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Integrated safety planning for underground systems

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Abstract

Underground systems are becoming increasingly popular for business activities, transportation systems, and storage purposes. Safety planning for underground systems calls for an integrated approach which considers the interests of many parties, the dynamics of different activities, and the potential threats posed by hazardous materials. A visual interactive modeling approach is presented which helps organizations to derive a safety concept for underground systems. The modeling approach emphasizes procedural aspects of dealing with multiple parties, as well as conceptual and analytic aspects of assessing risks and defining safety goals. The paper summarizes the framework for developing a safety concept for underground systems which was developed for the Dutch Ministry of the Interior. A hypothetical example is discussed to illustrate the theoretical constructs. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Safety; Underground system; Hazardous

1. Introduction

Underground infrastructures are becoming increasingly attractive alternatives to aboveground systems. This is partly due to the growing density of urban and regional land use, but also because of technological considerations, such as the possibility to use the underground space more efficiently.

Underground infrastructures can be divided according to their function into: (1) *public*, e.g. shopping centers, metro stations, and parking garages; (2) *transport*, e.g. metro systems and underpasses; and (3) *non-public*; e.g. storage places and work places. These systems are, with respect to their function, not necessarily different from their aboveground counterparts. For example, parking garages or shopping centers function the same way, regardless whether they are stationed aboveground or underground.

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The underground systems, however, are surrounded by rock, soil, or water, and there are several characteristics that distinguish them from aboveground systems, especially with respect to risk and safety. The users of underground systems know when they enter and leave the system. This means that the users expose themselves knowingly to a special class of hazards.

The hazards of underground systems can be divided into physical hazards, e.g. train derailments, fire, and pollution; social hazards, e.g. fear of violence and theft, terrorism, stress, and aggressions; and economic hazards, e.g. fear to loose business opportunities. Safety aspects for underground systems are both positive, in the sense that the systems are closed and controllable with few access ways, and negative, in the sense that they have few escape ways and they are surrounded by rock, soil, and water. These characteristics justify the consideration of a comprehensive safety approach for underground systems in several regards:

- Economic, financial, and social risk aspects play an important role, in addition to risks to life and property.
- The question ''How safe is safe enough'' must, therefore, be reformulated to ''How attractive is attractive enough.''
- Safety analysis and decision-making must emphasize both a participative process and a technical analysis; users and third parties must also be involved in the decision-making process.
- An organization deriving a safety concept for underground systems must seek to coordinate the safety concept with those of other organizations; including firefighters, government, and police.

Underground systems go through several phases in their life-cycle: planning phase, construction phase, user phase, and disassembly phase. Different parties are concerned with safety during these phases, including workers, owners, users, insurers, society, government, organizations, businesses, etc. Any proposed framework for a safety concept should be applicable to all these phases and for any party concerned with safety.

The Dutch ministry of the interior commissioned a project on safety of underground systems in 1997. Its scope was to derive first a broad vision on safety for underground systems. This vision should then result in an integrated approach to safety management for technical and social hazards in underground systems. The study group was divided into several sub-projects, including risk appraisal, social risks, scenarios, and methodology of risk assessment. This paper summarizes the results of the sub-project Methodology of Risk Assessment [2].

2. Visual interactive safety modeling

Deriving a safety concept entails two important aspects:

1. The *process* of deriving the safety concept, considering participative and computational methods.
2. The *analytic methods* to formalize the elements of the safety concept, considering normative and descriptive theories.

The process of defining a safety concept can refer to different levels. General procedures of how to derive the safety concept, how to assess it, and how to implement it, are defined at a very high level. More specific definitions of processes refer to how to go about assessing risks and how to define safety goals. An important aspect for the process of defining a safety concept is the involvement of experts, policy makers, industry, and the public which is affected by the safety concept. Processes must be defined for participative and also for computational issues.

Analytic methods refer to the identification of the relevant issues and their relations, the formalization of these issues and relations in terms of safety goals and safety measures, and the search for the best suited safety measures to comply with the safety goals.

Large quantities of conceptual techniques and computerized tools have been developed over the last two decades to support risk analysis and the definition of safety concepts, many of them are summarized in guidelines, such as the Guidelines for Hazard Evaluation Procedures, developed by the Center for Chemical Process Safety [7]. Although these techniques and tools have proved to be very valuable in industrial settings, they do not provide a comprehensive framework for deriving safety concepts for situations where public concerns, marketing aspects, and sustainability are of major consideration. It is, therefore, obvious to look at other sets of tools that can be useful for deriving safety concepts. Such sets of tools have emerged from the fields of decision analysis, systems analysis, and data analysis [5].

The modeling approach discussed in this paper integrates the processes and the analytic modeling steps into one framework. It consists of a three-step decomposition of analytic modeling into: (1) structural modeling, (2) formal modeling, and (3) resolution modeling. Structural modeling refers to the identification of the relevant elements and their relations, formal modeling refers mainly to the definition of safety goals, and resolution modeling refers to the processes of operationalizing the formalized safety concept.

The mental model which a decision-maker makes of the system under investigation is translated into an analytic model, from which a safety concept is derived. The safety concept must then be related to the system and a validation, with possible calibration, of the analytic model must be done. Fig. 1 shows the proposed modeling cycle to derive a safety concept.

The modeling cycle in Fig. 1 comprises analytic and computational aspects and processes to perform computations and to elicit subjective risk attitudes, and it can be applied at any level of management and decision-making.

2.1. Structural modeling

The structural model is a ''picture'' of the safety concept which shows the elements and their relations in an intuitive way. The elements are divided into the following classes: decision-makers, uncertain events, damage types, safety goals, decision options, and choice goals. These classes have been derived form the many theories and methods in safety management, risk analysis, and decision analysis. The concept of structural

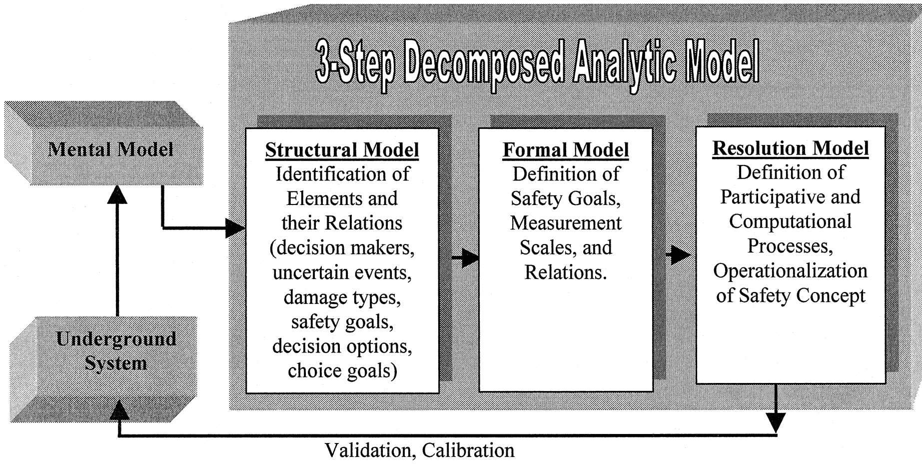


Fig. 1. Modeling cycle for deriving a safety concept.

modeling is an extension of the more traditional approach of influence diagrams; in fact, an influence diagram is a special case of the more general concept of structural modeling as introduced in this section [1].

The main benefit of defining a visual structural model is to stimulate discussion among all the parties involved in the management of the system. Table 1 summarizes the six elements used to derive a structural model and gives some examples.

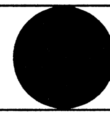
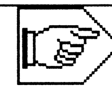
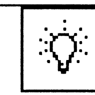
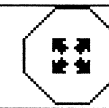
An arrow between two elements in the structural model indicates that the predecessor element is necessary to define the successor element. This evaluation is done as part of the formal model. The resolution model derives or computes solutions, based on the formal model, in terms of what should be done and in which sequence.

A structural model can be defined for the purpose of solving a decision problem, for example, to find the optimal safety measure. It can also be used to solve a systems analysis problems, such as would be done with fault-trees or event-trees. Fig. 2 shows, on the left, a structural model for a decision problem, and, on the right, a structural model for a systems analysis problem.

The decision model on the left in Fig. 2 says that one out of four decision options must be chosen, where the four decision options are: (1) to install a sprinkler system, (2) to install a video monitoring system, (3) to install both, or (4) to install neither of the two. The two damage types are individual risks and group risks. All four decision options must be evaluated, as part of the formal model, in terms of individual and group risks. The evaluation must also consider the amount of people which might be present in the underground system. The presence of people is assumed to be an uncertain event. The safety goals are to keep the individual risks below 10^{-6} per year and to have the group risk curve in the F/N diagram be in the acceptable range.

The systems analysis model on the right in Fig. 2 contains only uncertain events. The factors influencing the presence of people in the underground system are analyzed. The presence of people depends on the time of day and on the weather; weather is influenced

Table 1
The elements of safety modeling

Elements:	Decision Makers	Uncertain Events	Damage Types	Safety Goals	Decision Options	Choice Goals
Symbols:						
Examples:	- users - interest groups - organizations - society - insurers - public - ambulance - police	- fire - recession - terrorism - vandalism - incident - accident - flooding - inappropriate use	- death of user - death of response personnel - injuries - economic loss	- minimize expected number of death - optimize risk-cost-reduction tradeoff - keep individual risks below 10^{-6}	- above versus underground - use of fire walls - automatic brake systems - inspections - police presence - escorts	- minimize number of metro stations - implement at least two stations - combine safety measures

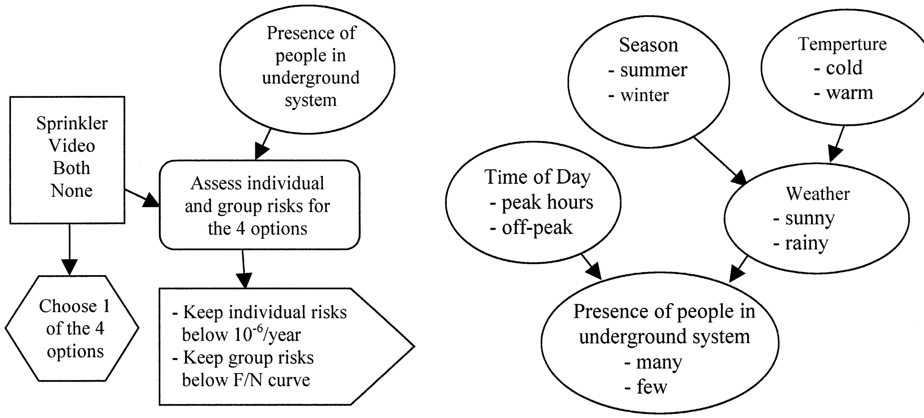


Fig. 2. Structural model for decision analysis (left) and systems analysis (right).

by season and temperature. Two possible states have been identified for each uncertain element. This allows one to formalize the structural model in terms like ''There are many people in the underground system if it is off-peak OR sunny, and it is sunny if it is summer AND warm OR winter AND cold''. This type of statements are known from fault-trees, indicating that the proposed modeling approach is more comprehensive than the traditional approaches used in risk analysis.

It should be noted that the system analysis model (on the right in Fig. 2) could be added to the decision analysis model (on the left in Fig. 2), by replacing the uncertain presence of people in the left model with the model on the right-hand-side. The two examples in Fig. 2 indicate the breath and depth of this proposed modeling approach. Decision-makers could be added to the models, with arrows showing who of them defines which of the elements. For example, it could be illustrated that the government defines safety goals for individual and group risks, by introducing an element for the government with an arrow to the safety goal element. A new element could be introduced, for example, for the management of the underground system, with an arrow to a new safety goal addressing technological risks.

2.2. Formal modeling

The safety concept is identified as soon as the structural model is accepted by all parties involved. The next step in analytic modeling is to use a formal notation to describe how to evaluate the elements of the structural model and how to express the relationships in terms of analytic functions. When the problem is formally described in terms of a formal model, we say that the problem is defined.

The formal model which belongs to the structural model shown in Fig. 2 on the right, for example, must define what the chances of having many or few people in the underground system is. This could be done by expressing the chances for the different uncertain events in terms of probabilities. Temperature, season, and time of day are defined as marginal probabilities, e.g. $p(\text{summer}) = 0.2$ and $p(\text{winter}) = 0.8$, while weather and presence of people in underground system are defined as conditional probabilities, e.g. $p(\text{sunny}|\text{summer,cold}) = 0.1$, $p(\text{rainy}|\text{summer,cold}) = 0.9$, $p(\text{sunny}|\text{summer,warm}) = 0.9$, and $p(\text{rainy}|\text{summer,warm}) = 0.1$.

The definition of how to compute the marginal probabilities for having many or few people in the train station is also part of the formal model; e.g. $p(\text{many}) = (\text{many}|\text{sunny,peak}) \times p(\text{sunny}) \times p(\text{peak}) + p(\text{many}|\text{sunny,off-peak}) \times p(\text{sunny}) \times p(\text{off-peak}) + p(\text{many}|\text{rainy,peak}) \times p(\text{rainy}) \times p(\text{peak}) + p(\text{many}|\text{rainy,off-peak}) \times p(\text{rainy}) \times p(\text{off-peak})$.

To complete the formal model, i.e. the definition of the safety concept, all other elements must be defined. The definition of how to perform the assessments, as was done for the uncertain events in terms of probabilities, is based on measurement scales. The most commonly used measurement scales in safety management are:

- *Ordinal*: for example, ''many,'' ''average,'' ''few'' people in a train; ''hot,'' ''medium,'' ''cold'' temperature; etc.
- *Cardinal*: for example, 10°C on an interval scale; 120 kg of explosive materials on a ratio scale; 10^{-6} annual probability of death an absolute scale, etc.
- *Fuzzy*: for example, full train with membership value 0.3.

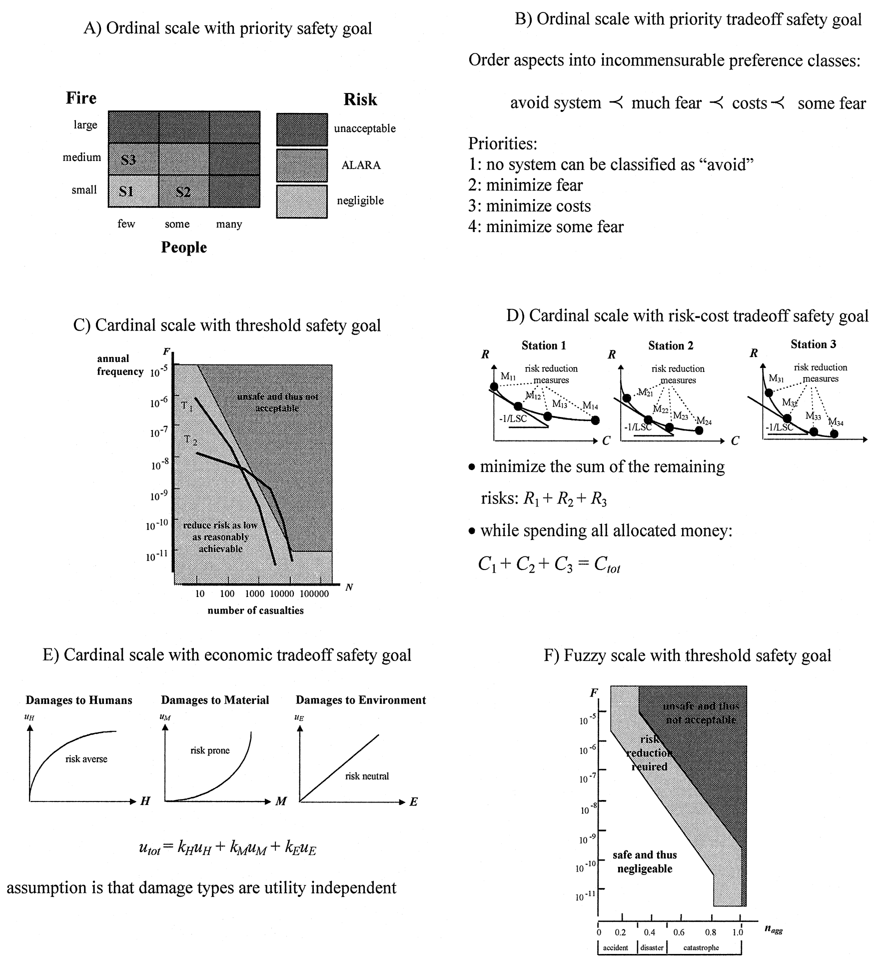
A ''fuzzy'' measure consists of a verbal statement (e.g. ''full train'') and a membership value (e.g. 0.3), expressing the belief in the statement. The membership values vary from 0 (no belief) to 1 (very strong belief). Cardinal scales are ratio, interval, or absolute. The most important characteristics of cardinal scales are their admissible transformations, where values retain their meaning after the transformations. The admissible transformation for the interval scale is the positive affine (linear) transformation, such as the transformation of degrees Celsius (C) into degrees Fahrenheit (F) through: $F = (9/5)C + 32$. The proportions of differences in degrees are the same in Celsius and in Fahrenheit. The admissible transformation for the ratio scale is the similarity transformation, where the proportions of values remain the same. For example, twice the mass in kilogram is also twice the mass in pounds. The admissible transformation for the absolute scale is the identity transformation; for example, probability values cannot be changed without losing their meaning.

The safety goals are also part of the formal model of a safety concept. The most common ways to define safety goals for underground systems are:

- *Threshold*: for example, annual probability of death cannot exceed 10^{-6}; number of consecutive working hours in underground shopping system cannot exceed 10 h.
- *Trade-off*: for example, risks are reduced as low as economically reasonable; risk exposure must be rewarded through higher salary.
- *Priority*: for example, first avoid all ''high-risk'' options, among the remaining options, find the socially best accepted ones, among those choose the cheapest one.

The combination of scales and approaches to define safety goals leads to the most commonly used types of safety goals for underground systems, as summarized in Table 2. An ordinal scale with priority safety goals is used for the US Technical Guidance for Hazards Analysis [11]. A cardinal scale with threshold safety goals is used in the Dutch national safety concept for technological risks [12]. A cardinal scale with economic

Table 2
Overview of most commonly used concepts to define safety goals



trade-offs was used for the portfolio analysis of underground storage places for nuclear wastes in the US [9]. A fuzzy scale with threshold safety goals is used in the Swiss National safety concept [6].

A problem with ordinal scales is that an arithmetic to add up risks must be introduced. For example, the total risk of two metro stations S_1 and S_2 (Table 2A) must be defined. One approach is to define the sum ($\oplus$) of two risks as the larger of the two: $R_1 \oplus R_2 = \max(R_1, R_2)$. The total risk of S_1 and S_2 for the example shown in Table 2A would then be the risk of S_2. There are three safe combinations of two systems with this definition of adding up risks: S_1 and S_2, S_1 and S_3, and S_2 and S_3. This definition of the ''sum'' operator makes sense if the metro stations are far apart, such that different parts of the population are affected by each system. This means that no new system would be considered unsafe, based only on the fact that there are already some other systems with acceptable risks.

An additive risk operator would be: $R_1 \oplus R_2 = (P_1, F_1) \oplus (P_2, F_2) = R[(P_1 \oplus P_2), (F_1 \oplus F_2)]$; that is, the ''sum'' of the two risks is the risk caused by the sum of people and sum of fire. To compute this risk, definitions for the ''sum'' of few and many people, small and large fire, etc. must be introduced. Such an additive approach is appropriate if the two systems are close together, affecting the same group of people.

The ordinal scale with priority trade-off safety goal asks first for an ordering of damage classes (Table 2B). All systems, or parts of a system, are assessed in terms of the chosen damage types. The decision regarding which of two systems is safer is done by comparing the systems according to the defined priority order. For example, two metro lines are compared, the first where people have much fear of use and costing US$10 million to build, and the second where people have no fear of use but costing US$15 million to build. The decision would be, based on the priority defined in Table 2B, to build the second, because it scores better on fear of use, regardless of the higher costs. We would have decided to build the first and cheaper line, only if the fear of use it poses was at most as much as that of the second line.

Ordinal priority trade-offs can also be used to compute damage preferences of multiple systems. Let us assume, for example, that we compare two subway rides. The first one consists of one change over and the second of no changes. The first leg of the first ride is assumed to cost US$7 and to pose some fear. This can be written, using the preference order defined in Table 2B as (0,0,US$7,1). The second leg is assumed to be assessed as (0,1,US$6,1), meaning that there is a part posing some fear, e.g. waiting at the station, and another posing much fear, e.g. riding in the train, and that the ride costs US$6. The second ride is assessed as (0,1,US$12,1). We now have to ''add up'' the damage classes of the two legs for the first ride, to be able to compare it to the second ride. An intuitive method is to add up the two vectors component-wise: (0,0,US$7,1) $\oplus$ (0,1,US$6,1) = (0,1,US$13,2), which shows that the second ride is preferred to the first one. Such an ordinal algebra is often used for operational risk management [3], which is an equally important consideration for a safety concept as strategic safety planning.

The F/N diagram approach to define safety goals has become increasingly popular, although the Netherlands remains the only nation to use it as a binding legal decree for the licensing of hazardous facilities and infrastructures (Table 2C). The example in Table 2C shows that technology T_1 is considered to be safe, while T_2 is unsafe. This is so because the F/N curve of T_1 lies completely below the threshold line, while the F/N curve of T_2 crosses the safety goal line and extends into the unacceptable region.

This example, however, shows two major flaws of the F/N approach. First of all, the safety goal line has a negative slope of factor two in the $\log(F) - \log(N)$ diagram, which is meant to account for risk aversion. If a smaller risk aversion is assumed, the slope will be steeper, which could lead to the conclusion that both T_1 and T_2 are safe. The other flaw is that if we use the expected damage, which is the area under the curve, as the criterion to judge safety, then T_2 would be safer than T_1, which contradicts the F/N assessment. These two flaws are theoretical in nature, but there are many more problems with this approach which are based on practical, legal, and societal considerations [4].

A cardinal scale with a risk–cost trade-off safety goal is used to define safety goals for an anonymous collection of people (Table 2D), referred to as collective risks. For example, assume that the individual risks and the group risks safety goals are met for an underground storage area of hazardous materials. There are still the risks for the many anonymous people walking unknowingly by the storage place. The operator of the storage place is interested in reducing these collective risks for fear of image loss and reparation costs if an accident occurs. The amount to which these collective risks are reduced depends on how much has to be invested; that is, it is a purely economic consideration, since individual and group risks are already taken care of.

The example given in Table 2D assumes that there are three underground systems, each posing a certain risk, and a total amount of money to invest in the three systems to improve safety. The solution can be shown to be to invest the same trade-off amount in each of the three systems, rather than one-third of the total money. The trade-off amount is defined by the life-saving-costs (LSC), which are the costs that an organization, or society, is willing to invest to reduce the probability of one anonymous fatality. The order of magnitude for LSC is US$10 million for people who are not aware of the hazards, while LSC is around US$1 million for personnel involved in the operations.

The cardinal scale with an economic trade-off safety goal is based on multi-attribute utility theory (Table 2E). The concept has been applied for portfolio analysis of underground storage places for nuclear wastes in the US [9]. A total of 16 damage types are considered to determine the most promising three out of five possible sites. The damage types include death and injuries of workers, environmental and cultural degradation, and costs.

A multidimensional utility function can only be additive if the different damage types are utility independent. This means that the risk attitude for any damage type must be independent of the levels of the other damage types. Often, however, it is not possible to state unambiguously if, for example, human or environmental damages are of more concern. Some damages to humans are more important than some damages to the environment, and vice versa. In such cases, more complicated formal models have to be employed.

The component utility functions, which are defined for each damage type, reflect the decision-maker's attitude. A concave function reflects risk aversion, a convex function risk proneness, while a linear function equates with risk neutrality. Risk aversion means that one is not willing to gamble for a safer system, at the costs of possibly higher damage. This means that one large accident is perceived to be worse than multiple small accidents which result in the same overall damage. These thoughts are applied in the definition of the Dutch F/N safety goals; however, no in-depth analysis of the risk aversion factor has been done [4]. The reasoning for introducing a risk aversion of factor two in the F/N diagram was that if the number of expected fatalities increases by factor 10, then the probability of such an event should decrease by factor 100, while for a risk neutral decision the probability should decrease by only a factor 10.

The Swiss National safety regulation extended the Dutch safety approach by considering nine damage types instead of only fatalities (Table 2F); these are: number of deaths, people injured, people evacuated, alarm factor, loss of large animals, area of damaged ecosystem, area of contaminated soil, area of contaminated ground water, and material losses [6]. The expected damages are transformed into membership values, ranging from 0 (no concern) to 1 (catastrophe). For example, 20 deaths are considered to be a disaster, comparable to 200 injured people; the membership function or indicator is for both damages about $n_1 = n_2 = 0.4$. The aggregated damage coefficient, n_{agg}, is computed as:

$$n_{agg} = \min\left[1, \left(\sum_{i=1}^{9} (n_i)^w\right)^{1/w}\right], \text{ where } w \in [1,\infty].$$

This aggregation function takes on two interesting forms: for $w = 1$, we get: $n_{agg} = n_1 + \ldots + n_9$; and for $w = \infty$, we get: $n_{agg} = \max(n_1, \ldots, n_9)$. The parameter w is chosen by the decision-maker. A conservative decision-maker chooses a small w, while a progressive decision-maker chooses a large w.

Formal modeling involves specifying all the elements and the relations that were identified in the structural model. When the safety concept is formalized, we say it is defined. The next step is to operationalize it, which is done in terms of a resolution model.

2.3. Resolution modeling

Resolution modeling refers to collecting data, estimating and assessing risks and other damage types, eliciting preferences and risk aversion, performing computations, and involving all actors, experts, and decision-makers in structural and formal modeling. Resolution modeling involves, therefore, setting up and performing computational processes and procedural processes. The decision as to who to involve, and why, must be part of the safety concept; that is, it must be a conscious decision and not an opportunistic one to save time or to avoid delays in the definition of the safety concept.

Choosing the right computational processes amounts mostly to choosing the right software packages. More comprehensive software systems must be considered for this task than the many traditional risk analysis packages available for fault-trees, event-trees, dispersion plumes, debris trajectories, pressure expansion, etc. Examples are geographic information systems, multimedia systems, data analysis systems, and spreadsheet programs with extensions for risk analysis. The decision regarding which systems to use can best be done together with a technical information system expert. The formal models are then coded into the chosen software systems to compute impacts and solutions and to conduct sensitivity analysis.

The involvement of experts, management, public, and interest groups must also be prepared very carefully. The methods to support the participation of actors can be grouped according to the types of groups into: (1) teams of experts, (2) groups of general experts, and (3) public participation.

Methods of hazard identification are well-described in the Guidelines for Hazard Evaluation Procedures published by the Center for Chemical Process Safety [7]. These methods refer to teams of experts and include Safety Review, Checklist Analysis, What-If-Analysis, Hazard and Operability Analysis, and Cause–Consequence Analysis. The methods involving groups of general experts include Brainstorming, Nominal Group Technique, and Delphi Technique [2].

A well-known model for deciding what the role of public participation should be is the Vroom–Yetton model [8]. Factors influencing the role of public participation are: (1) the quality requirements, (2) the amount of information, (3) the structure of the problem, (4) the expected public acceptance, (5) the decision competence of the ministry, (6) the goals, and (7) the expected conflict. Possible ways of public involvement are: (1) autonomous agency decision without public participation, (2) semi-autonomous agency decision where public opinion is taken into account, (3) segmented public consultation where the agency's decision reflects the influence of representatives of the public, (4) unitary public consultation where the agency's decision reflects the influence of the whole public, and (5) public decision such as through a referendum.

An overview of important issues in citizen participation is given in Ref. [10]. The issues refer to fairness, discourse techniques, problems of legitimization, citizen juries, regulatory negotiation, environmental mediation, voluntary siting of systems and compensation, and direct participation. The models discussed and compared to one another in Ref. [10] are: Citizen Advisory Committees, Compensation, Mediation, Citizens Juries, Planning Cells, Initiatives, and Study Groups.

3. Operationalization of safety concept

3.1. The elements of operationalizing a safety concept

The general process of deriving a safety concept for underground systems is summarized in Fig. 3. It starts with the identification of the management level. Management refers to strategic planning and operational actions, as well as to resource management. If both strategic and operational management must be assessed, it might be necessary to pay special attention to the link between the two. For example, if a safety concept for strategic management is defined in terms of probabilistic safety goals, then it is of little use in an operational setting. A ''translation'' of the probabilistic safety concept to an operationally meaningful interpretation must be done.

When the management level is identified, it is important to define the environment. Safety concepts are usually not derived in isolation; rather, they must often be coordinated with other safety concepts. This can refer to higher levels, such as national or international considerations, or to coordination at the same level. For example, the police, ambulances, and fire brigades must coordinate their operational safety concepts. Coordination might also be necessary with lower level safety concepts. For example, if a government agency plans to define general safety guidelines for underground metro systems, then it must consider the already existing safety concepts of the metro line operators.

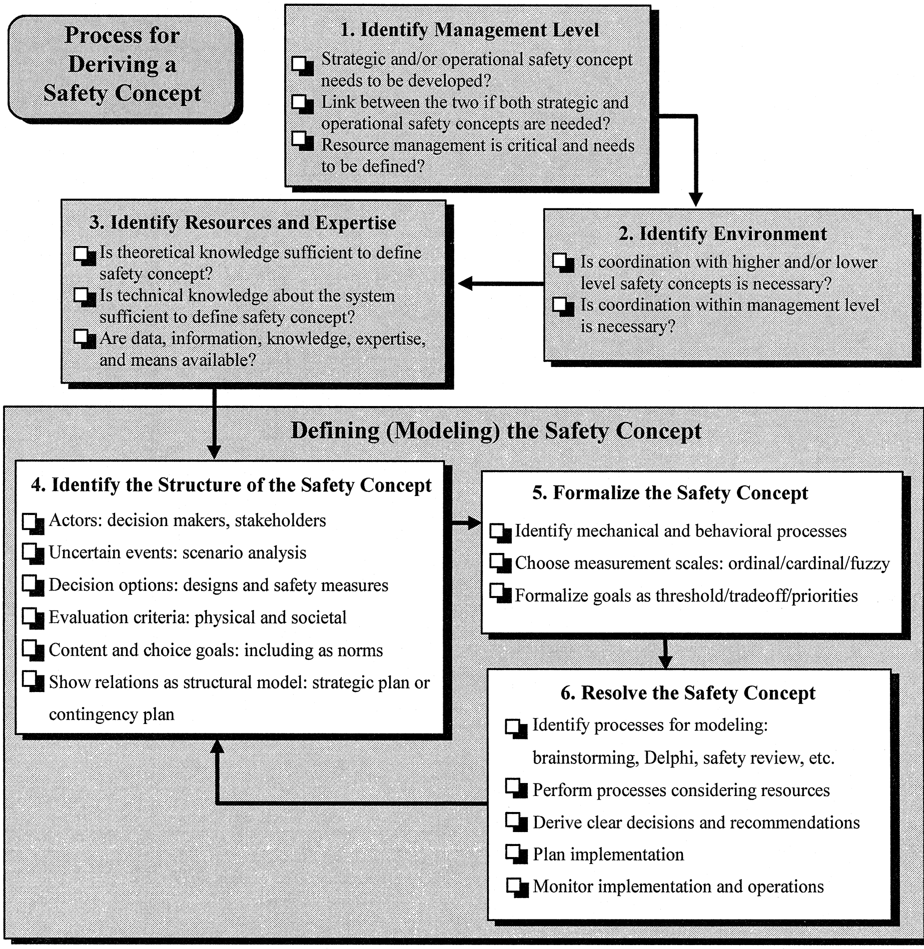


Fig. 3. Process for deriving a safety concept.

The third preparation step before starting modeling is to identify the available resources and expertise. It is most important that the theoretical knowledge available is sufficient to grasp the strengths and weaknesses, the do's and don'ts, and the plusses and minuses of the different analytical concepts. Technological knowledge about the system is of equal importance. If theoretical or technological knowledge are insufficient, then external advise should be sought. Another important consideration is the availability of data, information, knowledge, expertise, and the means of collecting and processing data, including time, work force, finances, etc.

When the three sets of preparation work are completed, the modeling process can start. It should be remembered that the modeling process takes place at different levels. The top level identifies generic issues and actors, while computations and participative processes are conducted at a lower level. The following hypothetical example illustrates the use of the proposed framework and the operationalization of a safety concept.

3.2. An illustrative example

A hypothetical example is discussed to illustrate the use of the proposed framework for deriving a safety concept, as summarized in Fig. 3. A department of defense (DoD) stores ammunition and explosives in many underground storage places which are dispersed all over the nation. The ministry would like to derive a comprehensive safety concept, especially for those installations which are in close proximity of populated areas.

3.2.1. Identification of management level, environment, resources, and expertise

Safety issues regarding the storage of hazardous materials in DoD installations refer mostly to strategic planning issues, and less to operational aspects. The hazardous materials stored are mostly flammables and explosives with up to a few tons of TNT equivalent explosive power. Major hazards are debris and air pressure in case of an explosion which could lead to fatalities through direct hits or indirectly through collapsing buildings or infrastructures.

The activities of and the hazardous materials stored by DoD are mostly classified, and the safety level cannot be publicized as it is done for other systems. It is, however, in the interest of DoD to coordinate its safety concept with the DoDs of other nations and international organizations, such as NATO. Most military regulations use safety distances as the sole criteria for safety, assuming that the storage sites can be built at isolated places, far away from urban areas. In our hypothetical example, however, this is not possible, with the consequence that trade-offs between risks and other aspects must be taken into consideration. The proximity of the installations to urban areas also requires coordination with regional planning organizations. The DoD installations must comply with all national safety goals for technological installations. Coordination with fire brigades and ambulances, and the need to devise evacuation plans in case of accidents must also be considered.

DoD has some sophisticated models to compute the impact of debris on humans and buildings, as well as for air pressure hitting humans and causing buildings to collapse. These models, which allow one to compute safety distances, must be embedded in a comprehensive safety concept. The models can be used to compute individual and collective risks to the population and risks to the environment surrounding the installations. The chances of individual deaths in the event of an accident can be plotted as a function of the distance to the hazard source on a geographic background. A probability density function can now be superimposed on this map. The aggregation of the hazard map with the population distribution map provides a measure of risk.

It is assumed that DoD already possesses topological maps of the areas surrounding its storage places. The detailed patterns of human exposure, however, must be acquired on-site by inspection and interviews with local people. These data and information can be fed to the computer and individual, group, and collective risk levels can be computed. It is recommended that DoD builds up a risk information system where data on all installations, the topological maps, the human activities, as well as the risks, are stored. This allows one to compare the risks of different installations, to decide on risk reduction measures, and to build up an inventory of the total risk situation for all installations.

3.2.2. Structural, formal, and resolution modeling

The structural model depicts the relevant elements and their relations. The main decision-maker is DoD since the underground installations clearly have a non-public function. Due to the proximity of most installations to inhabited areas, however, public aspects must be considered. These refer especially to coordination with spatial planning, transportation planning, and land use planning. These types of public planning do not take into consideration that their plans might be in conflict with DoD's safety goals. It is therefore DoD's main interest to consider the public planning plans and to seek to cooperate and coordinate with the appropriate agencies.

Fig. 4 shows a screen view of the structural model for DoD. The two important actors are DoD and public planning. The damage types that matter most for DoD are individual risks, group risks, collective risks, and financial implications. The actions that DoD can take for each of its installations are to reduce the risk, to close the site, to build new sites, or to buy the site from public planning. Buying the site implies investing in safety improvement with the assurance of public planning that the site will not be affected by any future public plans.

The choice goals for DoD are to provide enough storage for all ammunition and explosives and to disperse it homogeneously over the whole nation. There are two sets of safety goals. One set is imposed by public planning and it refers to complying with the minimum requirements for individual and group risks. The other set is defined by DoD and refers to a trade-off between collective risks and costs. This means that DoD is willing to invest in risk reduction measures to avoid image losses in case of an accident, but only if the safety measures justify the investments.

The important criteria for public planning are land value and investments required to improve it. The actions that public planning can decide on are to invest in the surroundings of the different sites, to keep them as they are, or to sell them to DoD. The choice goal of public planning is to provide needed space, especially in form of enough housing. The content goal for public planning is to optimize growth of the community.

The formal model of this safety concept can take on different forms. We are obviously dealing with a negotiation situation between DoD and public planning. Public planning is in a stronger position at the level of the individual site, but it is obvious that public planning has to comply with DoD's goals on a national level. DoD and public planning will have to coordinate their activities at the local level. The formalization of the safety goals for group risks is done using the approaches given in C and F of Table 2, and approach D the for collective risks. The LSC for approach D might be set to US$10 million. An approach similar to D is used by public planning to decide on the investments for improving the land surrounding the storage sites.

The resolution models indicate how to derive a safety concept that fulfills all requirements stated in the structural and formal models. The individual and group risks require that certain safety levels be not exceeded. DoD and public planning can decide,

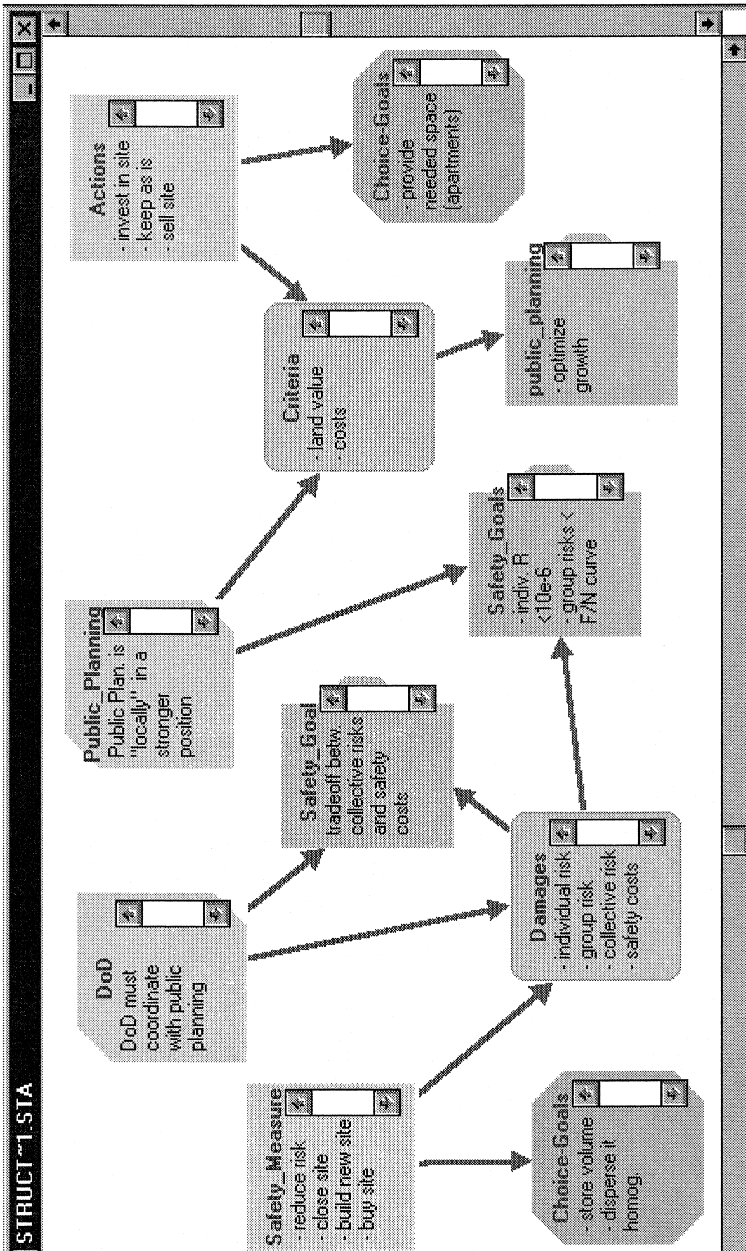


Fig. 4. Structural model of DoD safety concept.

independently, to invest or to sell some of the sites. Given that they cooperate, they would find a compromise for each site in the sense that either one sells and the other buys, or that they agree on a balanced extension plan where both can benefit. For the collective risks, it is up to DoD to decide how far to go.

There are different computational methods from game theory and conflict resolution that could help in finding a computational solution to this problem. It would be more effective, however, to stimulate face-to-face meetings between DoD and public planning. These meetings can be supported with the different participative methods mentioned in this paper, such as brainstorming, policy gaming, or nominal group technique.

4. Conclusions

Underground systems are becoming increasingly interesting alternatives to their aboveground counterparts. Of special consideration in underground systems are the safety issues which are addressed as a part of the safety concept. A coordination of safety concepts among the many organizations involved in the operations and emergency response activities is indispensable. A visual interactive modeling approach was presented in this paper that allows organizations to derive a safety concept. The analytic modeling process is decomposed into three steps: structural, formal, and resolution modeling. Both procedural and computational aspects are emphasized as part of the modeling approach, which allows the integration of technical and social safety aspects.

A software system has been developed for structural modeling, a screen view of which is given in Fig. 4. It is embedded in a multimedia authoring environment which allows one to add video, audio, and animation as part of the safety concept. The system also supports several computational concepts that are discussed in this paper. This computer system is designed to be used in a participative manner, where multiple decision-makers can interact, state their preferences, and resolve their conflicting interests.

The next step in this research is to derive procedural aids for the practical operationalization of the proposed framework. This will be done through case studies with selected organizations of underground systems. The results will be compiled in the form of guidelines and implemented in the multimedia system.

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