:

$$EMV(e_0, a_1) < EMV(e_0, a_2) \qquad (11)$$

---

[1] By working with expected values, we assume that the decision maker is risk neutral. He is indifferent between on the one hand a lottery with 50 % chance on 100 and 50 % chance on 0, and on the other hand 50 for certain. However, the described principles can easily be extrapolated to take risk-averseness into account as well.

Before introducing the options approach, it is important to note that the decision criterion expressed by the above inequality is in fact a Net Present Value (NPV)-rule. This rule says that you should only invest if the investment has a positive NPV, i.e., if the present value of the benefits is at least as large as the present value of the costs. Otherwise, it is better not to invest.

4.2 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 [22] and Dixit and Pindyck [4], 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 3, 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 [10], allowing to postpone the decision for a certain time. As the two necessary conditions of irreversibility and the possibility to delay are fulfilled, the use of the traditional NPV-rule in (11) 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 2.

The possibility of a decision maker to postpone an investment 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 [3]. Clearly, such a 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 NPV>0 to NPV>K, where K is the opportunity cost of killing the option.

Knowing this, the problem of the decision maker 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 revised decision problem is shown in figure 3a-b.

Branch e_0 represents our basic decision problem, i.e., the situation in which the decision maker decides to evacuate (or not), as soon as he receives the information i_1 of a nuclear alarm. The resulting cost $C(e_0, a_1, s_1)$ 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_1. 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:

$$C_{(e_0,a_1,s_1)} = \begin{cases} C_1 & if\, t_{av} \geq t_n \\ C_1 + C_{ad,e_0} & if\, t_{av} < t_n \end{cases} \qquad (12)$$

A possible course of the additional cost as a function of the available time is shown in figure 4. 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.

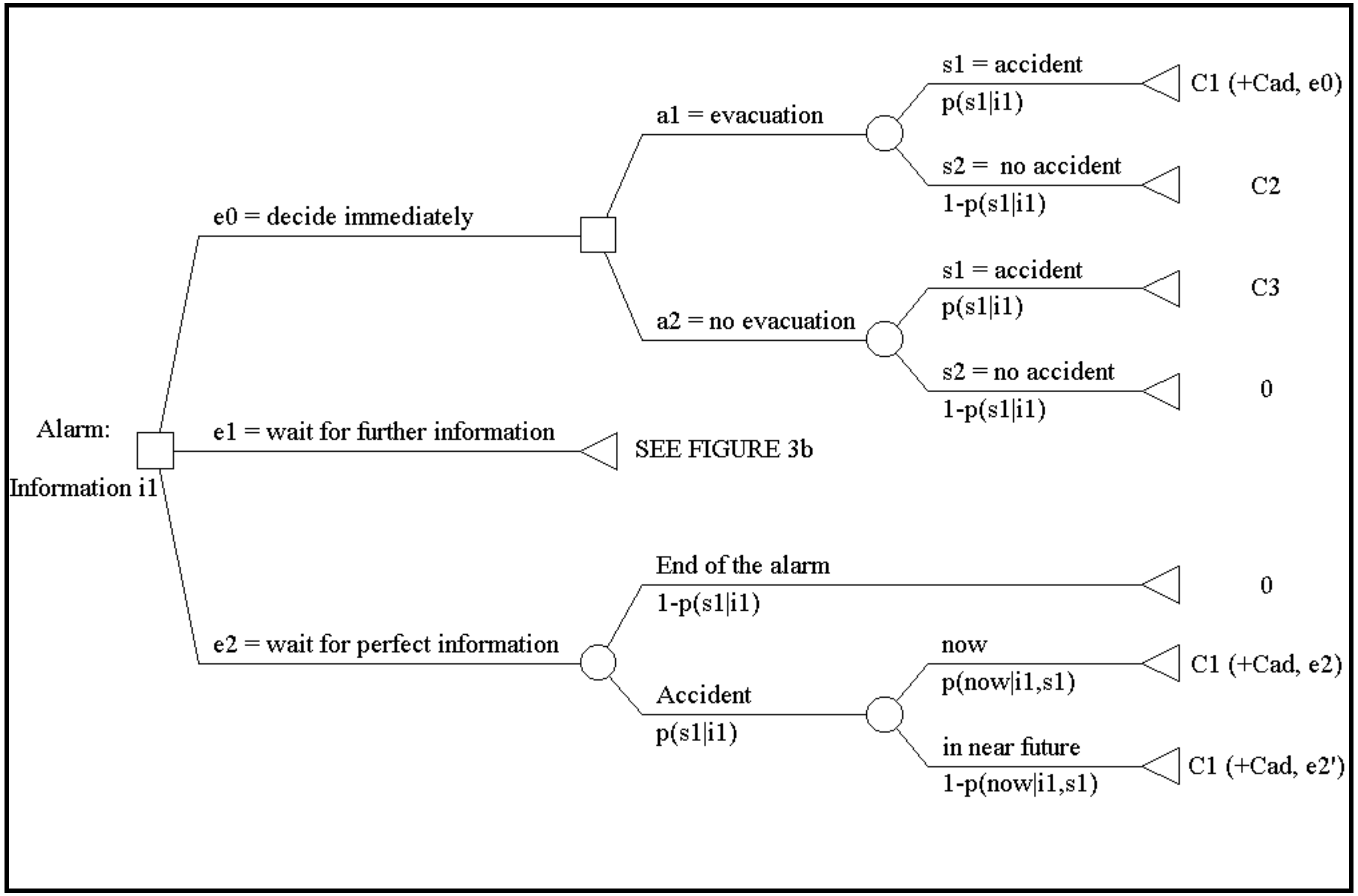


Figure 3a. Graphical presentation of a more elaborate decision problem

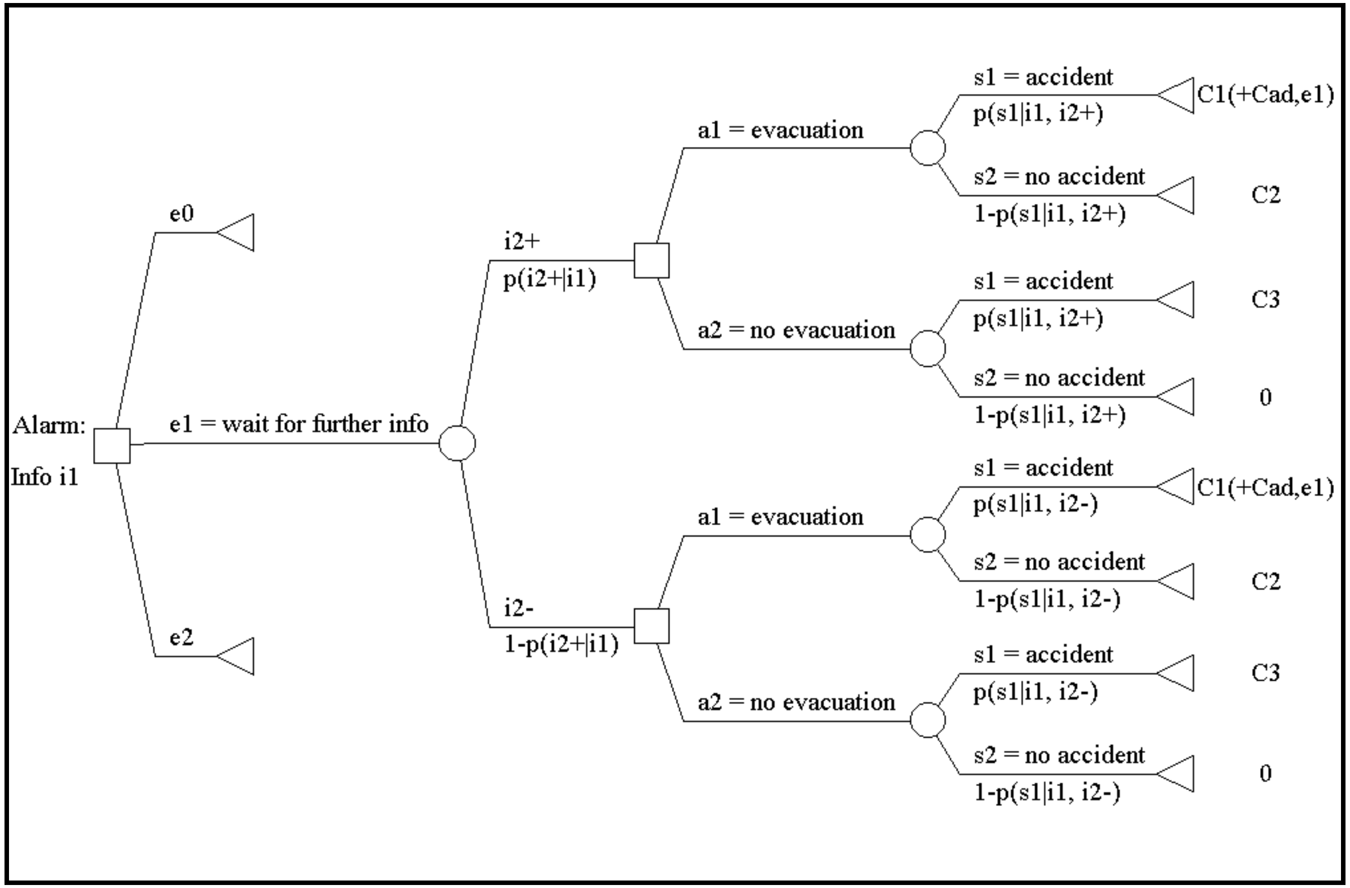


Figure 3b. Graphical presentation of a more elaborate decision problem

In branch e_1 (figure 3b), the decision maker decides to wait for further information on the course of the alarm. This 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 decision maker will be able to better assess the probability of the accident actually taking place. Note that:

$$p\left(s_1 \middle| i_1, i_{2+}\right) \geq p\left(s_1 \middle| i_1\right) \geq p\left(s_1 \middle| i_1, i_{2-}\right) \qquad (13)$$

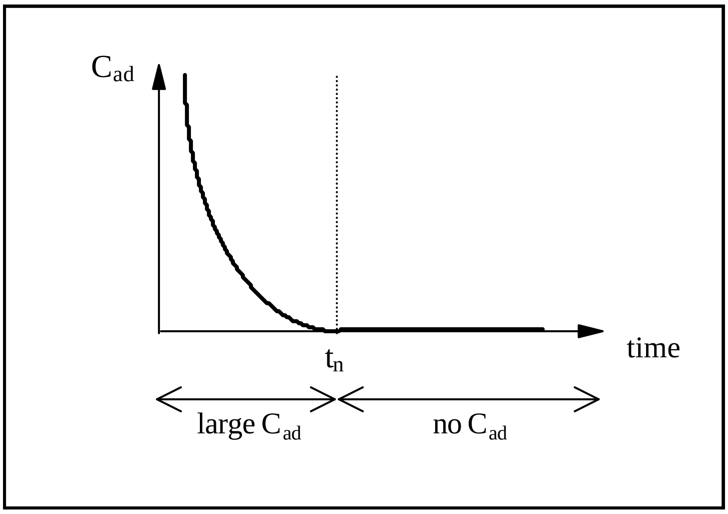


Figure 4. Possible course of additional cost as function of t_{av}

Hence, the chance grows that the decision maker takes the right decision, i.e., evacuate when an accident occurs, not evacuate when no accident takes place. On the other hand, the available time to evacuate will be smaller, possibly resulting in higher additional costs $C_{ad,\ e1}$, as is shown in figure 4.

The extreme case, in which the decision-maker 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. The price that has to be paid for this certainty, are the possible, large additional costs $C_{ad,\ e2}$ and $C_{ad,\ e2'}$, ($\leq C_{ad,\ e2}$) in the case of a release starting now or in the near future, respectively.

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

$$EMV(e_0, a_1) < MIN\left\{EMV(e_0, a_2), EMV(e_1), EMV(e_2)\right\} \qquad (14)$$

Note that (14) includes:

$$EMV(e_0, a_1) < EMV(e_0, a_2),$$

i.e., condition (11).

4.3 Discussion

As we have mentioned before, the ECONOM model, originally integrated in COSYMA, is used in RODOS as well to calculate the evacuation and health effect costs. In its current status[2], RODOS provides costs C_1 and C_3 from figure 2. Moreover, the decision whether or not to evacuate, will be based on a NPV-criterion.

Although this approach may be sufficient for residential regions, it is certainly not in an industrial area. We have therefore presented the options approach as a possibility of dealing in a more elaborate way with the evacuation problem in this specific environment. This approach showed that on the one hand waiting for further information on the course of the alarm, and maintaining the flexibility to react when necessary, has a certain value. On the other hand, it is obvious that there is also a cost associated to this waiting, as the time that is available to execute the evacuation will be smaller. This is very important in industrial areas, as certain evacuation costs will be largely time-dependent.

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[2] It is intended to extend RODOS in the future, for use in pre-accidental situations as well, when there is a considerable risk of an imminent release [8].

It has to be stressed, that the options approach is but a possible way to deal with the evacuation problem. We considered the decision to evacuate as an “all or nothing” decision, i.e., evacuate the complete area, or not evacuate at all. Instead of taking one fundamental decision, the decision maker could proceed in steps and make a sequence of smaller decisions. Such a decision could be for instance to evacuate certain factories, but wait on further information for other firms, or let certain factories prepare themselves for a possible emergency stop, or 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. Future research will focus on these problems.

CONCLUSION

In this paper, we have firstly analysed the way in which ECONOM, the economic model that is integrated in the Probabilistic Risk Assessment code COSYMA and the Real-time On-line DecisiOn Support system RODOS, determines the evacuation cost in case of a nuclear emergency.

This analysis clearly indicated that the ECONOM-model is too general to be of use in industrial areas as time aspects of the decision, although very significant, 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, ...).

Furthermore, it was shown that the decision to evacuate an industrial region in case of a nuclear emergency, can be compared with the decision to invest in a risky project. These decisions both require the spending of money, while their pay-offs remain uncertain.

The options approach to the evacuation decision indicated that the “real” problem of the decision maker is not whether to evacuate the industrial region in case of a nuclear emergency 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. In so doing, the decision maker preserves the flexibility to evacuate when the obtained information points in the direction of a real accident. However, the time that remains available to carry out the evacuation will be smaller, possibly resulting in higher costs.

REFERENCES

[1] Bana e Costa, C.A. (1990). *Readings in Multiple Criteria Decision Aid*. Springer-Verlag, New York.

[2] Commission of the European Communities (1991). *COSYMA. A new programme package for accident consequence assessment*. Commission of the European Communities, Brussels.

[3] Cox, J.C. and Rubinstein, M. (1985). *Options Markets.* Prentice-Hall, New Jersey.

[4] Dixit, A.K. and Pindyck, R.S. (1995). “The options approach to capital investment”, *Harvard Business Review*, 3, 105-115.

[5] Ehrhardt, J. and Weis, A. (1995). *Development of a comprehensive decision support system for nuclear emergencies in Europe following an accidental release to atmosphere*. Forschungszentrum Karlsruhe, Karlsruhe.

[6] Faude, D. (1992). *COSYMA. Modelling of Economic Consequences*. Kernforschungszentrum Karlsruhe, Karlsruhe.

[7] Faude, D. and Meyer, D. (1994). *Extension of the COSYMA-ECONOMICS Module. Cost Calculations Based on Different Economic Sectors*. Kernforschungszentrum Karlsruhe, Karlsruhe.

[8] French, S. (1996). “Multi-Attribute Decision Support in the Event of a Nuclear Accident”, *Journal of Multi-Criteria Decision Analysis*, 5, 39-57.

[9] Govaerts, P., Declercq-Versele, H., Samain, J.P., Walthoff, P. (1991). “Nuclear emergency planning and response in an industrial area”, *International Seminar on Intervention Levels and Countermeasures for Nuclear Accidents*, 650-661.

[10] Govaerts, P. (1993). “Review of Potential Accidents Requiring Off-site Emergency Planning”, *Off-site Emergency Response to Nuclear Accidents*, 1-20.

[11] Haywood, S.M., Robinson, C.A. and Heady, C. (1991). *COCO-1: Model for Assessing the Cost of Offsite Consequences of Accidental Releases of Radioactivity.* National Radiological Protection Board, Chilton.

[12] Haywood, S.M. (1993). “The Assessment of the Consequences of Accidental Releases”, *Off-site Emergency Response to Nuclear Accidents*, 55-72.

[13] Hidalgo, A., Gallego, E., Munoz, A., Pavon, J. (1995*). Evaluación del impacto económico externo de los accidentes nucleares*. Universidad Polytécnica de Madrid, Madrid.

[14] Jones-Lee, M.W. (1994). “Safety and the saving of life: The economics of safety and physical risk”, *Cost-Benefit Analysis*, 290-318.

[15] Keeney, R.L. and Raiffa, H. (1993). *Decisions with Multiple Objectives. Preferences and Value Tradeoffs.* Cambridge University Press, Cambridge.

[16] Morgan, M.G. and Henrion, M. (1990). *Uncertainty. A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press, Cambridge.

[17] Nationale Bank van België (1995). *Tijdschrift van de Nationale Bank van België.* december 1995, NBB.

[18] Nationaal Instituut voor de Statistiek (1991). *Regionaal Statistisch jaarboek*. NIS, Ministerie van Economische Zaken.

[19] Nationaal Instituut voor de Statistiek (1995). *Industriële statistieken*. oktober 1995, NIS, Ministerie van Economische Zaken.

[20] Nationaal Instituut voor de Statistiek (1995). *Sociale statistieken. Enquête naar de beroepsbevolking*. NIS, Ministerie van Economische Zaken.

[21] OECD (1996, draft). *Methodologies for assessing the consequences of nuclear reactor accidents.*

[22] Pindyck, R.S. (1991). “Irreversibility, Uncertainty, and Investment”, *Journal of Economic Literature*, 29, 1110-1148.

[23] Proult, D. and Desaigues B. (1993). *L’évaluation de l’impact économique des situations post-accidentelles: Présentation et analyse du modèle COSYMA*. Centre d’étude sur l’Evaluation de la Protection dans le domaine Nucléaire, Fontenay-aux-Roses.

[24] Raiffa, H. (1970*). Decision Analysis. Introductory Lectures on Choices under Uncertainty.* Addison-Wesley, Massachusetts.

[25] Van de Walle, B. (1996). “Decisions with multiple conflicting objectives: tools and techniques”, *Annals of the Belgian Radiation Protection Association*, this issue.

[26] Zerbe, R.O. Jr. and Dively, D.D. (1994*). Benefit-Cost Analysis: In Theory and Practice*. HarperCollins College Publishers, Washington.

ABSTRACT

Zowel in de Probabilistic Risk Assessment code COSYMA als in het Real-time On-line DecisiOn Support system RODOS, is het uitermate belangrijk om de economische implicaties van het opleggen van tegenmaatregelen in geval van een nucleair alarm juist in te schatten. Om dit te realiseren, beschikken beide programma’s over het economisch model ECONOM.
In dit artikel, tonen we aan dat het ECONOM-model echter niet geschikt is, en ook nooit bedoeld was, om de economisch impact te bepalen van een evacuatie in een industriële omgeving. Bovendien geven we aan hoe huidig en toekomstig economisch onderzoek aan het Studiecentrum voor Kernenergie SCK•CEN, kan bijdragen tot een mogelijke oplossing voor de vastgestelde tekortkomingen.

RESUME

Dans le Probabilistic Risk Assessment code COSYMA comme dans le Real-time On-line DecisiOn Support System RODOS, il est extrêmement important d’évaluer de façon correcte les implications économiques à la suite d’une application des contre-mesures en cas d’une alarme nucléaire. Afin de réaliser ces objectifs, les deux systèmes disposent du modèle économique ECONOM.
Dans cet article, nous démontrons que ce modèle ECONOM n’est pas apte à, et en aucun cas réalisé à déterminer l’impact économique d’une évacuation dans des territoires industriels. En outre, nous signalons comment la recherche économique actuelle et future au Centre d’étude de l’Energie Nucléaire SCK•CEN, peut contribuer à combler des lacunes constatées.

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ASSESSMENT OF ECONOMIC CONSEQUENCES OF COUNTERMEASURES AFTER A NUCLEAR ACCIDENT : THE USE OF INPUT-OUTPUT MODELS

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ABSTRACT

Some countermeasures adopted in case of a nuclear accident can produce significant economic impacts. The paper makes in first place a short review of the existing models for assessing the economic consequences of accidents, including the intercomparisons performed. For the study of effects in both the area directly affected, and in the areas with which it has economic relations, the Input-Output methodology is considered very appropriate, since it is based in the transactions existing between all the economic sectors and can be very useful for the assessment that changes in final demand or restrictions in primary inputs may have on the production of the economic system, direct and induced, for the affected and non-affected areas.

The essential principles of I-O methods are presented together with examples based on the recent research, leading to conclusions on their applicability for deterministic (single case) and probabilistic (risk) analyses. One interesting conclusion is to see that positive effects in the areas non-directly impacted by the countermeasures can normally overcome the negative effects in the same regions.

INTRODUCTION

The economic consequences of accidental releases of radioactive material to the atmosphere are one of the main endpoints of Probabilistic Consequence Assessment (PCA) codes. Economic impact is originated by the implementation of countermeasures (population movements, decontamination, intervention on food , mainly) as well as by the health effects potentially caused by the exposure to radioactive products. However, its evaluation is not a simple task and, as it was observed in the conclusions of the last CEC/NEA Benchmark Exercise on PCA codes (*Nixon et al. , 1994*) , this was the least mature area of PCA modelling, with a need identified of research on the potential importance of indirect economic impacts that were not modelled in any of the existing PCA codes.

For that reason, one of the main topics in the EC MARIA-4[1] project was economics modelling, leading to the development of new models for the COSYMA code which can be used dependin on the objectives of a particular study and on the availability of data (*Gallego, 1995a)*.

In this paper an introduction is first made to the costs of nuclear accidents, followed by an schematic description of the existing models and codes for assessing economic consequences of accidents, which is including the conclusions of the main intercomparisons between models. The second section of the paper will review the new model MECA3 based on the use of Input-Output tables, that allows an assessment of the indirect impact outside the areas directly affected by the implementation of countermeasures, also including some representative case studies.

THE COST OF NUCLEAR ACCIDENTS. DEFINITION AND LIMITATIONS.

The definition of 'cost' of an accident is normally representing a concept broader than the simple monetary impact. It would represent a benefit foregone, that can be measured by the amount of money that would be required to restore the pre-accident level of well-being, in case it would be possible. Therefore, the total cost is including not only the direct monetary impact but also more indirect and personal aspects such as pain and anxiety, including a degradation on the quality of life and welfare.

Apart from the nature of some elements of the cost, which are difficult to evaluate, or which can be of a controversial nature -like the costing of health effects-, the evaluation of economic consequences of nuclear accidents is subject to a number of limiting conditions, both in space and time.

While some elements will last for a short time period after the accident, other can continue or can emerge a long time after the accident. In the last case, a discounting is needed to obtain comparable costs[2]. However, no unanimity exists between economists about the validity of discounting environmental damages in risk assessments, but, if an accident is assumed to have taken place, it is evident that not all their consequences will occur soon after the accident, and thus a more correct picture of the cost is obtained if delayed costs are discounted. In this sense , there is now an increasing consensus on using normal discount rates (about 10% per year) for market goods in general but, for non-market goods , like health effects or environmental damage, a much reduced discount rate (between 1 % and 3 % per year) is preferably used for medium term and no discounting at all for effects appearing with a long delay in the future, thus avoiding its total neglection. On the other hand, another limitation for the evaluations is, as it can be imagined, that the uncertainties in the predictions increase with time, given the concurrence of multiple uncertain factors and the imperfect knowledge of their behaviour on a long term.

Concerning the spatial ambit, for very large accidents -when different countries or regions become affected-, the more different are the economic systems of the affected countries the stronger would be the uncertainties. Past experience in the case of the TMI-2 and the Chernobyl accidents shows that for small scale accidents, like the first, it was relatively easy to account for all the off site costs caused by the accident, but for large scale accidents like the second, the only possibility is to assess country-by-country costs . An example of this is available for the Nordic countries *(Tveten, Ed. , 1990)*.

Additionally, some effects result 'unquantifiable' and usually impose a forced boundary to the assessments. These are effects like the loss of image that the company, the region or even the country affected by an accident would experience, or the losses of environment recreational uses. Alternative methods like the willingness-to-pay for avoiding these effects may be useful to evaluate them, but a substantial development would be needed.

THE COST OF COUNTERMEASURES AS AN ELEMENT FOR DECISION-MAKING.

Countermeasures adopted to limit the individual and collective exposure to radioactive products released in case of an accident (off-site accident management) are an obvious source of economic costs, since they will generally affect the normal living activities of the population, they can involve destruction of contaminated products or will require the use of special techniques and tools to restore pre-accident conditions. Indeed, all the existing models consider the costs associated with the implementation of countermeasures.

This evaluation is often used as part of the decision-making process to reach optimal intervention levels for the application of alternative countermeasures. According to the international recommendations for intervention after a radiological accident *(IAEA, 1994; ICRP, 1993)*, the protective actions to avoid delayed health effects *should be initiated when they produce more good than harm in the affected population, and should be introduced and withdrawn at levels that produce a* ***maximum net benefit to the population***. In applying these principles, the terms 'good', 'harm' and 'benefit' should include, obviously, health and safety and the tangible costs of protective actions, as well as other unquantifiable factors such as reassurance stress and other societal values that should be taken into account by the decision-maker. In any case the economic cost of the countermeasures will be always an important factor to consider, since their implementation can seriously affect, in case of a large accident, the economy of the country and the society=s welfare thus inducing indirect consequences to the population as a whole, which should be not neglected by the decision-maker.

MODELS AND CODES FOR THE ASSESSMENT OF ECONOMIC CONSEQUENCES.

The first significant attempt to a comprehensive evaluation of the consequences of accidental releases of radioactive material including economic consequences was the *Reactor Safety Study (U. S. NRC, 1975)*. It is in this context of risk assessment that a number of accident consequence assessment (ACA) computer programs have been developed since then, by which the effects of postulated accidental releases may be predicted. Between them two have wide international groups of users, the U.S. MACCS code *(Jow et al. , 1990)* and the European COSYMA code *(Hasemann and Jones, 1993).*, developed in the framework of the MARIA project (Methodology for Assessing the Radiological Impact of Accidents). These programs are capable of predicting the consequences of accidents in particular weather conditions, and also of performing probabilistic assessments , which take into account the range of weather conditions which may occur. Such models may be useful in emergency planning, and in studies in connection with the siting, design and licensing of nuclear facilities.

Computer systems are also being developed which will aid the formulation of decisions on protective actions in the event of an actual accident, and assist in emergency planing. An example is the RODOS system *(Ehrhardt et al., 1993)*, currently being developed jointly by several European organisations under a CEC funded programme of work. As already explained, the economic impact of protective countermeasures is a very important input factor for decision-making about their implementation. Several economic consequence models exist which can be used as the basis of an economics module appropriate for application in programs of both of the above types. The predictive nature of all these models is also the cause of many of their limitations, since they must be applied to a variety of scenarios, using generally applicable techniques, which can not be so precise as the use of classical accounting methods for specific cases.

The are two outstanding models with regard to the detail in which economic consequences are considered: COCO-1 *(Cost Of Consequences Off-site; Haywood, Robinson and Heady, 1991),* which is the standard model of COSYMA *(Faude, 1992)* and of the British code CONDOR *(SRD, NE and NRPB, 1993),* and MECA *(Model for Economic Consequence Assessment; Gallego, 1994)* which was coupled initially to MACCS, and later to COSYMA. Their basic characteristics together with those of the model in MACCS, much simpler, are summarized in Table 1.

From that table, we will just remark the greater complexity of MECA, like a research model developed to study more in depth the nature of each component of the cost, making use of the maximum statistical information readily available in EU countries. In its last version (named MECA3, *Gallego, 1995b*), it also includes an Input-Output model to evaluate the direct and indirect costs caused by population movements, which is described later.

Between the precursor models it is worth to mention that developed by the U.S. Bureau of Economic Analysis *(Cartwright, Beemiller and Gustly, 1981),* called RIMS *(Regional Industrial Multiplier System).* It was based on economic production and on the Input-Output methodology for estimating the effect on a regional economy of a change in demand for goods in a given sector of that economy. For reactor accident impacts, the regions under consideration were divided into '*physically affected'* and '*physically unaffected'* areas. However, the economic effects were only calculated for the first year after the accident, and the model was considered unsuitable for direct use in probabilistic accident consequence assessment because it required a very detailed data base and a great deal of computational effort.

Intercomparison exercises.

Intercomparison exercises are needed to compare the capacities and identify lacks in the models and future guidelines to investigate. The most recent international exercise was that included in the recent *NEA/EC Second International Comparison of Probabilistic Accident Consequence Assessment Codes (NEA/OECD, 1994)*, in which all the models described above (plus the Finnish ARANO) were included together with other ACA codes not specifically addressing the problem of economic consequences.

The results of that exercise showed not only the differences between the various *economic models* but those coming from the previous steps of accident consequence assessment, specially in the calculation of the impact of countermeasures and the number of health effects.

Additional differences were originated from certain assumptions the users made to adapt the data in the specifications of the exercise to their own model. In general, the differences in the results obtained were within reasonable variation factors, and the exercise presented a lower dispersion in the results from modelling differences than previously expected.

For example, with regard to the cost of population movement, the differences between the predictions of the codes for this endpoint were relatively small, within a factor of 4 for a large magnitude release and the CCDF[3] were in reasonable agrement. The difference observed were due largely to differences in output from the countermeasures module, such as the extent and duration of relocation and, for a low magnitude release, from the assumed duration of short-term evacuation, with a less significant contribution from differences in economic modelling.

Concerning the cost of food bans, the differences were also certainly small, within a factor 5 for the two releases, also showing a reasonable agreement in the CCDF curves. The differences observed were due partly to differences in output from the food countermeasures modules, and partly to different assumptions made in adapting the data in the specification of the exercise for food, which were not directly adaptable to all the codes .

In relation to the total cost, it was apparent that food bans costs were the dominating costs for all the codes and calculations, population movements were the next in importance for the large magnitude release, and health effects for the low magnitude[4]. The total combined spread was by about a factor 2 or 3 for the cases analysed. This explains the comment made above on the differences lower than expected that were observed in the exercise.

INCORPORATION OF MECA2 IN COSYMA.

The model MECA2, coupled to MACCS, was one of the participants in the CEC/NEA Intercomparison Exercise. However, the incorporation of MECA2 to COSYMA was considered as the best way to obtain a real intercomparison between the two economics models developed in connection with the MARIA project: the COCO-1 and the own MECA2. This complemented previous theoretical comparisons, like that of Table 1.

MECA2 has been coupled to COSYMA as a post-processor independent module. No modifications in the main COSYMA system have been made. The description of the accident and weather sequences that should be analyzed by the model is transferred from COSYMA through the corresponding intermediate results files containing the sample of weather sequences, the flags for the kind and duration of the countermeasures in each element of the calculation grid, and the number of health effects estimated by COSYMA. Economic estimates made for each weather sequence are stored and processed by the own program, which produces itself the CCDF curves and percentiles of a quite large number of related consequences (not only costs, but also amounts of persons, areas or produce affected by countermeasures).

The tests performed have include an intercomparison of results for three hypothetical scenarios, based on two real Spanish nuclear sites. The calculations were made using generic source terms, taken form the specialised literature, non specific from the actual nuclear power plants at the sites, and merging meteorological data measured at different sites so that the conditional probabilities obtained are not representative at all of the site atmospheric conditions. The only truly representative of the sites were the economic-relevant data, such as all the distributions of the population, agricultural and livestock products, crop areas, and more specific data like the Gross Value Added at factor cost by economic sectors. It is important to remark that the results obtained are thus only valid for economic modelling intercomparison purposes, but they do not represent the risk or the consequences associated to any real

Table 1. Characteristics of the main models for assessment of economic consequences.

Type of Effects	Economic Impacts / Items	COCO-1 In COSYMA and CONDOR	MECA Linkable to MACCS and COSYMA	MACCS
Population Movements	Management-Control	Not Considered	Unitary cost per person and day Reduced for relocation	Not Considered
	Transport	Unitary costs (private/public transpon) per person	Unit cost for for private and public transport (per person-km)	Not Considered
	Lodging & Food	Unit cost of accommodation lost (during recovery period)	Unit costs (lodging and food, in private / public) (per person-day). Reduced for relocation. Only during transitory period.	Single Unit Cost (per person-day)
	Loss-of-Income	GDP (per person-year) 15 regional values maximum up to a mean recovery time	GVA (Gross Value Added, per person-day) by economic sectors except agriculture. Distributed in the grid (up to 50 regions). Sector specific recovery time. **Optional Input-Output model:** In and out the relocation area (+ & - effects).	
	Lost Capital Services	4 categories: 1) Non-residential; 2) Housing and buildings; 3) Consumer durables; 4) Land. (per person, up to 15 regional values)	5 categories **Urban Areas:** Dwellings, Public buildings, Public open areas (Per person in up to 50 regions) Industrial installations, Commercial & other buildings (Per employee in industry and services, up to 50 regions) **Rural Areas:** Land (value per hectare) (up to 15 categories, hasta 50 regions)	**Non-farm property:** (single value per person) **Farm property:** (single value per hectare). Up to 99 regional values.
		1) & 2) Depreciation from recovery time on. 3) & 4) Depreciation all the time.	**Urban:** Normal + accelerated depreciation due to lack of use and maintenance (different rates for each category and period, before and after recovery times) **Rural:** No depreciation for land. Loss-of-capital only if relocation.	Depreciation of improvements (not land) during loss of usage
Decontamination	Direct Cost of Decontamination	One decontamination level for each relocation period: Unit cost per person (Urban) Unit cost per hectare (Rural)	Up to 6 decontamination levels and 6 types of urban and rural surfaces: Rural zones: Up to 15 types of land uses (Unit cost of decont. per hectare). Urban zones: Areas of each decontamination category per person.	Up to 3 levels: Cost per person (Urban) Cost per hectare(Rural)
Food Control & Bans	Consumption restrictions (lst year)	Cost of lost food + food disposal Lost Agricultural Capital (with depreciation): Non residential, Buildings and Land.	Lost food at the price perceived by farmers (up to 50 categories, 40 crops and 10 livestock products) Productions distributed in the grid.	Milk & Non-milk crops: Annual production per hectare
	Production restrictions	GDP contribution by products (during recovery period) + Lost Agricultural Capital	GVA (Gross Value Added, per person-day) for agriculture during recovery time. Distributed in up to 50 regions.	Only capital losses

site.

The main characteristics of the three cases studied are summarised in Table 2, and the mean values obtained for each run are included in Table 3. In these calculations, the same weather sequences and patterns of countermeasures calculated by COSYMA are used by MECA2 to assess their economic impact.

The first important conclusion is that no big differences are resulting in the endpoints obtained due to the differences in the economics models used. Obviously, some tendencies can be observed, and probably are amplified depending on the site characteristics. In general, for the relocation of people MECA2 predicts higher values than COCO- 1, probably due to the differences in modelling the costs of interdiction. For **decontamination** costs, although MECA2 can use a more complete data base on decontamination techniques and costs for different types of surfaces, it was limited to only one type and technique, as it is commonly made in COSYMA, and the result, as can be seen is a lower cost prediction. **Food bans** result always a very important item, and the differences in the models and categories of costs considered in both models result in opposite behaviour depending on the scenario; this may be reflecting a greater detail of MECA2 in the data base managed. Finally, although the costing of **health effects** is not the subject of this paper, it can be said that MECA2 normally results in smaller costs, at least for latent effects, which are the most representative from this point of view.

Looking to the probability distributions, Figure 1 shows the CCDF curves produced by both models for the Zorita scenario A, in which it can be seen that relocation and health effect costs seem very similar for the two codes, MECA2 relocation costs being always higher and health effect costs smaller, and the most signifcant differences being attributable to food ban costs, which have the greater weight in the total costs, as it was already seen for the mean values. Figure 2 displays the curves for Vandellós scenario B, in which again relocation and health effects cost curves are very close, and not the curves for food bans costs, which this time are greater for MECA2.

In any case, the results for food bans costs are strongly conditioned by the assumed countermeasures in case of food contamination, basically a complete disposal of crops in the first year, and condemnation of terrains in the following years if food contamination would result above permissible levels; with no other alternatives which could be more cost-effective. Therefore, the modelling of alternative countermeasures for food is considered as a priority before trying to improve cost assessment for food countermeasures in PCA codes.

Table 2. **Main characteristics of three hypothetical scenarios**.

- **Scenario A:** Zorita site (Guadalajara).
  N.P.P. Westinghouse PWR - 1 Loop . 510 $\mathrm{Mw_{th}}$. 160 $\mathrm{Mw_{e}}$.

- **Scenarios B & C:** Vandellós site (Tarragona).
  N.P.P. Westinghouse PWR - 3 Loop. 2775 $\mathrm{Mw_{th}}$. 992 $\mathrm{Mw_{e}}$.

- End of equilibrium cycle inventories for 60 radionuclides.

- Source terms representative of LOCA with core fusion and late overpressure containment failure (A & B) or explosive early containment failure (C) .

SOURCE TERM CHARACTERISTICS			
A) CLUSTER 27 Zion (NUREG- 1150) **B)** RZ2 Zion (NUREG/CR-6094) **C)** CLUSTER 11 Zion (NUREG- 1150)	**A**	**B**	**C**
Start of release (from reactor scram)	7.90 h	12 h	2.4 h
Release duration	1.82 h	3 h	5 h
Warning time (from reactor scram)	5.75 h	5 h	0.4 h
Thermal power in the release	2.5E + 5 w	-	5.0E + 6 w
Height of the release	10 m	10 m	10 m

TOTAL RELEASE FRACTIONS BY RADIONUCLIDE GROUPS							
	Kr Xe	I	Cs Rb	Te	Sr Ba	Ru	La Ce
A	9.3E-1	8.0E-2	9.7E-3	5.3E-3	5.9E-4	3.4E-6	7.0E-5
B	1.0	3.0E-2	6.0E-6	7.0E-6	1.0E-6	2.0E-8	1.0E-7
C	9.2E-1	1.8E-1	7.0E-2	3.4E-1	1.2E-1	4.0E-2	5.0E-2

Countermeasures criteria:

C Short-term emergency actions (evacuation, sheltering, iodine prophylaxis) according to Spanish regulations.

C Population relocation criterion: 10 mSv effective dose in 30 days.
Resettlement: 50 mSv in 365 days.

C Food ban criterion: 5 mSv in 1 year (COSYMA default values).

Table 3. **Mean values of economic consequences for three hypothetical scenarios.**

Zorita scenario A

ECONOMIC COST (MPTA)	**COSYMA 93/1**		**MECA2**	
Relocation of population	5.01 10^{2}	3.2 %	7.66 10^{2}	9.8 %
Decontamination	8.40 10^{0}	0 %	5.45 10^{0}	0.1 %
Food Bans	1.14 10^{4}	72.2 %	3.74 10^{3}	48.1 %
Early Health Effects	0.0	0 %	0.0	0 %
Late Health Effects	3.89 10^{3}	24.6 %	3.27 10^{3}	42 %
Total Costs	1.58 10^{4}	100 %	7.78 10^{3}	100 %

Vandellós scenario B

ECONOMIC COST (MPTA)	**COSYMA 93/1**		**MECA2**	
Relocation of population	1.38 10^{2}	10.1 %	2.02 10^{2}	9.8 %
Decontamination	0.0	0 %	0.0	0 %
Food Bans	6.94 10^{2}	51 %	4.72 10^{3}	89.5 %
Early Health Effects	0.0	0 %	0.0	0 %
Late Health Effects	5.29 10^{2}	38.9 %	3.51 10^{2}	6.7 %
Total Costs	1.58 10^{4}	100 %	7.78 10^{3}	100 %

Vandellós scenario C

ECONOMIC COST (MPTA)	**COSYMA 93/1**		**MECA2**	
Relocation of population	6.80 10^{4}	33.8 %	1.00 10^{5}	43.2 %
Decontamination	6.42 10^{3}	3.2 %	1.05 10^{3}	0.5 %
Food Bans	7.05 10^{4}	35.1 %	9.50 10^{4}	41.1 %
Early Health Effects	8.77 10^{0}	0 %	9.32 10^{0}	0 %
Late Health Effects	5.61 10^{4}	27.9 %	3.53 10^{4}	15.2 %
Total Costs	2.01 10^{5}	100 %	2.31 10^{5}	100 %

Figure 1. CCFD comparison between MECA2 and COSYMA for Zorita scenario A

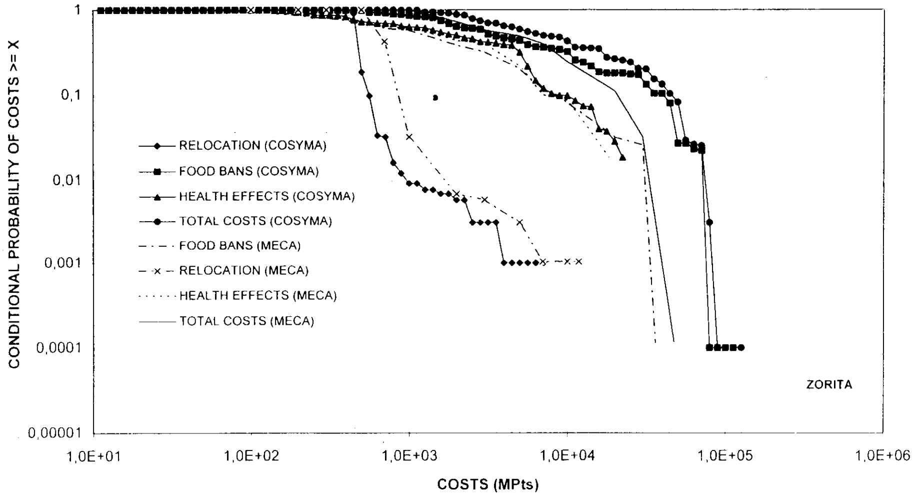
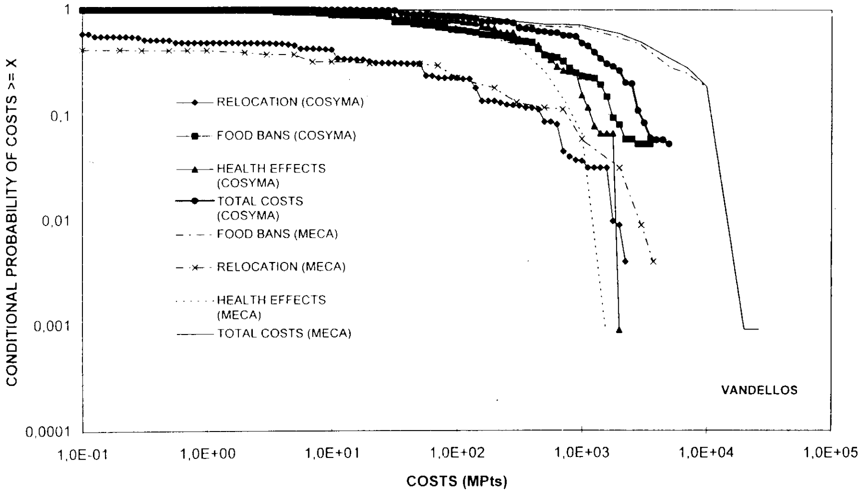


Figure 2. CCFD comparison between MECA2 and COSYMA for Vandellós scenario B



INPUT-OUTPUT MODEL FOR THE STUDY OF DIRECT AND INDIRECT ECONOMIC IMPACT.

As said above, one objective of the research was to evaluate the economic impacts of the accidents on both the area directly affected, and the areas which have economic relations with the area directly affected. In coincidence with other authors *(Assouline, 1984; Cartwright et al., 1981)* the Input-Output methodology was considered the most appropriate for the study of such effects, and a simple Input-Output model was developed, tested and incorporated in the MECA code, thus allowing to run it in connection with COSYMA.

The Input-Output Table.

Before describing models and case studies, it is probably worthwhile to take a short look to the definition and structure of the Input-Output Tables. The main equation in the I-O Table is the equilibrium between Input (Resources) and Output (Employments) for each economic branch *i*, so that it is possible to write:

$$\text{Production}_i + \text{VAT}_i + \text{Commercial margins}_i + \text{Imports}_i$$
$$=$$
$$\text{Total intermediate Consumption}_i + \text{Final Consumption}_i + \text{Gross Formation of Fix Capital}_i + \text{Stock Variations}_i + \text{Exports}_i$$

Looking to the left side of the above equation, Production means <u>total</u> production: GVA (Gross Value Added) at factors cost plus the intermediate consumption of the corresponding branch. There exists a direct relation between Income and taxes (VAT) and GVA. Resources are normally considered as (Production + Imports - Exports).

On the other side of the equation, Final Demand can be seen as the sum of Final Consumption, Gross Formation of Fix Capital (investments), Stock Variations and Exports.

In summary, the I-O Table it is a good schematic representation of the structure of a given economic system. It is normally presented as shown in the Table 4 below.

In order to meet the demand, firms must produce a certain quantity of goods and services: not only those which will actually be meant for final consumption, but also those which enter into the intermediate consumptions of the production process. The ratios between these intermediate consumptions and the total Input of a given branch are known as *technical coefficients*, which are thus defined as:

$$\mathbf{a}_{ij} = \mathbf{X}_{ij} / \mathbf{I}_j \tag{1}$$

Combining the technical coefficients of the Input-Output table, the following system of equations can be obtained:

$$\begin{array}{c}
\mathbf{a}_{11}\,\mathbf{I}_1 + \mathbf{a}_{12}\,\mathbf{I}_2 + \dots + \mathbf{a}_{1n}\,\mathbf{I}_n + \mathbf{FD}_1 = \mathbf{O}_1 \\
\mathbf{a}_{21}\,\mathbf{I}_1 + \mathbf{a}_{22}\,\mathbf{I}_2 + \dots + \mathbf{a}_{2n}\,\mathbf{I}_n + \mathbf{FD}_2 = \mathbf{O}_2 \\
\cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot \\
\cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot \\
\mathbf{a}_{n1}\,\mathbf{I}_1 + \mathbf{a}_{n2}\,\mathbf{I}_2 + \dots + \mathbf{a}_{nn}\,\mathbf{I}_n + \mathbf{FD}_n = \mathbf{O}_n
\end{array} \tag{2}$$

Since, for the same sector (i=j) the input is equal to the output ($I_i = O_j$), it results

$$\begin{array}{lllll}
(\mathbf{1-a}_{11})\,\mathbf{I}_1 & -\,\mathbf{a}_{12}\,\mathbf{I}_2 & -\dots & -\,\mathbf{a}_{1n}\,\mathbf{I}_n & = \mathbf{FD}_1 \\
-\mathbf{a}_{21}\,\mathbf{I}_1 & +\,(\mathbf{1-a}_{22})\,\mathbf{I}_2 & -\dots & -\,\mathbf{a}_{2n}\,\mathbf{I}_n & = \mathbf{FD}_2 \\
\cdot\ \cdot\ \cdot & \cdot\ \cdot\ \cdot & \cdot\ \cdot & \cdot\ \cdot\ \cdot & \cdot \\
\cdot\ \cdot\ \cdot & \cdot\ \cdot\ \cdot & \cdot\ \cdot & \cdot\ \cdot\ \cdot & \cdot \\
-\mathbf{a}_{n1}\,\mathbf{I}_1 & -\,\mathbf{a}_{n2}\,\mathbf{I}_2 & -\dots & +\,(\mathbf{1-a}_{nn})\,\mathbf{I}_n & = \mathbf{FD}_n
\end{array} \tag{3}$$

which can be expressed with matrices as

$$\begin{Bmatrix} FD_1 \\ \cdot \\ \cdot \\ FD_n \end{Bmatrix} = \begin{Bmatrix} (1-a_{11}) & -a_{12} & \dots & -a_{1n} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ -a_{n1} & -a_{n2} & \dots & (1-a_{nn}) \end{Bmatrix} \cdot \begin{Bmatrix} I_1 \\ \cdot \\ \cdot \\ I_n \end{Bmatrix} \tag{3}$$

This expression can be abbreviated as

$$\{\mathbf{FD}_j\} = \{\mathbf{I} - \mathbf{A}_{ij}\} \cdot \{\mathbf{I}_j\} \tag{5}$$

where $\{FD_j\}$ is the array column of final demand, I is the unit matrix, A_{ij} is the technical coefficient matrix, and I_j is the array column of total outputs (= inputs). The matrix $\{I\text{-}A_{ij}\}$ is usually known as Leontieff's matrix.

Table 4 . Structure of the Input-Output Table

	S_1	S_2	....	S_n	FD_i	O_i
S_1	X_{11}	X_{12}	....	X_{1n}	FD_1	O_1
S_2	X_{21}	X_{22}	....	X_{2n}	FD_2	O_2
...	....	....	X_{ij}	....	....	....
S_n	X_{n1}	X_{n2}	....	X_{nn}	FD_n	O_n
F_j	F_1	F_n	....	F_n		
I_j	I_1	I_2	....	I_n		

Where:

S_i - Economic Sectors.

FD_i- Final demand of each sector : private and public consumption, investment, stock variations and exports.

F_j - Payments to the productive factors of each sector: GVA at factors cost, indirect taxes , subsides to companys, and imports .

O_i- Output or total production of each sector

I_j- input of each sector .

X_{ij}- The production sold by sector i to j (Intermediate Consumption).

The Impact of countermeasures in Production.

Inverting Leontieff's matrix, the variations in Inputs could be expressed as a function of the variations in the final demand. That is, once known the final demand $\{FD_j\}$ the total productions can be obtained as:

$$\{\mathbf{I}_j\} = \{\mathbf{I} - \mathbf{A}_{ij}\}^{-1} \cdot \{\mathbf{FD}_j\} \tag{6}$$

Which means that any modifications of the inputs will be a function of the increments of the final demand:

$$\{\Delta\, \mathbf{I}_j\} = \{\mathbf{I} - \mathbf{A}_{ij}\}^{-1} \cdot \{\Delta \mathbf{FD}_j\} \tag{7}$$

Therefore, the model can be used to evaluate the impact on the total production of an economic system, in case of variations in their final demand, like in the case of countermeasures being implemented in a certain area. This kind of models are "demand models" (known as *demand driven*), which consider that variations in demand will influence the output level and the amount of productive factors employed.

Once estimated this loss of total Input, the corresponding loss of Value Added can be obtained from the ratio (Value Added / Total input) existing for each branch.

After the initial impact it could be possible to consider a feedback, since the loss of input will be linked to a new loss of final consumption (demand) initiating an iterative process through the economic system (see Figure 3), which will reach an asymptotic value for the total loss of production.

There are some examples of this kind of application of the Input-Output methods. Two of them were performed in France: Assouline (Assouline, 1984) studied a scenario in the North of France-Pas de Calais (Gravelines), considering one month evacuation of an industrialised area. Only the losses in the affected area were considered, with resulting initial and induced losses of Value Added amounting:

Initial:	1829 MFF (1980)
Induced:	500 MFF (1980)

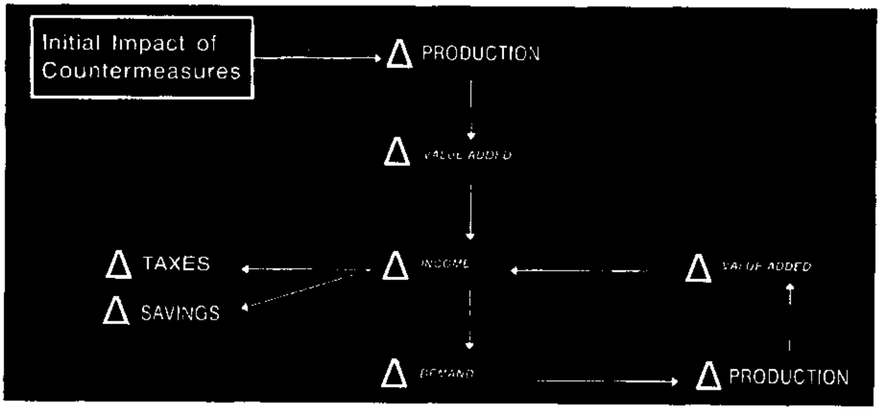


Figure 3 . Effects induced in the economic system by an initial decrease in production.

(adapted from Assouline, 1984)

More recently, Cour*(Cour, 1994)* analysed a scenario in the region of Champagne/ Ardenne (Nogent-sur-Seine). A set of "realistic" countermeasures was defined after an accident analysis with the COSYMA code, with the result of some areas being relocated for up to 1 year (66000 persons) and 10 years (1091 persons). Only the losses in the affected area were considered, with resulting total initial and induced losses of Value Added for the first year :

Initial:	7424 MFF (1989)
Induced:	4900 MFF (1989)

The analysis included more detailed distributions of the effect by economic branches .

The mentioned case studies give some hint to value the importance that the induced effects can have on the global economic impact of an accident (almost 30 % of the initial impact for the first study and 66 % for the second). It is also clearly seen that such induced effects are undoubtedly dependent on the characteristics of the site being studied.

The impact in the surrounding regions.

It is reasonable to think that countermeasures implemented in a given area will affect directly the demand of that area, but also that of the surrounding regions.

Countermeasures like evacuation or relocation, meaning a stop in the economic activity, will imply a loss of the final demand of the affected areas. For the surrounding regions, a loss will come from the loss-of-demand normally going to the relocated area (no exports can be made during the relocation period to the affected area). But also positive effects can be estimated from the consideration that private consumption of the relocated population is transferred to the non-relocated areas, thus originating an increase in their final demand, and an input increase at the end.

Other countermeasures, like crop banning, will only affect the agricultural branch, and also to the economic branches using agricultural products as raw material. Decontamination activities, that may be for instance needing use of additives for soils, or replacement of some surfaces, could have a positive effect in the industrial branches producing these materials needed.

However, to develop a model for such effects, a certain number of difficulties arise, that have been summarised in Table 5, that also shows some of the assumptions made in the model.

During the development of the model some studies of this kind have been performed in Spain. The first type of studies were deterministic, with two scenarios defined from consequence analyses made with COSYMA for the two sites included in the Table 2: one was mainly agricultural (Zorita, scenario A) and the second more industrial and touristic (Vandellós, scenario B) *(Hidalgo et al., 1995)*. This studies were based on detailed statistical information about the affected provinces. The study only considered losses in the affected and non-affected areas, with no attention being paid to induced effects or positive impacts. The results are summarised in Table 6.

The different economic structure of each site is clearly reflected in the results. Also interesting is to note that the impact on the non-affected areas (defined in this study as the non-affected part of the provinces in which countermeasures are implemented) is well below that of the regions affected by the countermeasures.

The MECA2 plus the new model was renamed as MECA3, and it can use the new model as an option, or the previous MECA2 model. The new model is intended to cover fully probabilistic assessments of the economic impact of population movements, both in the affected and in the non-affected zones; in this last case also considering positive effects. A reference guide has been prepared for the users *(Gallego, 1995b)* , and some test cases have been analysed, based on the same scenarios described above. The basic results are presented in Table 7.

Table 5 . Difficulties for a model of the impact of countermeasures based in the Input-Output Table.

DIFFICULTIES	ASSUMPTIONS NEEDED
There are no I-O Tables at regional or local level	- Scaling of Final Demand and Input according to ratio of regional / local GVA to national GVA - Technical Coefficients constant (same technology all across the country)
There are no I-O Tables for the areas affected and non-affected by the countermeasures	- Scaling of Final Demand and Input according to ratio of area GVA / region GVA
The duration of countermeasures is different in different areas	- Construction of as many I-O Tables as time periods for the affected areas in each - The structure of the economy is unaltered after implementation of countermeasures - Economic impacts must be discounted in each time period.

Table 6. Summary of results of two scenarios analysed in Spain (Hidalgo et al., 1995).

	Zorita, Scenario A Losses in Millions Pesetas (1988)		**Vandellós, Scenario B** Losses in Millions Pesetas (1987)	
Affected Area:	Total production (Input) losses: 24,358	Agriculture:11,084	Total production (Input) losses: 16,740	Agriculture:2,995
		Industry : 5,213		Industry : 7,522
Non-Affected Area:	Total production (Input) losses: 6,818	Agriculture: 5,558	Total production (Input) losses: 6,404	Agriculture:1,754
		Industry: 1,036		Industry: 3,783

For the Vandellós scenarios, since an I-O table is available for Catalonia, it was used as a test to compare with the results using the national I-O table of Spain. As can be observed, no significant effects were observed, thus indicating that, probably, for many sites within a given country, the non-avaibility of specified I-O tables is not a serious limitation for the kind of exercise that PCA represents. Probably, the most interesting conclusion is to see that positive effects in the areas non-directly impacted by the countermasures can largely overcome the negative effects in the same regions. This can be only partially true, since, as the deterministic studies performed have shown, for peculiar sites, like the Vandellós is, with a large tourism sector, if that sector would be paralysed it could represent as much as 4.16 10^5 MPTA, even for relatively small releases, since these effects are more of psycho-sociological nature, and are not amenable to be included in a PCA model. Needless to say that such effects, of course, would also not be strongly affected by the criteria followed to implement countermeasures, but more by the public attitude shown by the authorities with respect to the affected populations.

Table 7. Mean economic impact in the areas affected and non-affected by the countermeasures for three scenarios analysed with the system COSYMA-MECA (Gallego, 1995b).

Zorita scenario A

Economic Impact (MPTA, 1989)	Total
Areas directly affected	8.30 10^2
Areas non-affected, Loss of Input	1.48 10^2
Areas non-affected, Increase of Input	4.78 10^2

Vandellós scenario B

Economic Impact (MPTA, 1989)	**Total (Spain I-O Table)**	**Total (Catalonia I-O Table)**
Areas directly affected	2.44 10^2	2.91 10^2
Areas non-affected, Loss of Input	6.66 10^1	7.15 10^1
Areas non-affected, Increase of Input	1.14 10^2	1.27 10^2

Vandellós scenario C

Economic Impact (MPTA, 1989)	Total (Spain I-O Table)	Total (Catalonia I-O Table)
Areas directly affected	$9.81\ 10^4$	$1.19\ 10^5$
Areas non-affected, Loss of Input	$8.86\ 10^3$	$9.02\ 10^3$
Areas non-affected, Increase of Input	$5.15\ 10^4$	$5.73\ 10^4$

CONCLUSIONS.

After the presentation made it is useful to extract some conclusions .

On the differences between economic models.

* Theoretical and numerical intercomparison between existing models for economic consequence assessment have been presented. As a general conclusion, numerical results are closer than expected from the differences in modelling .

* More in-depth investigation lead to the coupling of different economic models (COCO-1 and MECA2) linked to the same PCA code (COSYMA). This reflects more clearly the uncertainties due to modelling that economic consequences can present.

* For the cases studied, no big differences are observed, and no systematic deviations are resulting. However, in general, for the **relocation** of people MECA2 predicts higher values than COCO-1. For **decontamination**, the prediction of costs by MECA2, is slightly lower. For **food bans**, the greater detail of MECA2 in the data base managed makes it very site dependent. And for **health effects** MECA2 normally results in smaller costs, although this strongly depends on the subjective values used.

* The results for food bans costs must be conditioned by the kind of countermeasures assumed, and they normally have a high importance on the total cost of an accident. Therefore, the modelling of alternative countermeasures for food is considered as a priority before trying to improve cost assessment for food countermeasures in PCA codes.

On the Input-Output Models.

* COSYMA with MECA3 is the only PCA code actually incorporating an Input-Output model for the calculation of the economic impact of population relocation.

* Input-Output modelling is only useful for countermeasures directly affecting the economic system, like population movements, agricultural countermeasures, and, maybe not without large uncertainties, decontamination.

* Several difficulties are found to make a rigorous application of I-O models to accident scenarios. The most important can be the unavailability of Regional or local I-O Tables; the time effects associated with long-duration countermeasures and, probably introducing a larger uncertainty, the variations in the economic structure that can be caused by a large accident.

* However, it seems that reasonable estimates of the economic impact can be obtained, at least in the same range of uncertainty than for other steps of Consequence Assessment.

* The cases studied indicate that the objective economic impact of population movements outside the areas directly affected by this countermeasure would be normally of a net positive sign.
However, psycho-social reactions of the markets, difficult to be modelled, could alter this conclusion.

REFERENCES.

Assouline M., *Evaluation des conséquences socio-économiques d'une évacuation de population en cas d'accident grave d'origine industrielle*, CEA-IPSN, Département de la Protection Sanitaire, (1984) .

Cartwright, J.V., Beemiller, R.M., and Gustly, R.D. *Regional input-output modelling system (RIMS-II); estimation, evaluation and application of a disaggregated regional impact model.* Washington, Department of Commerce (1981).

Cour Ph., *Conséquences Macroéconomiques d'un Accident Nucléaire.* CEPN (1984).

Ehrhardt, J., Päsler-Sauer J., Schüle O., Benz G., Rafat M. and Richter, *Development of RODOS, a Comprehensive Decision Support System for Nuclear Emergencies in Europe-an Overview.* Radiation Protection Dosimetry, 50, 2-4, (1993).

Faude D., COSYMA. *Modelling of Economic Consequences.* Report KfK 4336, Kernforschungszentrum Karlsruhe. (1992) .

Gallego E., "MECA2. *Model forEconomic Consequence Assessment, Version 2. Reference Guide.*" Report CTN-43/92. Cátedra de Tecnología Nuclear, UPM (1994).

Gallego E., *Alternative Models for the Evaluation of Economic Consequences in COSYMA.* In Proc: Second COSYMA User's Group Meeting, Budapest, June (1995a) .

Gallego E. , MECA3. *Model for Economic Consequence Assessment, Version 3. Reference Guide.* Report CTN-50/95 (Draft). Cátedra de Tecnología Nuclear, UPM (1995b) .

Hasemann I. and Jones J.A., COSYMA: *User guide.* CEC Report EUR 13045. Brussels (1993) .

Haywood S. M., Robinson C.A. Heady C. COCO-1: *Model for Assessing the Cost of Offsite Consequences of Accidental Release of Radioactivity.* Report NRPB-R243. National Radiological Protection Board (1991) .

Hanson A. L., Davis R.E., Mubayi V. *Calculations in Support of a Potential Definition of a Large Release.* U.S. Nuclear Regulatory Commission Report NUREG/CR-6094, BNL-NUREG-52387, (1994).

Hidalgo A., Gallego E., Muñoz A., Pavón J., *Evaluación del Impacto Económico Externo de los Accidentes Nucleares,* Report CTN-88/94. ETSII-UPM (rev. 1, 1995).

International Atomic Energy Agency, *Intervention Criteria in a nuclear or radiation emergency.* Safety Series No. 109. IAEA (1994) .

International Commission on Radiological Protection, *Principles for Intervention for Protection of the Public in a Radiological Accidents.* ICRP publication 63. Annals of the ICRP 21 (4). Pergamon Press (1993).

Jow, H-N. , Sprung, J.L. , Rollstin, J.A. , Ritchie, L.T. y Chanin, D.I. , *"MELCOR Accident Consequence Code System (MACCS) . Model Description ".* U . S . NRC Report NUREG/CR-4691, (SAND86- 1562) , Vol .2 . Sandia National Laboratories (1990).

Nixon W. et al., *Probabilistic Accident Consequence Assessment Codes - Second International Comparison - Technical Report.* Nuclear Energy Agency-OECD/EC Report EUR 15109 EN. CEC (1994).

Nuclear Energy Agency, *«Probabilistic Accident Consequence Assessment Codes. Second International Comparison. Overview Report».* OECD (1994).

SRD , NE and NRPB, CONDOR 1 : *A Probabilistic Consequence Assessment Code Applicable to Releases of Radionuclides to the Atmosphere.* Report SRD R598, TD/ETB/REP/7021, NRPB-R258 (1993).

Tveten, U. (Editor), *Environmental Consequences of Releases from Nuclear Accidents. A Nordic Perspective.* Nordic Liaison Committee for Atomic Energy (1990).

United States Nuclear Regulatory Commission, *Reactor Safety Study. Appendix VI.* U. S. NRC Report WASH-1400 (NUREG-75/014). U.S. NRC. (1975).

United States Nuclear Regulatory Commission, *Reactor Risk Reference Document.* (Draft for Comment). U.S. NRC Report NUREG-1150. U.S. NRC (1987).

Résumé

Certaines contremesures prises en cas d'accident nucléaire peuvent avoir un impact économique singificatif. On passe en revue et on compare les modèles utilisés pour estimer les conséquences économiques. L'étude des effets, aussi bien dans la zone directement affectée que dans les zones avec lesquelles celle-ci a des échanges économiques au moyen de la méthode des entréees et sorties (I-O)peut être considérée comme très appropriée, puisqu'elle englobe les transactions de tous les secteurs de l'économie et qu'elle permet d'évaluer les conséquences, directes ou induites, qu'une modification de la demande finale ou des entrées primaires, peut avoir sur le système économique des régions, qu'elles soient affectées ou non.
On présente les principes essentiels des méthodes (I-O) et quelques exemples basés sur la recherche récente pour en tirer des conclusions quant à leur applicabilité pour l'analyse déterministique(cas singulier) ou probabilistique(évaluation du risque).
Une conclusion intéressante est que dans les régions non directement affectéees par les contremesures les effets positifs peuvent dépasser les effets négatifs.

Samenvatting

Bepaalde tegenmaatregelen genomen na een nukleair ongeval kunnen een economisch impact hebben. De modellen die gebruikt worden om deze economische gevolgen te berekenen in het getroffen gebied en in de gebieden waarmee economische wisselwerkingen bestaan, worden kort voorgesteld en vergeleken. De Input-Output Methodologie wordt beschouwd als zijnde bijzonder aangepast omdat zij baseert op de uitwisselingen tussen alle sektoren van de economie en omdat zij hulp biedt bij het schatten van de gevolgen op de economie van de getroffen en niet getroffen gebieden die voortvloeien uit schommelingen van de uiteindelijke navraag en uit de beperkingen van de primaire toevoer
Basisprinciepen van de I-O methoden worden gepresenteerd met voorbeelden uit recente opzoekingen om er conclusies uit af te leiden met betrekking tot de toepasbaarheid van de deterministische (alleenstaand geval) dan wel de stochastische(risico) analyse. Een interessante conclusie is dat in de niet door tegenmaatregelen getroffen gebieden de positieve de negatieve gevolgen overtreffen.