Calculation of risk rating for hospital networks
Application of a GIS

Tullio J. Tanzi
Laboratoire d'Ingénierie des Systèmes d'Information
INSA, Lyon
Ets Jean GRANIOU, Nice

ABSTRACT

The subject of reliability and risk that critical installation present has a rapidly growing importance. In addition, the knowledge of risk linked to the function of such equipment may become useful in the context of their management and maintenance because it allows us to bring forth its most critical parts. We present here a study on the definition and the calculation.of the "*risk rating*" for each user and each component of an oxygen distribution network in a hospital. The method by which we determine the necessary reliability figures, essentially the frequence of failure, is the crux of our study. This method can be applied, in prinvciple, to anyfluid network that we know of with the condition that it does not have too many links and that it uses network topology. Concerning the evaluation of damages, the problem has been easily bypassed by implying the correlation with know values.

Such method has been translated in algorithm in view of one of its possible applications in the framework of an evolved structure such as a Geographic Information System (GIS). This will allow, in addition to the basic management of Geographical data (construction and maintenance of the network), showing the most critical parts of the system on the user's demand.

KEY-WORDS

Geographical Information System, GIS, risk rating, utility network management, topological consistency

1. - INTRODUCTION

The conception of a system is offen favored over the analysis of the reliability of its components. Nevertheless the malfunctioning of some technologic networks may have serious repercussions. Moreover, concerning finance, we show that a network designed by common standards and conceived witch certain predisposition for malfunctioning generates more substantial coasts than a highly reliable network. These coasts are made up of, in the best case, maintenance expenses, breakdown investigations, various repairs, loss of time and operation and even, in the worst case, bodily injury or loss of humam life.

To illustrate this, we note the example of fluid distribution network in a hospital setting. We have chosen the example of an oxygen distribution network in accordance with the risks induced at various level. In effect, a block in the flow of oxygen at a wall outlet may have consequences for patient who is using that outlet but a leak on the level of the distribution network may bring about severe damages to all or part of the hospital. The components of this network must function non-stop from the central fluid production side to the various wall outlets at the heads of the patients'beds. We have not carried out a study on the medical problems due to the sudden inavailability of therapeutic gases but one on the reliability allowing us to evaluate the risk that such an incident would occur and to take that reisk into account in the maintenance policy. The notion of reliability does not indicate the degree of criticity of the installation's different parts and does not supply information on possible damages. We have developed a better adapted factor wich we have named *"risk"*.

Another constraint which we have fixed at the beginning of this study is that it is easier to construct a correctly functioning system from the beginning rather than to assure the conformity of existing equipment. It is very rare that this type of concept is taken into account during the construction phase of the hospital. Therefore we have used as an example an existing infrastructure on which we want to carry out an audit and optimized the existing network in order to reduce the financial burden bearing in mind the present state of the structure.

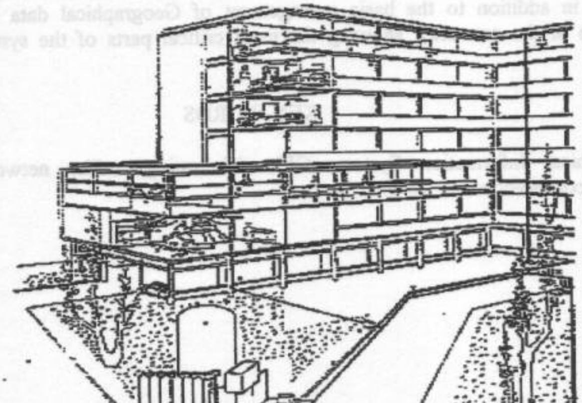

Fig.1 - Oxygen Distribution Network Example

2. - PRESENTING THE PROBLEM

Any virtual system components has a working history caracterized by a sucession of breakdowns and repairs (or replacements). The time period *T* between a brakdown and the next one, or between the brakdown and repair is a random variable which obey to a decreasing exponential distribution.

$$f_T(t) = \lambda \cdot e^{-\lambda t} \qquad (2.1)$$

in which λ.is the brakdown rate; that is, the average number of breakdowns in the given unit of time (usually one year) or in other words, the frequency in which the component breakdown

The application of this low reveals that breakdowns are chance occurences. In reality, it is shown the occurences of breakdowns are more or less concentrated at the beginning and at the end of the components life. In spite of this, however, the uses of this exponenential approximation is common place in the theories of reliability. This makes calculations easier and the intrinsic error generated is comprised in the aera of incertainty of estimating the breakdown rateλ. The breakdown rate λ is very important because in addition to measuring the quality of the component, it is the basic of the calculations of reliability, of which here is one of the more common definitions :

Reliability is the probability A (t) that a component, properly working at time t = 0, will cary out without interruption and in proper fashion the job for which it has been designed during a given time interval [0,x] and with given working conditions.

A(t) is easily derived as a function of λ.

$$A(t) = e^{-\lambda t} \qquad (2.2)$$

The above definition shows the relationship between the reliability function and time as well working conditions. These conditions have a great influence on the breakdown rate and represent the fundamental problem of deriving its estimation from experimental data. It obvious that a component exposed to mechanical agressions (cyclic charges vibrations) or physico-chemicals changes is more likely to break down than the same component which is in a more favorable environment. We find the same difference between a regularly maintained component and one which is not regulary maintained or supervides.

This shows the impossibility of estimating a breakdown rate by lab experiments. One of the most efficient method of estimating the breakdown rate consists in collection and the statistical analysis of breakdown data on components operating under similar conditions (*event data collection*) or operating under conditions best of each particular components (*field data collection*). This last method may seem paradoxal because it means evaluating the quality of component by hindsight. In the limits of this study we are not concerned with determining the breakdow rate,rather with the way of calculating the reliability of a complex system once the breakdown rate values have been determined. Once we have fixed the reliability data of each of the distribution netwoks' different component, its sections (*network arcs*) as well as irs rechnical equipment : valves, diverses parts (*network nodes*), we will calculate the global reliability of the network by mathematical relations derived from the theories of reliability keeping in mind the interaction between the components themselves.

In the case of our network, the final user is represented by a wall outlet or an outlet at the head of the patient' bed in different rooms in different hospital units. We will have not only one function *A(t)* but as many as there are terminal distribution outlets. Reliability by itself doesn't quantify the criticity of the system if we understand that the system is the sum of its components allowing, directly or indirectly, the fluid to be conveyed from the source (*central therapeutic gas production site*) up to the considered terminal outlet. In effect, *A* is firstly a function of time and secondly is not tied to probable damages caused by the faillures of the system : for example, in the same network two outlets can have the same reliability but different criticities because they are destined for different uses and therefore prone to different types of damages in the case of malfunction. For that reason we choose to uses the risk function to formulate criticity ratings in order to overcome the limitations imposed by reliability function.

Risk R is defined as the damage can be expected on average during any year of the working life of the equipment. It is given by the equation :

$$R = F \cdot D \quad (2.3)$$

in which F is incident frequency, D the possible damage whenever the incident occurs.

We think that factor F can be deducted, not without a certain difficulty, from the rules of the reliability theory which we will expand upon. The estimation of D is much less obvious because it implies the possibility to quantifying by means of unit measure, in general economic, all the damages and disturbances due to the incident which are related to different categories. The exact definition of F and D, presented above in its general form, depends on the type of risk that we want define. However, the general form of ratings used is (2.3)

Here we have introduced two types of risk.

User risk rate

This deals with the parameters that allow determining which outlets are the most critical in a given network, that is, the ones that associated with a major risk. The knowledge of criticity of different outlets becomes useful in the case where we decide to change the topology of the network, and we want to check the risk variation associated witch the outlets. These ratings are very important information in a conception phase of a network or in the modification phases of an existing network and used in determining the optimal configuration.

Component risk

This deals with the parameters that indicate the most critical components of a network, those of which the breakdown causes an average major annual damage. This second type of rating is useful in determining which components will need the most maintenance. In the course of last twenty years the maintenance optimization criteria has been developed based on the knowledge of the reliability of the different system components.

3. CALCULATING RISK RATINGS

We first consider the user risk rating, of which the determination is more complex, which is then used in calculating the component risk rating. The correct working in order of a wall outlet is an oxygen (or any other fluid) distribution network may be defined as the capacity to supply at any given moment a minimal given flow Q under a given residual presure p. The French norms NF.S 90-155 supply a table where one can find for any hospital unit the recomanded flow values and use coefficient (aimed at the conception network). For the pressure a values of 4,5 relative atmospheres is required except in particular cases (high pressure therapy). The draconian definition of incident can be a sudden and significant lack of flow during the use of the outlet itself, that is, while the patient is connected with a respirator. This is why F is equal to the outlet's frequency of failure F_d multiplied by the probability of use (which is approximately equal to the coefficient of use u)

$$F = F_d \cdot u \quad (3.1)$$

such a falure could be ascribed to :

a) to a bad dimensioning of the network, so the system is not capable of satisfying the demand for therapeutic gas if a certain number of outlets are being used simultaniously. In technical terms, the auther of the project used an abundance coefficients that was too smalls.

b) the breaking of a pipe, welding or joint causing a gas leak sufficient enough to significatly lower pressure.

c)a crushing or obstruction of the pipe.

We beleived a and c are les likely compared with b. Therefore we will consider as a principal mode of component's of failure its lack of airtightness. Before calculating the F_d factor for the user risk rating, we will show how we fix a value for *D*. Damage *D* is difficult to quantify in an economic sense because it could also be a physical damage in regards to the patient using the oxygen, a disturbance for the doctors and nurses who must use use emergency tank, which could be a future damage for the hospital's image if the consequences of the incident weren't immediatly brought under control. We have not found another solution for the quanity we consider adimentional and that is correlated with the real damage. Theefore we are simply using :

$$D = Q \cdot u \cdot \frac{d}{s} \tag{3.2}$$

where *Q* and *u* are the required flow and the use coefficient of the outlet, respectively. Two hidraulic figures that NF S 90-155 furnishes for each hospital unit and that seem proportional to the importance of the outlet (we have high values for critical units and lower values for general impatient units). *d* is the distance of the closest emergency tank and *s* is the degree of surveillance (average number of nursing staff per unit area). These last parameters have an influence on the speed in which the gasflow is restored to the patient. Formule (3.2) can be improved, for example, by putting an upper limit on *s* in the case of continuous patient monitoring (for example the recovery room).

Estimation of F_d represents the most complicated part of the problem because it requires making a hypothesis on the working order of the network. If the installation were made of a source linked to only one user by means of *n* components in series, the calculation would be done without difficulty because each of the *n* components being absolutely necessary to the function of the outlet, we would use the rules for system in series :

$$R = R_1 \cdot R_2 \cdot \ldots \cdot R_n \tag{3.3}$$

$$F_d = \lambda_1 + \lambda_2 + \ldots + \lambda_n \tag{3.4}$$

where R1 et λ.1 are reliabilities and breakdown rates of different components.

The problem is more difficult when are in the presence of a parallel or series-parallel configuration. This difficulty is due to two types of problematical aspects. The first laspect is that two components in parallel on topological plan are not necesssarily in parallel on a working plan. To illustrate this we will use the example of many pipes having a common end, and a topology of parallel system, even though they are equally and collectively between the source and the user in the fluid transport line, on a working plan what happens is that they are closer to a system in series. This analogy is not as true for electrical systems and much more realistic for systems destinded foir the transport of fluids, especially gases. A small leak is capable of causing a significant decrease in pressure and therefore a decrease in flow in the nearby sections.

The second problem, even if we admit a works according to a series-parallel logic (the system worksas long as at least one of the components works), is that for F_d there is not a formula as simple as (3.4) that also takes into account the problem of the repairability/irrepairability of the components.

A major difficulty is reached in case of a network in which the components are arranged neither in series, in parallel nor in series-parallel, this deals witch networks having closed, contiguous links like the one represented in fig. 2 ("*bridge configuration*"). The maximum complexity is attained in the case of a network having many nodes and sources.

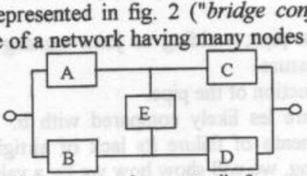

Fig. 2 *"Bridge configuration"* of a network

In case of oxygen distribution, fortunately we have networks that for the most part have only one source and an arborescent structure with few links : in general like the sketch in fig 1. In this case there is only the *"primary network"* link whose purpose is a better pressure distribution. We have chosen to calculate the ***non reliability*** *U(t)* of the outlet, that is the probability of failure given by :.

$$U(t) = 1 - A(t) \qquad (3.5)$$

We can calculate it with the help of

$$F_d = \int_0^{\infty} \frac{1}{t} \frac{d}{dt}[U(t)]dt = \int_0^{\infty} \frac{dU(t)}{t} \qquad (3.6)$$

As for complex systems, it is impossible to find one analytic expression for *U(t)*, it is necessary to calculate *U* at differents instants *t1, t2... tn* and therefore solve the integral in a numerically. For this we have used the two principal known methods to calculate the reliabillity/non-reliablility for fluid networks, then we have defined a third one which if placed in an intermediary position between the two is destined to offset their insuffisances.

3.1 Direct simulation method

This is the best although by far the most expensive method. Its consists in simulating a breakdown of the component one at a time, then two at a time and so on, then observing for each case, by means of the fundamental equations of fluid dynamics applied to networks, which outlets breaks down (thatr is, the ones for with the flow becomes insufficient). If a component, (or a group of components) is sufficient to cause the failing of a certain outlet, it is called an *cut-set* for that outlet. A useful approximation is to take into account only the smallest *cut-set*, that is, those formed by a small number (two maximum) of components, reason being that a simultaneous breakdown of several components is very unlikely. *C1, C2,... Cn* are ***minimal cut-sets*** of the considered outlet, that is, those strictly sufficient to cause the failure of that outlet. The letter *P* indicates their probability of failure (in an interval *[0,t]*). The outlet's probability of failure (its non-reliability calculated at t) reduces itself by means of the probability theorem's event union :

$$U = \sum_{i=1}^{n} P(C_i) - \sum_{i}^{n} \sum_{j>i}^{n} P(C_i \cap C_j) + \sum_{i}^{n} \sum_{j>i}^{n} \sum_{k>j}^{n} P(C_i \cap C_j \cap C_k) - \dots \qquad (3.7)$$
$$\dots + (-1)^{n+1} P(C_1 \cap C_2 \cap \dots \cap C_n)$$

If we consider that for every user it is necessary to calculate the integral of equation (3.6), and that in order to do so calculate also (3.7) for a certain number of time intervals and that there may be about a thousand users and even more components of the hospital network, and that for every possible cut-set it is necessary to repeat the hydraulic simulation on the network, we immediately become aware of the operational complexity of this method. This method, even though appreciable, shows itself completely disproportional in comparison with the goal forwhich we are searching (to find the ratings taking into account the difficulty of quantifying the damages) and in comparison witch the quality of the data we have at hand (the breakdown rates assigned with a consequents uncertainty).

3.2 Topologic analysis method

This method is easier to apply . We will be able to reduce the problematic aspect to a problem of the *route* between the source and the outlet. In other words, we do not take into account any fluid dynamic factors such as flow or pressure and the good working order is reduced to the existence of a least one intact *minimal route* cooecting the outlet and the source. *Minimal route* meaning a succession of "*edges*" and "*nodes*", these paths never having to cross the same node.

The concept of *minimal cut-set* is always valid being a general part of the reliability theory, and depending only on the adopted definition of the good working order of the system. In the case of topologic method a user's *minimal cut-set* is a group of components whose failure is strictly sufficient to "*interrupt*" all the minimal routes possible between the given outlet and the source. For example, in the case of fig. 2 where there is a source at one end and a user at the other, the *minimal cut-sets* are *AB*, *CD*, *ADE* and *BCE*, the minimall routes obviously being *AC*,*BD*,*ADE* and *BCE*.

As for the direct simulation method, the calculation of F_d is obtained by solving equation (3.6) and (3.7). Even if the total operational load is less where we use the topology of the network, the error due to this method is in the fact that only the "reachability" of the outlet is the necessary, but not always sufficient, condition for its good working order. We have already shown the common case of an outlet supplied by two pipes in parallel (and therefore with two minimal routes) where, in reality, both pipes are necessary for the outlet to work properly (problem induced by a leak in one of the two pipes for example). It is obvious that the reachability criteria is close to the real condition of good working order in case where each outlet has only one route, that is, the case of the arborescent network, whereas this is not the case in very linked networks. In any case this method is simpler and requires less calculating resources than the direct simulation method.

3.3 Modified topologic analysis method

We have elaborated on a third method that keeps the simplicity of the topological approach while trying to overcome the fluid dynamics limitations and reducing the other two methods' consumation of resources. The idea is to keep "*reachability*" criteria on good working order and require the existence of not only one minimal route but rather the existence of a certain number of intact niminal routes (limited to all the possible ones). More exactly, we have introduced a *majority logic* of percentage X arbitrary chosen but greater than *50 %*.

In other words, we have fixed the good working order of an outlet to the integrity of a least the percentage X of all the possible minimal routes. I for example $X = 70\ \%$, we obtain that for an outlet having 2 or 3 routes all the routes must be intact whereas for an outlet having four routes, it is only necessary for three to be intact.

As a consequence, a good part of components arranged in parallel or "*bridge configuration*", are automatically treated as if they were arranged in series, that is, they become *minimal cut-sets* of the first order (the order being the number of components in the *set*). If the network is for the most part arborescent with few contiguous links and if the value of X is large enough, the first order minimal cut-sets cleary predominate over those of a higher order, which therefore become negligible. The practical results is that for any outlet the equation (3.4) for a system in series can be applied, where the λ_is are the breakdown rates of the first order *minimal cut-sets*. In this method one may object to the arbitrarity of X and to the not taking into account the possible different diameters of the pipes. Fort the instant we have destined this method to be applied to small networks which have few links and homogeneous characteristics, and not to aduction type network.

Established in similar fashion to the calculation of the user risk rating, the component risk rating can be deduced from the considerations made up until now. We recall the failure of a component brings about a risk if the component is a first order niminal cut-set for that outlet. Then, if the component is part of a higher order minimal cut-set there is no associated risk. The simultanious failure of all minimal cut-set components could happen but such an event is highly unlikely and in addition the minimal cut-sets of order>1 are practically inexistant for small networks.Component risk rating is given by the relation

$$R_c = \lambda_c \cdot \sum u_i \cdot D_i \qquad (3.8)$$

where λ_C he is the breakdown rate of component, that is, its frequency of failure, the summation being extended to all the outlets for which c is a first order *minimal cut-set*, u_i and D_i are their use/utilization coefficient and their associated "*damages*" respectively(see 3.2).The consequent damage caused by the gas leak itself should be added under the summation symbol (immediate economic loss, possible fires or explosions, given that oxygen is a combustible gas). In this study we preferred not to take this into account in finding a unique unit of measure for the global damage because we wanted to draw attention to the disturbances of the users : patients and hospital staff.

4. - SUCCINCT DESCRIPTION OF OBTAINED ALGORITHM

The method of calculating risk ratings with majority logic illustrated above has been translated in algorithm and then experimentally applied by creating a software model using Matlab© 4.0. The entry data are topologic relationships between arcss and modes (the two terminal nodes identify each arc), the codes that caracterize the nodes (users, sources and simple transits), the breakdown rates of the arcs and nodes, a possible pre-orientation of the branches (in order to take into account the physical limitations of the flux)and all parameters relative to the user nodes that figure in the defintion of D (see 3.2). Moreover, we fix the percentage X of majoritaty logic and the adopted working order criteria in the case of many sources in the same network(This deals with fixing if all the sources are necessary or if, on the contrary, only one source is sufficient for the outlet to be in good working order).

The routine checks the network connections and the existence of incoherent pre-orientations. After having constructed the connection matrix (node/node), were we find all the necessary information on the successive research of the routes we have a first reduction of the network by eliminating the simple chains (arcs in series that are condensed in the structures called "hyperarcs" having an equivalent breakdown frequency). Then the true research on the routes begins, starting from the user nodes then advancing along the antennae, that is, the arborescent structures of the network, in looking for the source nodes. The users are ideally concentrated where the antennea are linked ("hyper-users" nodes), this is where the most difficult part of the algorithm begins (the research on the routes in the interior of a linked structure) with the exploration in the course of which the software checks the minimality of the routes found in proportion to the research at each step. Once all the routes of each outlet are determined, the successive determination of the first order minimal cut-sets is almost immediate as well as the final calculation of the risk rating.

Although the algorithm is optimized, from the point of view of speed as well as of memory space required by the variables, we could be able to demonstrate that the time and the required memory increases exponentially with the number of closed links. That is why the field of application is limited to network with a small number of link.

5. - USEFULNESS OF INTEGRATION IN A G.I.S.

We use more and more Geographic Information Systems (GIS) to manage technological networks : drinking water, city gas, purification, and small-medium building service equipment (mostly in the aspects of maintenance and planning its installation). We have therefore conceived the algorithm of minimal cut-set research and risk ratings calculation to be integrated into a GIS. software program. Some basis advantages include facilitating the updating process, the possibility to visualizing the different layersof information selected by the user one at a time or visualizing the coherent storage of a very large quantity of numeric or alphanumeric georeferenced information, facilitating data repeair on demand and executing possible statistical developements. We can add more specific advantages in the particular case of an GIS for hydraulic or fluid networks: the possibility of interacting with simulation software programs which, while managing the appropriated information contained in the data base, allow, for example, the dynamic verification of network fluids either in the phase of conception or in the anticipation of modifications or particular situations. In is in this framework that we see the usefulness of integrating the software that calculates the risk ratings into a GIS. The result being, for example, a more practical introduction of the necessary entry data by using the network plans and a more attractive display of the output data by using the possibility of the GIS's interface user (thematic,...). It seems to us that this would be an interesting tool for the manager or operator of a network.

Concerning the entries of the calculation software, it is necessary to have the parameters relative to the network components' reliability in thhe existing GIS files. For the components classified as "nodes" the GIS will have to differenciate "users", the "sources" and those for simple transit. Concerning the use nodes we have to furnish, in the relative files, the parameters Q, u,d and s (if necessary d could be calculated by the GIS itself once the geographic position of the emergency tank has been indicated in the hospital unit). The topologic relations between the arcs and nodes will be taken automatically at the end of the numeration and validation phases of the network and stored in the data base managed by the GIS. Concerning the results, that is, the risk rating values, they can be visualised either in numeric form after the interrogation of the different components and use nodes, or in thematic plan form by marking the components with different colors (3 or 4 maximum in order not to lose significance) according to the risk catagory to which it belong (for example : yellow if $0<R<a_1$, orange if $a_1<R<a_2$, red if $R>a_2$).

The perfecting of the prototype could be the use of data base concerning the maintenance as in field data collection, that which would allow being able to evaluate the breakdown rates by way of a software program suitable to statistical data.

6. - CONCLUSION

Risk evaluation of an installation requires several competences and allows obtaining satisfactory results only in certain cases. In most cases we must have an idea of the size of the risk associated with the different parts of the system. At the base of the problem there is the inherent difficulty of quantifying the damages and the difficulty to knowing the exact breakdown rates. To this is added the coast of calculating the incidents frequency that is easily and correctly obtainable only for very simple systems.

What we have succinctly shown here does not claim to be a risk evaluation in the real definition of the word, on the contrary, it deals more with a sort of evaluation of a network's reliability where the reliability values in reference to its differents parts are "weighed" by factors roughly take into account the most or least possible damages in case of a breakdown.

We mostly wanted to furnish ideas in order to rapidly calculate the breakdown frequencies in a simple network, and to present a new application for Geographical Information System in the field of network management in order to respond to risk management problems.

REFERENCES

[Bertho92] Bertola P. Salandin P. - "Tecniche di calcolo dell'affidabilità nei sistemi di trasporto dell'acqua" in *Atti del 23°Convegno di Idraulica e Costruzioni idrauliche* - Firenze, 1992.

[Billin87] Billinton R. Allan R.N. - *Reliability evaluation of engineering systems: concepts and techniques* - Plenum Press, New York 1987.

[Cannon91] Cannon A.G. Bendell A. - *Reliability data banks* - Elsevier Applied Science, London 1991.

[Dauphin91] Dauphin A. Segui M. - *Le gaz à usages médicaux* - Arnette, Paris 1991.

[Haupt91] Hauptmanns U. Werner W. - *Engineering risks evaluation and valutation* - Springer-Verlag, Berlin 1991.

[Henley81] Henley E.J. Kumamoto H. - *Reliability engineering and risk assessment* - Prentice Hall, Englewood Cliffs (New Jersey) 1981.

[Mays89] Mays L.W. - *Reliability analysis of water distribution systems* - ASCE, New York, 1989.

[Tanzi94] Tanzi T.J. - *Applications des bases de données spatiales à la gestion des réseaux. Vers la cohérence et la certification* - DEA Ingénierie. Informatique, LISI-INSA, Lyon 1994.