The GO-FLOW reliability analysis methodology - analysis of common cause failures with uncertainty

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ABSTRACT: The Ship Research Institute has been developing a new reliability analysis methodology GO-FLOW⁽¹⁾ which is a success-oriented system analysis technique. This paper describes a function of analyzing common cause failures together with uncertainty analysis in the GO-FLOW methodology.

1 INTRODUCTION

The Ship Research Institute has been developing a new reliability analysis methodology GO-FLOW⁽¹⁾ which is a success-oriented system analysis technique, and is capable of evaluating a large system with complex operational sequences. The function of common cause failure analysis⁽²⁾ together with uncertainty analysis has been provided to the GO-FLOW methodology.

In PSA(Probabilistic Safety Assessments), uncertainty ranges of system failure probabilities are important information for the evaluation of the results of system reliability analyses. The inclusion of common cause failures causes the degradation of system reliability, especially for systems with high redundancy. It produces sometimes more than one order larger system failure probability than the one expected on the assumption of random failures. But the effects of common cause failures are usually evaluated by the point values. As system analysis techniques become mature, it will be important to evaluate the effects of common cause failures together with uncertainty analyses.

This paper describes a function of analyzing common cause failures together with uncertainty analysis in the GO-FLOW methodology.

2 GO-FLOW METHODOLOGY

The GO-FLOW methodology, which is a success-oriented system analysis technique, is capable of evaluating system reliability and availability. The modeling technique produces the GO-FLOW chart, which consists of signal lines and operators. The operators model function or failure of physical equipments, logical gates and a signal generator. Fourteen different types of operators are currently defined as is shown in the figure 1.

Signals represent some physical quantity or information. In the GO-FLOW the existence of a physical quantity is interpreted as both the actual and the potential existence of a physical quantity. "Potential existence" means that a physical quantity exists when all the resistance "downstream" is removed.

A quantity called "intensity" is associated with a signal line. Usually the intensity represents the probability of signal existence. When a signal is used as a sub-input signal to type 35, 37 or 38 operators (standby or operating failure of a component), the intensity represents a time interval between the successive time points.

A finite number of discrete time values(points) are required to express the system

operational sequence. The value does not necessarily represent the real time but corresponds to it and represents an ordering.

An analysis is performed from the upstream to the downstream signal lines. In most cases, only one or, at least, few of all the defined signals are of interest; these signals are called final signals. An analysis is completed when the intensities of these final signals at all the time points are obtained.

The GO-FLOW methodology possesses the following significant features.

- (a) The GO-FLOW chart corresponds to the physical layout of a system and is easy to construct and validate.
- (b) Alterations and updates to a GO-FLOW chart are readily accomplished.
- (c) The GO-FLOW contains all possible system operational states
- (d) The analysis is performed by one GO-FLOW chart and one computer run.

If an engineering system to be analyzed becomes large, the analysis procedure requires a great effort, especially to construct a GO-FLOW chart and to produce input data for the GO-FLOW analysis program. The authors have developed the GO-FLOW analysis support system⁽³⁾, which is a fully integrated personal computer (PC) based, menu driven analysis system. The objective of the development of this system is to improve the efficiency with which the GO-FLOW analysis can be conducted and to enable us to use the GO-FLOW methodology as a powerful tool in a living PSA.

Figure 1. Operators defined in the GO-FLOW methodology.

3 TREATMENT OF THE COMMON CAUSE FAILURES

Usually, there are more than one common causes, and also there are many possible combinations of component failures for one common cause.

An example of CCF analysis⁽⁴⁾ showed that the second-order terms of CCF contributed

less than 1% to total system unavailability. Therefore, in this framework, each common cause is separately evaluated and the total system unavailability is obtained by summing up the contributions from all the common causes based on the following discussions.

The top event of a fault tree or a system failure will be expressed in the following general Boolean algebraic formula.

$$T(A,B)=\{A E + B F + A B G \} H + K \quad (1)$$

where, A and B are basic events which are subjected to a common cause. From E to K are some Boolean algebraic terms composed of basic events. Basic events A and B are decomposed into independent events and a common cause failure as follows,

$$A = A_i + C_{AB}, \quad B = B_i + C_{AB}.$$

Substitute the above relations into equation (1), and rearrange it. Hence:

$$\begin{aligned} T(A,B) &= \{A_i E + B_i F + A_i B_i G \} H + K + C_{AB} (E + F + G) H \\ &= T(A_i, B_i) + C_{AB} (E + F + G) H \end{aligned} \quad (2),$$

where $T(A_i, B_i)$ means that basic events A and B are replaced by independent failure events A_i and B_i , respectively.

The above expression could be converted into the expression of occurrence probability by considering the inclusion-exclusion relations between basic events $A_i, B_i, C_{AB}, \dots$ as:

$$P\{T(A,B)\} = P\{T(A_i, B_i)\} + P\{C_{AB}\} (P\{T(1,1)\} - P\{T(0,0)\}) \quad (3),$$

where, $P\{T(1,1)\}$ and $P\{T(0,0)\}$ mean the system failure probabilities when occurrence probabilities of basic events A and B are replaced by 1.0 and 0.0, respectively. The first term is the contribution from the independent events, and the second term is from the common cause event C_{AB} .

More general formula is obtained as the next equation.

$$P\{T(A,B,\dots)\} = P\{T(A_i, B_i, \dots)\} + \sum_{C_j} \sum_{m=2}^N \sum_m P\{C_{jm}\} (P\{T(1,1,\dots)\} - P\{T(0,0,\dots)\}) \quad (4),$$

where, the summations are performed on the common cause kinds C_j , the number of failed components m, and the possible combinations of m component failures.

4 COMMON CAUSE FAILURE ANALYSIS WITH UNCERTAINTY

The procedure for the treating the CCFs with uncertainty consists of the following steps in the GO-FLOW methodology. The Monte Carlo method is applied to the uncertainty analysis.

(1) Construct the GO-FLOW chart, in which CCFs need not be explicitly expressed.

(2) Assign failure rates or probabilities to basic events by using random numbers.

One of the following distributions can be selected as a distribution of a basic event.

The Normal distribution, Log-normal, Homogeneous, Log-homogeneous, Gamma, Binomial, Weibull, Beta, and Histogram distributions.

(3) Obtain the system unavailability which takes into account only independent events.

(4-1) Identify the common cause component group.

(4-2) Select the parametric model of common cause failure.

Four parametric models are provided in this framework; β -factor model⁽⁵⁾, Multiple Greek Letter model⁽⁶⁾, Binomial Failure Rate model⁽⁷⁾, and α -factor model⁽⁸⁾.

(4-3) Give the estimated values for model parameters.

(4-4) Obtain the contribution from a specific common cause.

(5) Repeat the steps from (4-1) to (4-4) for other common causes.

(5) Sum up the contributions from all the CCFs.

(6) Repeat the steps from (2) to (5) for sampling times, for example 5000 times.

(7) Arrange analysis results.

The above procedure is illustrated in the figure 2.

The analysis program automatically performs above steps if the analysis conditions are given in advance as input data. The input data consists of type of failure distribution and values of distribution parameters for uncertainty analysis, and common cause component groups, type of parametric model, and values for model parameters for common cause failure analysis.

As the analysis results, the values of median, mean, error factor, 90% ranges of uncertainty, and cumulative probability distribution, probability density distribution are obtained, in which common cause failures are considered.

Figure 2. Analysis procedure in the GO-FLOW methodology.

5 AN ANALYSIS OF AFWS

As a sample system, a three-train Auxiliary Feedwater System of a Pressurized Water

Reactor has been selected. A simplified P&ID of the AFWS is shown in figure 3. The system consists of three pump trains, which take suction from a common condensate storage tank and supply header and provide auxiliary feedwater flow to four steam

generators. There are two identical electric motor-driven pumps and

a steam turbine-driven pump. There are four motor-operated valves at the pump discharge that are normally closed. Each motor-driven pump can supply flow through successful valve openings to two dedicated steam generators, and the turbine-driven pump can supply flow to up to four steam generators, depending on how many MOVs open. Although there are two kinds of pump drivers, all three mechanical pumps are identical.

It is assumed that the system must operate for 24 hours following its demand. For the successful operation of the system, it is needed to supply flow to at least two steam generators.

The system was modeled in the GO-FLOW chart as shown in figure 4. Three time points were declared: Time point 1 is an initial time; at time point 2, the system operation is demanded; time point 3 is 24 hours after time point 2. The values of component failure rates and demand probabilities are given in Table 1.

Two common cause component groups were considered. The first group is motor driven and turbine driven pumps and the failure mode is "fails to start"(operator numbers are 8,10

Figure 3. Flow diagram of PWR AFWS

and 14). The second group is the electric motors, and the failure mode is "fails to start"(operators 4 and 12).

The analysis was performed by the MGL model. We have assumed that the values of parameters β and γ equal to 0.697 and 0.304 , respectively for "pumps fail to start". The value of β has been assumed to be 0.390 for "motors fail to start".

Table 1. Failure rates and demand probabilities

Failure modes	Point estimates
Failure of Water Tank	2.00E-6/h
Failure of Check Valve	4.00E-6/h
Motor fails to start	1.65E-3
Turbine fails to start	3.15E-2
Motor fails to run	1.71E-5/h
Turbine fails during operation	1.01E-3/h
Pump fails to start	1.65E-3
Pump fails to run	1.71E-5/h
MOV fails to open	4.30E-3

Figure 4. GO-FLOW chart of the PWR AFWS

For the uncertainty analysis, the normal distributions were assigned for failures of water tank and check valves. A histogram distribution was assigned for "pumps fail to run", and the log-normal distributions were used for other failure modes, the sampling was repeated 5000 times.

Figure 5 shows the results of the analysis. Thin and thick lines represent the results with independent failures and common cause failures, respectively. The median values and 90 % range of uncertainties are also drawn in the figure.

Figure 5. Results of the common cause failure analysis with uncertainty.

6 CONCLUSIONS

By the framework presented here, parametric CCF models with uncertainty can be easily incorporated into a system reliability analysis with many advanced functions of the GO-FLOW methodology. Especially phased mission problems⁽⁹⁾ can be easily solved with CCFs and uncertainties.

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