

GO-FLOW methodology -Basic concept and integrated analysis framework for its applications-

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Abstract: GO-FLOW methodology is a success oriented system analysis technique, and is capable of evaluating a large system with complex operational sequences. Recently an integrated analysis framework of the GO-FLOW has been developed for the safety evaluation of elevator systems by the Ministry of Land, Infrastructure, Transport and Tourism, Japanese Government. This paper describes (a) an Overview of the GO-FLOW methodology, (b) Procedure of treating a phased mission problem, (c) Common cause failure analysis, (d) Uncertainty analysis, and (e) Integrated analysis framework. The GO-FLOW methodology is a valuable and useful tool for system reliability analysis and has a wide range of applications.

Keyword: system reliability; safety evaluation; GO-FLOW methodology

1 Introduction

Probabilistic Safety Assessment (PSA) is important in the safety analysis of technological systems, such as, nuclear plants, chemical and petroleum facilities, transportation systems.

Event tree and fault tree are the basic analytical tools that have been most frequently used for PSAs. Several system analysis methods can be used in addition to, or in support of the event tree and fault tree analyses. The need for more advanced methods of system reliability analysis has grown with the increased complexity of engineering systems in the society.

The authors have developed a 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.

This paper describes (a) an Overview of the GO-FLOW methodology, (b) Procedure of treating a phased mission problem, (c) Common cause failure analysis, (d) Uncertainty analysis and (e) Integrated analysis framework.

The GO-FLOW methodology is a valuable and useful tool for system reliability analysis and has a wide

range of applications. With the development of the integrated analysis framework of the GO-FLOW, this methodology becomes a powerful tool for the safety evaluation of engineering systems in various fields.

2 Overview of GO-FLOW methodology

The GO-FLOW methodology is capable to evaluating system reliability and availability. The modeling technique produces a chart which consists of signal lines and operators, and it represents the engineering function of the components/subsystems/system.

The operators model function or failure of the physical equipment, logical gates, and a signal generator. Fourteen different types of GO-FLOW operators are currently defined as shown in Fig 1. Specific probabilities (point estimates) of component operations or failure are given as input data to operators.

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

A quantity called "intensity" is associated with a signal. 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, 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 correspond to it and represents an ordering.

The first step of the analysis is to construct a GO-FLOW chart, which is a modeling of an engineering system. An analyst interactively constructs a chart on a PC display with the support of GO-FLOW chart editor. During the construction of a chart, component failure data and analysis conditions

are given to a chart.

An analysis is performed from the upstream to the downstream signal lines. In most cases, only one, or at most few of all the defined signals are of interest; these signal lines are called as 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 the system and is easy to construct and validate, (b) alternations and updates to a GO-FLOW chart are readily accomplished, and (c) GO-FLOW contains all the possible system operational states.

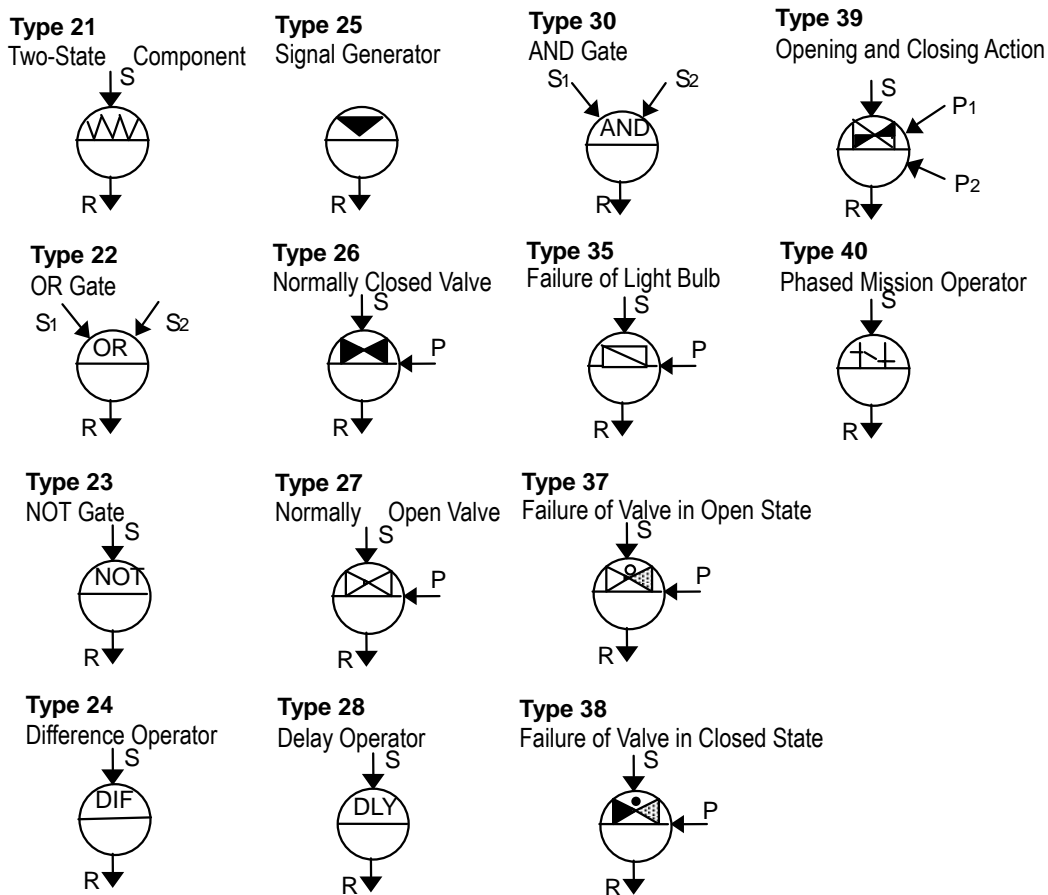


Fig. 1 Operators defined in the GO-FLOW methodology.

3 Phased mission problem

A phased mission is a task to be performed by a system. During the execution of the task, the system configuration is altered such that the failure logic model changes at one or more times. Mission reliability is defined as the probability that the system functions in successive phases. Therefore it is necessary to calculate the products of success probabilities among different phases. In this case, it is necessary to treat correctly the inclusion or exclusion relation between the failures of shared components.

In the GO-FLOW methodology, an AND gate (type 30 operator) combines two or more signals, in which it calculates the products of signal intensities in the same time point. The type 40 operator is prepared for the analysis of phased mission problem. This operator freezes signal intensity except during specific time period, as shown in Fig. 2. In this figure $S(t)$ and $R(t)$ are the intensities of an input and output signals, respectively. A specific phase is from t_i to t_j . Before this phase, $R(t)$ is always 1.0, and after this phase $R(t)$ holds the intensity of $S(t_j)$, that is, at the end of the specific phase.

Now consider the product of two signals A and B. Both signals are output signals of type 40 operators and represent success states of system in phases 1 and 2, respectively. In the time points during phase 1, the intensity of signal B is always 1.0. Then the product of signals A and B becomes signal A itself. In the time points during phase 2, the intensity of signal A is frozen to the state at the end of phase 1. Then the intensity of product of signals A and B represents the success state of system in successive phases 1 and 2.

Any signal line has information of shared signal line numbers which constitute the signal. When we calculate the product of output signal lines of type 40 operators, there are different shared signal numbers which originate same signal line. In this case, there exists dependency between these different shared signals. Here, represent the shared signals by A' , A'' , which original signal is A. In the GO-FLOW, the following Boolean calculations are performed, where $P(A)$ means the intensity of signal A.

$$\begin{aligned}
 A' + A'' = A' & : P(A') > P(A'') \\
 A' \cdot A'' = A'' & : P(A') > P(A'')
 \end{aligned}
 \tag{1}$$

By the above procedure, the GO-FLOW methodology can correctly treat the dependency between the failures of shared components in different phases. More detailed explanations about the procedure of treating the phased mission problem are given in reference^[2], which gives an analysis result of a sample system with the comparison of the result obtained by FT analysis.

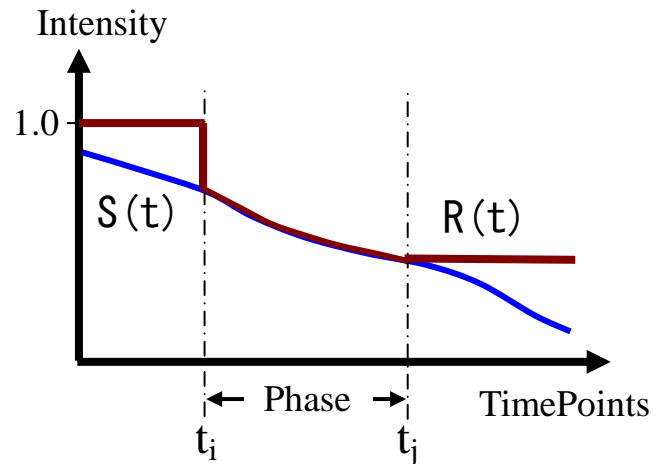


Fig. 2 Function of type 40 operator.

4 Common cause failure analysis

Common cause failure (CCFs) have long been recognized as an important issues in PSA. The high degree of reliability of safety systems in nuclear power plants has been achieved through the use of design principle of redundancy. Common cause failure arises from some common cause that fails more than one system or more than one train of a system, simultaneously.

In the treatment of CCFs, the first important task is to identify the possible common cause failures. If the cause-effect logic is clear, the explicit model can be used and the CCF can be directly incorporated into a system logic model. For the CCFs that are not modeled explicitly, the parametric common cause models have to be applied.

Usually, there are more than one common causes, and also there are many possible combinations of component failures for a specific common cause. If all these failures are treated at the same time in a single analysis model, the analysis becomes impractical. An example of CCF analysis^[3] showed that the second-order terms of CCF contributed less

than 1% of total system unavailability. Therefore, in this framework, each common cause is separately evaluated and the total system unavailability is obtained by summing up contribution from each CCF.

If A and B are basic events (failure events) which are subjected to a common cause. A system failure S, is expressed in the following general Boolean algebraic equation.

$$S(A, B) = (AE + BF + ABG) \cdot H + K. \quad (2)$$

From E to K are some Boolean algebraic terms not suffered by common cause. Basic events A and B are decomposed into independent events and a common cause failure as follows,

$$A = A_i + C_{AB}, \quad B = B_i + C_{AB}. \quad (3)$$

Substitute the above relations into Eq. (2), and rearrange it.

$$S(A, B) = S(A_i, B_i) + C_{AB} (E + F + G) \cdot H, \quad (4)$$

where $S(A_i, B_i)$ 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 failure probability.

$$P\{S(A, B)\} = P\{S(A_i, B_i)\} + P\{C_{AB}\} \cdot (P\{S(1, 1)\} - P\{S(\phi, \phi)\}). \quad (5)$$

where $P\{S(1, 1)\}$ and $P\{S(\phi, \phi)\}$ means the system failure probability 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.

$$P\{S(A, B)\} = P\{S(A_i, B_i)\} + \sum_{C_i} \sum_{m=2}^N P\{C_{im}\} \cdot (P\{S(1, 1, \dots)\} - P\{S(\phi, \phi, \dots)\}), \quad (6)$$

where, the summations are performed on the common cause kinds C_i , number of suffered components N, and the possible combination of m components.

The procedure for the treating the CCFs in the GO-FLOW methodology consists of the following steps.

A. Construct the GO-FLOW chart, in which CCFs

need not be explicitly expressed.

- B. Identify the common cause failure component groups.
- C. Select the parametric model of common cause failure. Four parametric models are provided in the GO-FLOW; β -factor model, Multiple Greek letter model, Binomial failure rate model, and α -factor model.
- D. Give the estimated values for model parameter.
- E. Execute the GO-FLOW program with CCF function.

System logic model without CCFs effect can be used in this analysis procedure. That is, usual GO-FLOW charts can be used for the evaluation of common cause failure effects.

5 Uncertainty analysis

There are two basic types of uncertainty: parameter value uncertainty and modeling uncertainty. The GO-FLOW handles the parameter value uncertainty. The distribution of a system failure probability is calculated by combining values selected by sampling from the probability distribution for all the basic events.

The analysis procedure consists of two steps. First, the minimal cut sets (MCS) are obtained for specific signal lines. The GO-FLOW is a success-oriented system analysis technique. System states expressed in success probability are converted into the expression in the failure probability, and the MCSs are obtained.

Next, the distributions of failure probabilities are assigned for the basic events in the MCSs and the distribution of a system failure probability is obtained with the Monte Carlo simulation. One of the following distributions can be assigned to the basic events. The normal distribution, Log-normal distribution, Homogeneous, Log-homogeneous, Gamma, Binominal, Weibull, Beta, and Histogram distributions.

As the analysis results, the followings are obtained; the values of median, mean, error factor, 90% ranges of uncertainty, cumulative probability distribution and probability density distributions. The time variation of uncertainty distribution is easily obtained.

Failure probability distribution at any part of a system can be obtained.

The function of common cause failure analysis together with uncertainty analysis has been provided to the GO-FLOW methodology^[4].

6 Integrated analysis frameworks

As an application of the GO-FLOW methodology, evaluation of general Elevator systems by the GO-FLOW has been performed. In Japan, an elevator accident has occurred in 2006, and a young high school student was killed. After that, the safety of elevator systems becomes a social attention. In this evaluation, an integrated and convenient analysis framework (ELSAT; ELevator Safety Analysis Tool) has been developed by the National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism.

In the analysis of elevator system, we need many information, which are inter-related each other. Records of elevator accidents in the past, detailed figures of mechanical structure of elevator, control logic of elevator operation, failure and maintenance data of components, GO-FLOW model and its explanation, analysis results, improved system model and corresponding GO-FLOW model.

Appropriate names and numbers are assigned for the above information for identification and distinction. Multiple windows, which express the information, can be opened at the same time for an analyst in the process of analysis. Figures of analysis results are automatically obtained in this analysis framework. Detailed explanations for these steps are given in the followings.

6.1 Preparation of analysis

Main menu screen of ELSAT is shown in Fig. 3. The analysis is started by this screen. It contains four items, “Accident events”, “Component data”, “Failure data” and “Analysis model (Execution of analysis)”, from top to bottom.

With the click of “Accident events” item, a window appears, in which accident events are listed up as shown in Fig. 4. Each event has the information of

event number given by an analyst, occurrence date, accident place, kind of event, failed component, and detailed description.

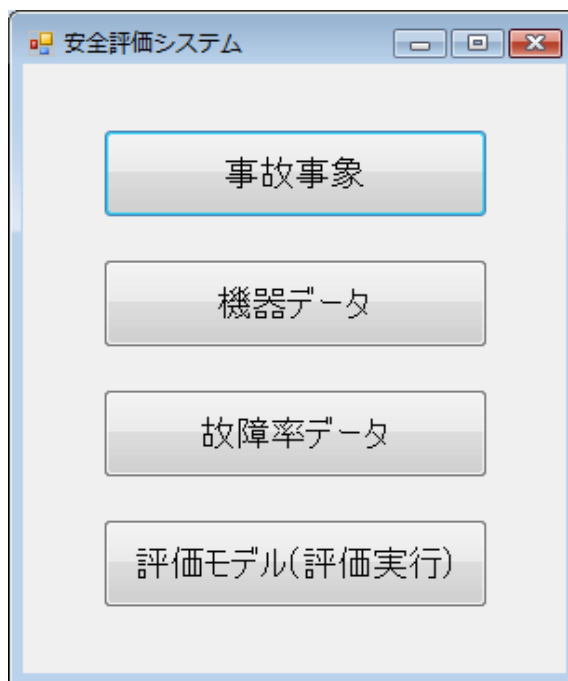


Fig. 3 Start up menu of the ELSAT.

事故事象	日付	場所	種別	故障部材	説明
00119	H17.03	東京	落下		11階で器具オーバードライブの警報が...
00081	H12.09	東京/病院	EV	落下	停電で停止し、復帰の再開...
00049	H09.12	兵庫/工場	EV	落下	クワイール破断(破断)
00044	H08.09	東京/事務所	EV	落下	クワイール破断(破断)
00037	H05.06	東京/住居	EV	落下	PP2の付具+
00034	H04.07	神奈川/倉庫	EV	落下	コンピュータエラー-
00031	H03.10	東京/事務所	EV	落下	コンピュータエラー-
00029	H02.11	石川/店舗	EV	落下	PP2の付具+
00021	H01.07	東京/百貨店	EV	落下	PP2の付具+
00018	H01.07	福岡/百貨店	EV	落下	PP2の付具+
00015		東京	EV	落下	自動着床レベラーで閉じ込め...
00012		東京	EV	落下	PP2の付具+
00107	H16.07	兵庫/百貨店	EV	落下	クワイール破断(破断)
00106	H16.07	大阪/百貨店	EV	落下	クワイール破断(破断)
00108	H16.06	東京/百貨店	EV	落下	クワイール破断(破断)
00076	H12.03	秋田/住居	EV	落下	クワイール破断(破断)
00013	S03.07	東京/事務所	EV	落下	クワイール破断(破断)
00126	H16.08	東京/事務所	EV	落下	クワイール破断(破断)
00140	H16.09	東京/百貨店	EV	落下	クワイール破断(破断)
00142	H16.10	熊本/管理	EV	落下	クワイール破断(破断)
00090	H12.09	東京/百貨店	EV	落下	クワイール破断(破断)
00112	H16.03	東京/百貨店	EV	落下	クワイール破断(破断)
00099	H14.11	愛知/駅	EV	落下	クワイール破断(破断)
00119	H16.03	秋田/事務所	EV	落下	クワイール破断(破断)
00101	H16.05	神奈川/百貨店	EV	落下	クワイール破断(破断)
00103	H16.05	東京/事務所	EV	落下	クワイール破断(破断)
00105	H16.05	東京/百貨店	EV	落下	クワイール破断(破断)
00107	H16.05	秋田/百貨店	EV	落下	クワイール破断(破断)

Fig. 4 List of accident events.

With the click of “Data Edit” item in this window, sub window appears which is used for inputting event data as shown in Fig. 5.

“Component data” item in the start up menu, gives list of components window. Names of components and their descriptions can be directly written in this list window.

List of component failure data appears by the click of “Failure data” item in the startup menu, as shown in Fig. 6. The list requires the data; component name,

failure mode, failure rate, uncertainty data, common cause failure data, name of the data source, related accident event number, and additional descriptions. An edit window appears by the click of “Data Edit” item in this “component failure data” window.

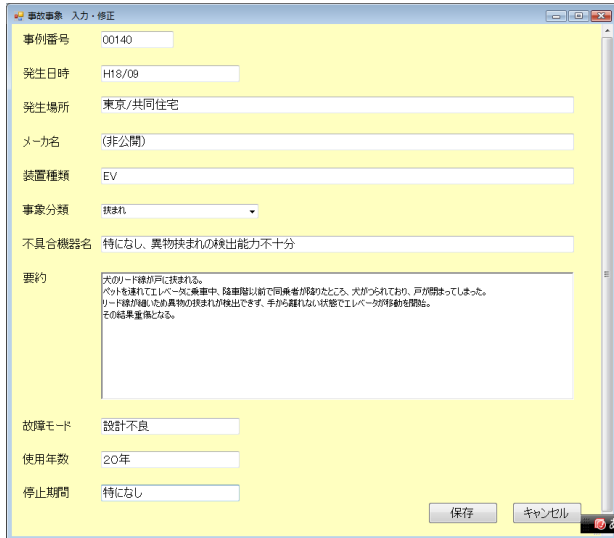


Fig. 5 Window for inputting event data.



Fig. 6 Component failure data window.

6.2 Evaluation of engineering systems

List of analysis models appears by the click of the “Analysis model (Execution of analysis)” item in the main menu screen, as shown in Fig. 7.

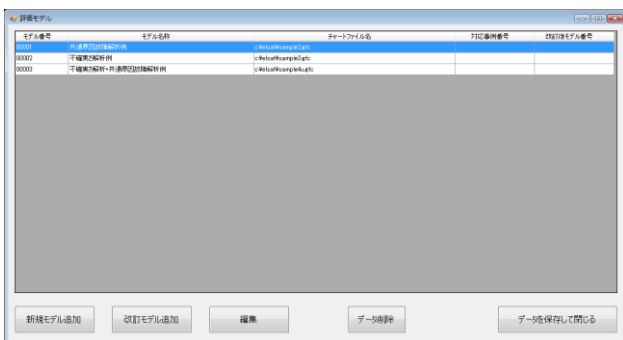


Fig.7 List of analysis models.

A new model can be defined through “model data” window, which is a kind of “edit” screen, and also a control screen for analysis.

Figure 8 in the next page shows this window. The following data are given in this window; model number, name of model, file name of GO-FLOW chart corresponds to the model, detailed description of GO-FLOW model, corresponding accident events, countermeasure for accident, additional description.

There is a button “Start of GO-FLOW chart editor / Chart display” in this window. If a GO-FLOW chart corresponding to the model is already developed, a file name appears in the text box of “File name for Chart”. In this case, with the click of the button, GO-FLOW chart appears as shown in Fig. 9.

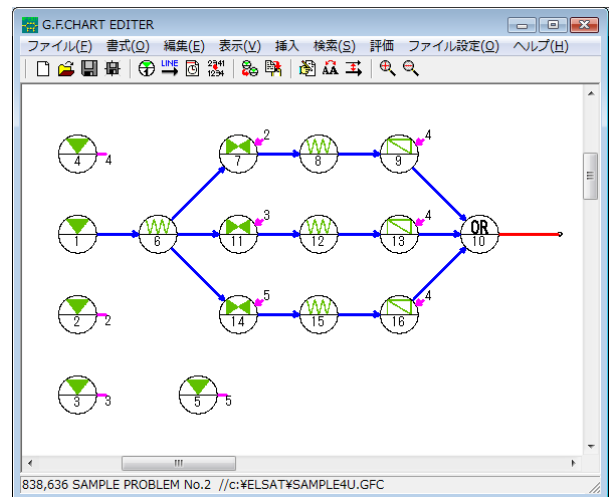


Fig. 9 GO-FLOW chart editor.

If there is no file name, the GO-FLOW chart editor with white page appears. Then, make a GO-FLOW chart model for an accident.

A window shown in Fig. 10 appears by the click of “Setting of failure data, uncertainty data” button. In this window, component failure data (point estimate) and uncertainty data are assigned as shown in this figure. In the lower half part of the window, it is shown the equation of selected probability distribution for uncertainty of component failure.

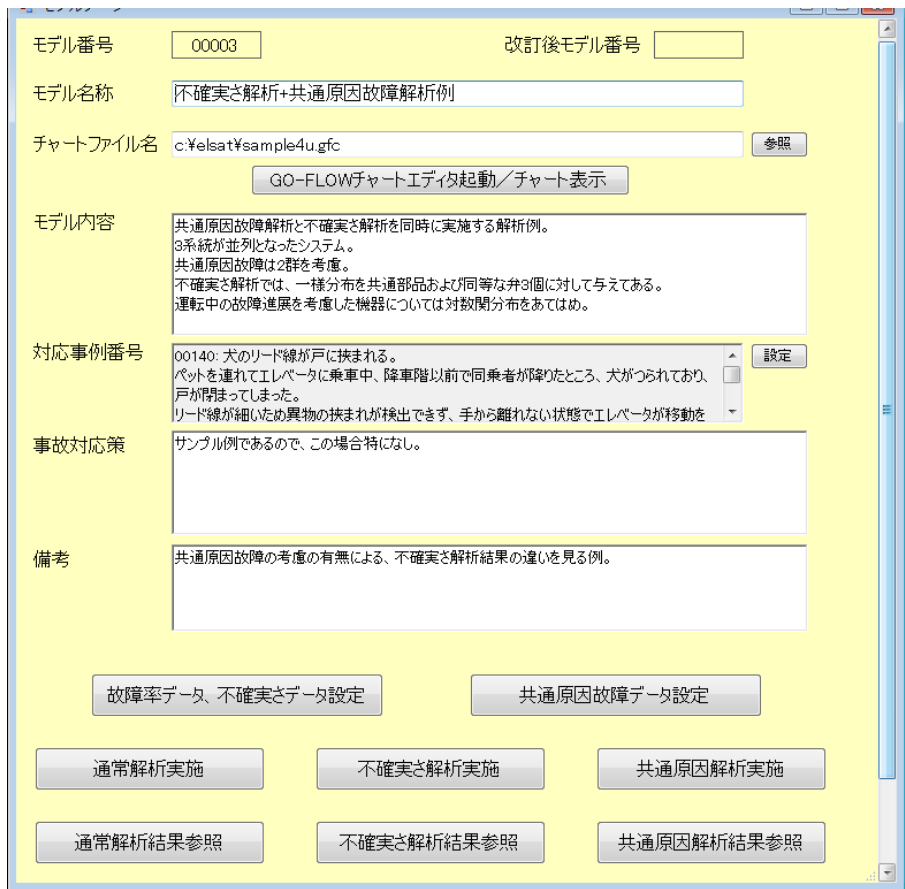


Fig. 8 “model data (Execution of analysis)” window.

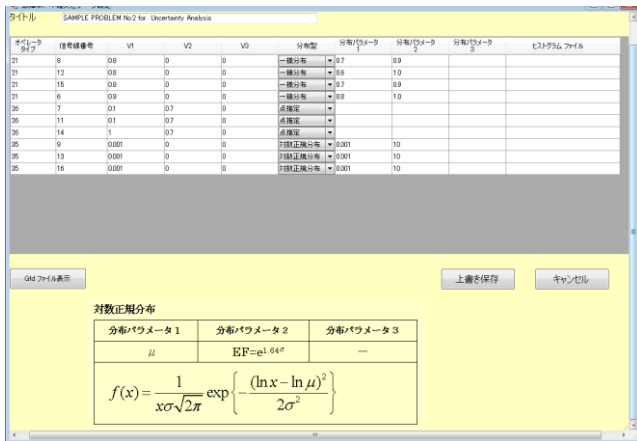


Fig. 10 Assignment of component failure data.

With the click of “Setting of common cause failure data” button, a window shown in Fig. 11 appears. In this window, component numbers are given for Common cause failure component group. In the lower half part of the window, values are given for parameters of common cause failure model. The equation of the selected common cause failure model is also written for the reference

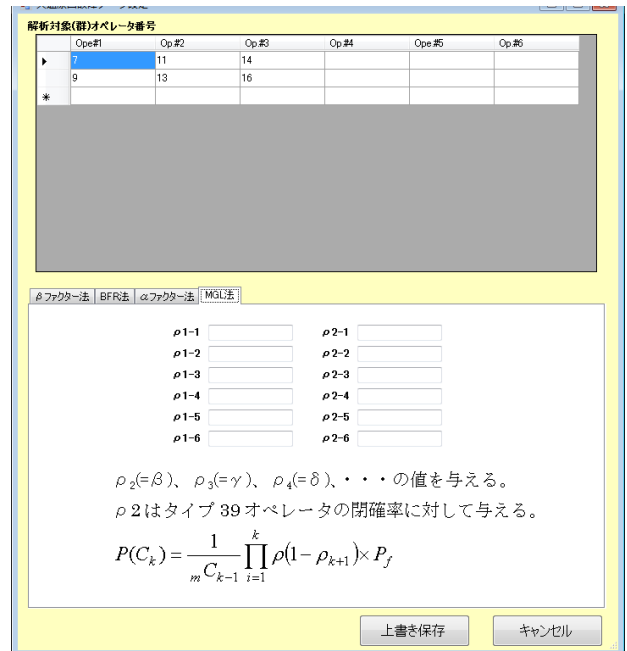


Fig.11 Assignment of common cause failure data.

“Execution of ordinary analysis” button starts the GO-FLOW analysis. First, control window for GO-FLOW analysis appears as shown in Fig. 12.

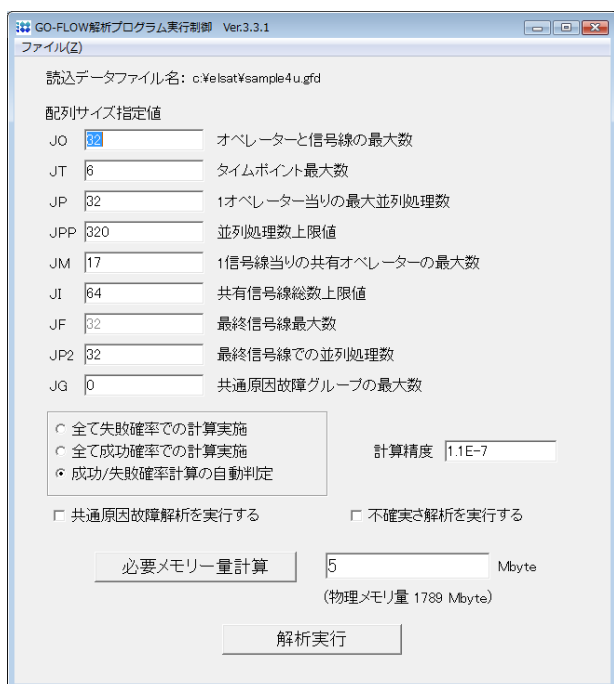


Fig. 12 Control window for GO-FLOW analysis.

In this window, a recommended dimension size is shown for the variables used in the GO-FLOW program. If the GO-FLOW model is not so complicated, the GO-FLOW analysis can be executed by the recommended size.

Analysis results are obtained in the form of Excel file. The first sheet is in the image of line printer outputs. In the second sheet, value of each item is given in separate cell, in order to be easily handled analysis results. The third sheet gives a figure of time points – success probabilities relation, and the fourth sheet gives a figure of time points – failure probabilities relation for final signals, as shown in Fig. 13.

Uncertainty analysis is started by clicking “Execution of uncertainty analysis” button in “Model data (Execution of analysis)” window. In the control window for GO-FLOW analysis, check the box of “Uncertainty analysis”. Analysis results are given in the form of line printer outputs, and uncertainty distribution is expressed as shown in Fig. 14.

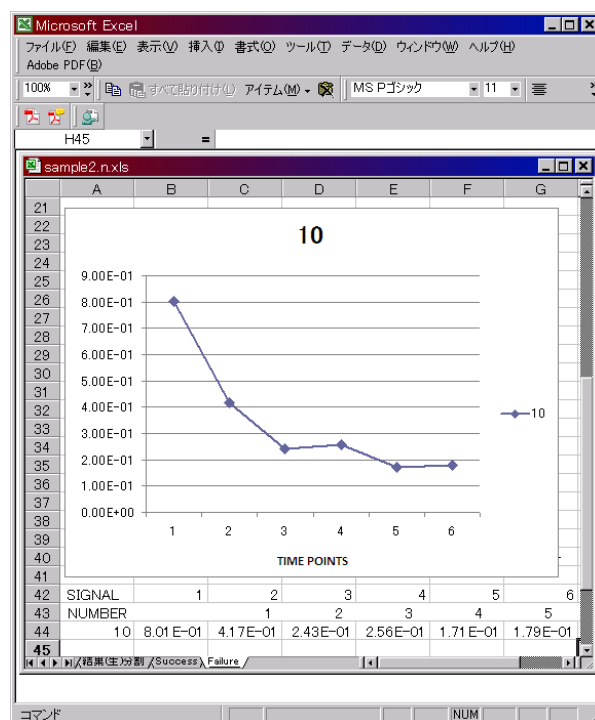


Fig. 13 Analysis results expressed in Excel file.

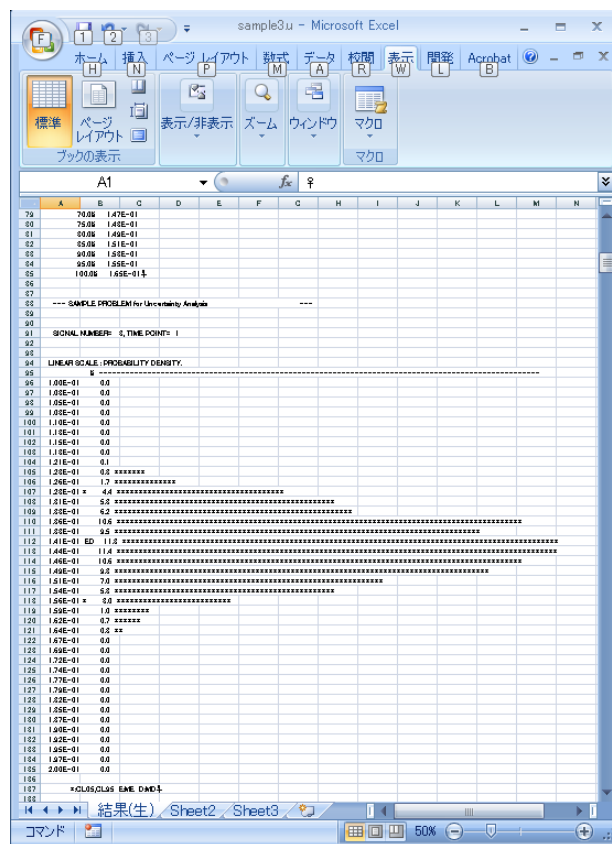


Fig. 14 Results of uncertainty analysis.

Common cause failure analysis is started by clicking “Execution of common cause failure analysis” button in “Model data (Execution of analysis)” window. In

the control window for GO-FLOW analysis, check the box of “Common cause failure analysis”. Analysis results are also obtained in the form of Excel file. The third sheet gives a figure of time points – failure probabilities relation as shown in Fig. 15. The ordinary analysis result, common cause failure analysis result, and contributions from common cause failure component groups are expressed for final signals.

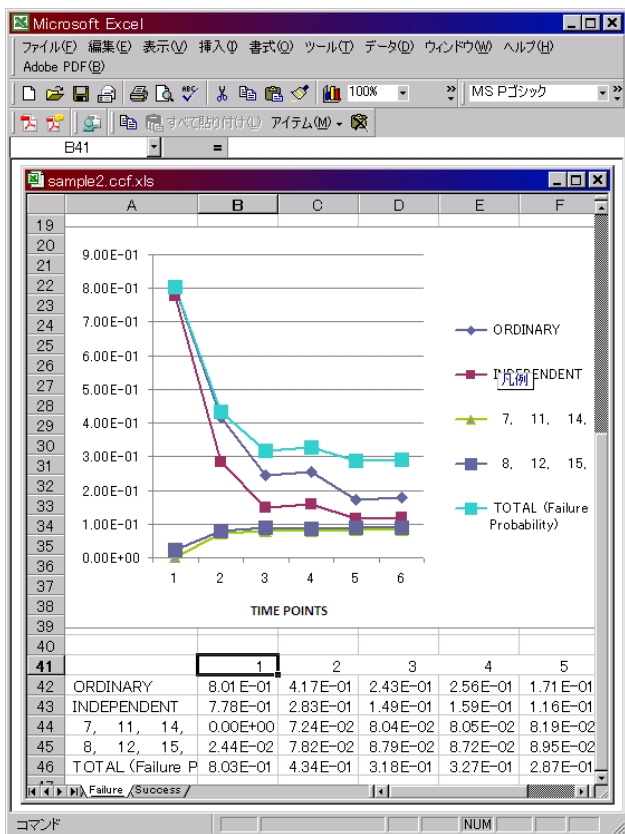


Fig. 15 Results of common cause failure analysis.

7 Conclusions

In this paper, the present status of the GO-FLOW methodology has been introduced. Explanations have been given for (a)an Overview of the GO-FLOW methodology, (b)Procedure of treating a phased mission problem, (c)Common cause failure analysis, (d)Uncertainty analysis, and (e)Integrated analysis framework.

Integrated analysis framework has been developed for the safety evaluation of Elevator systems as one of the useful application fields of GO-FLOW. Detailed explanations have been given to this integrated analysis framework.

It has been seen that the GO-FLOW is a valuable and useful tool for reliability analysis or safety evaluation of various kind of engineering systems.

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