Analysis and Study of System Safety Based on Event Sequence Diagram

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Summary
The Event Sequence Diagram (ESD) is one new method in system safety analysis, which can effectively solve the deficiency of the traditional methods in safety modeling and analysis. In order to get the risk on the level of system and to obtain the quantitative decision reference of safety, this paper proposes an analytic method of system safety based on newly expanded ESD. In the article, the dynamic logical diagram formulation and its mathematics description for the expanded ESD framework are produced to enhance its function of modeling and connection with the system structure. The method will divide the system into different subsystems according to some criterions and unify a new algorithm of ESD, last develop a sort of software of dynamic system visualization modeling and analyze an aeronautic subsystem and traffic accident system with it. Finally, two examples are introduced to explain the validity of this newly developed ESD method.

Key words:
Event sequence diagram, safety analysis, aeronautic subsystem, traffic accident analysis, visualization.

1. Introduction

In recent years, the electronic technology, the computer technology develop rapidly, the capability of all kinds of system and the equipment enhance greatly, their structures also change more and more complexly. Especially the application of the high redundancy level and dynamic redundancy, the abnormity of any linked events all possibly cause the harm to the system safety. In the entire life cycle of system, among the extrinsic factors have the complex correlations frequently, which are among the interior working units of system, the environment, the personnel and the regulations etc. Therefore the system displays the obvious dynamic characters in the total life cycle, namely the system safety state change unceasingly along with the time or the movement process or the stage. However the research of dynamic system safety with the traditional Fault Tree/ Event Tree analysis take on the very big insufficiency in the dynamic factors aspect, which the time, the process variables, human's operation behavior and so on. Although the traditional methods can introduce the correct lapse logic, then they can't provide the enough information that correct computation of dynamic probability, also can't estimate the time distribution of the resultant state [1-2].

Event Sequence Diagram (ESD) is a sort of visualization graphics tool, which can carry on the description to the correlative event order. It can be good at carrying on modeling and analysis to the dynamic system. Especially the use of direct-viewing describing the process of accident, the support of modeling based event tree as well as carrying on the qualitative and quantificational processing [3]. Serves as the quantitative investigation in the chemical industry; In the project of aerospace craft, carrying on the quantificational probability solution of the final state in the calamity accident of the cluster of engine; Also may serve as the records management in the nuclear industry, qualitative processing [4]; Also may take event sequence diagram of function In certain other domains, enhancing understanding of the personnel to the accident [5]. Based on this, this paper has further considered all kind of question of dynamic characteristic influence in the system. Based on the research of the ESD frame foundation which Swaminathan etc [4-7], importing the graph theory [8, 9] and the database technology [10] to extend ESD technique, we propose a sort of the visualization modeling method with improved event sequence diagram, a set of safety analysis software based on ESD is designed to solve a probabilistic risk assessment problem of dynamic system. The model and method have been proved to be useful for solving practical problems by two examples. We will elaborate the partial conclusions of the system realization and the arithmetic research.

This paper is organized as follows: in Section 2, the expanded ESD frame and graph element model are described in detail and in Section 3, the ESD hierarchy concept and systematic structure and database structure of model are presented, respectively. In Section 4, an analytical algorithm of ESD model is designed. Then Section 5, two numerical examples are given to reveal the effectiveness of the algorithm. Finally, some conclusions are drawn.

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2. Graph Element Model of ESD Frame

2.1 Graph Element Definitions and Expressions

An ESD framework of usual said has not standard definitions or expressions [4, 6]. In order to carry on processing rather to the dynamic system with the time of event occurrence, the order of event occurrence, the pertinence aspect of process variable, paper proposes a newly expanded ESD model framework.

The expanded and improved ESD is defined by 7-tupleΣ, described Events, Conditions, Logical gates, Process variable set, Constraints/Boundaries, Dependency/Connection rules, Hierarchy identifiers.

$$\sum = (E, C, G, P, CB, DR, H)$$

$E = \{e_1, e_2, \dots e_n\}$ is the finite set of event, $n > 0$. All observable physical phenomenon can define as the event, is composed of the initial event, the link event, the lingering event, the end event, the annotation event and so on.

$C = \{c_1, c_2, \dots c_m\}$ is the finite set of condition, $m \geq 0$. The event of different condition controls the rule of different branch development, such as YES, NO, IGNORE and so on.

$G = \{g_1, g_2, \dots g_l\}$ is the finite set of logical gate, $l \geq 0$. Using in the situation of the analog input and output. It is composed of the input And\Or gate, output And\Or gate, the ordinal gate, the "in N take K" gate, the extended gate and so on.

$P = \{t_n, p_m\}$ is the process variable set of the system time and physics and so on.

CB is the Constraints/Boundaries set of the event or the process parameters, simulates the competitive situation of various events sequence by the time connection with the event sequence of various levels.

DR is the important characteristic of dynamic simulation ability. Indicating the event, the parameter and their each mutually relations. It includes the dependence rules of process parameter and the dependence rules of random event and so on.

H is the identifiers of ESD hierarchy. Marking each condition of the function subsystem, the equipment, the module, the part and the element in the complex system in various levels of ESD model, establishes the corresponding relations between the system element and the ESD event, thus forms the ESD pyramid model. Therefore reflects in directly the part condition of system in each level from the ESD model.

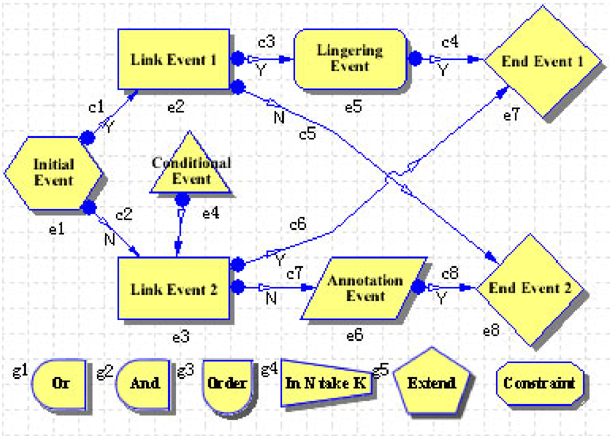

Fig. 1 Graph expression of ESD model

The ESD model may use the oriented graph expression with the graph theory [9], the graph expression which is built by the modeling and analysis software based on ESD shown in Fig.1. According to the principles of the ESD analysis method in the fig, initial event only can have one in the ESD model, various events by the oriented linking expressed the time order of event occurs. Because the fig is limited in the paper, simplify the model and only list the partial graph element is produced the partial improved set of ESD logical gate, for example the g1 is defined as OR gate, the g2 is defined as AND gate, the g3 is defined as ordinal gate, g4 is defined as the "in N take K" gate, g5 is defined as the extended gate.

2.2 Mathematical Formulation of Graph Element

Fig.1 is 7-tupleΣ of graphic expression. Where

$E = \{e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8\}$ //Event 1-8

$C = \{c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8\}$ //Condition 1-8

$G = \{g_1, g_2, g_3, g_4, g_5\}$ // Logical gate 1-5

$P = \{t_n, p_m\}$ //Definition variable by the software operation, and saves the record to the backstage database.

CB //Definition the event or the process parameter set of intervals, the condition set by the software operation, and saves the record to the backstage database.

DR //According to the linked relations of the graphic event in the backstage database of graph, saves the connection rule among the record of the event, the expression is "IF THEN ENDIF". For example "if the event e_5 occur, the probability of part fault is changed from λ_1 to λ_2".

$H = \{1\}$ //The current graph only have one level, the level of graph is 1 tacitly.

The graph expression of ESD model produces the visualization diagram of event ordinal model, other concrete data and the connection rules all save in the database completely, through the visualization property frame of graph element shows and modifies the data. The graph establish the ESD model of object system, has been able to carry on the qualitative analysis; for the quantitative analysis, the mathematics description of graph elements use the probability dynamics theory. It assigns, the process vector $\overline{x}$ in the situation, the probability density of the system being in state i , at time t the probability equation as:

$$\pi(i,\overline{x},t) = \int_{\overline{u}} \pi(i,\overline{u},0)\delta(\overline{x},-\overline{g}_i(t,\overline{u}))d\overline{u}(1-F_i(t,\overline{u}))$$
$$+ \sum_{j\neq i} \int_0^t \int_{\overline{u}} \pi(j,\overline{u},\tau)\, p(j \rightarrow i \mid \overline{u})$$
$$\times \delta(\overline{x}-\overline{g}_i(t-\tau,\overline{u}))(1-F_i(t-\tau,\overline{u}))d\overline{u}d\tau \quad (1)$$

Where $F_i(t,\overline{u})$ is the probability leaving state i before time t in the system, $p(j \rightarrow i \mid \overline{u})$ is in assigns condition vector $\overline{u}$, the transition rate of the system form state j to state i . $\overline{g}_i(t,\overline{x}_0)$ expresses the solution of the i th dynamics process vector of first order differential equations with initial conditions $\overline{x}(0) = \overline{g}_i(0,\overline{x}_0) = \overline{x}_0$, and δ is the direct function. In the formula, the first item represents the probability that the system is initially in state i and stays i till time t while the process reaches $\widetilde{x}$ at time t . The second item represents the situation where the system is in state j to state i at time τ and remains in state i from τ till t . After the ESD frame has been built, equation (1) changes:

$$\pi(i,\overline{x},t) = P_0 + \sum_{j\in z} \int_0^t \int_{\overline{u}} \pi(j,\overline{u},\tau)\, p(j \rightarrow i \mid \overline{u})$$
$$\delta(\overline{x}-\overline{g}_i(t-\tau,\overline{u})) \times (1-F_i(t-\tau,\overline{u}))d\tau d\overline{u} \quad (2)$$

Where,

$$P_0 = \int_{\overline{u}} \pi(i,\overline{u},0)\delta(\overline{x},-\overline{g}_i(t,\overline{u}))d\overline{u}(1-F_i(t,\overline{u}))d\overline{u}$$

is identical to equation (1) in the first item, $z = \{j \mid p(j \rightarrow i) \neq 0\}$. In typically instance, there will be only one state preceding state i , so equation (2) in the first item changes easy. Equation (2) is very important to the mathematical formulation of many components of the ESD frame. Equation (2) describes a transition from a single state to another. For dynamic situation like synchronizations, concurrent processes and competitions in safety modeling and analysis of dynamic system, the transition do not happen between two single states, thus usually happen between multiple states. To the question, these are situations where the system can be split into independent subsystems, which because of their independence can be examined and analysis separately. Thus they reset based on certain rules. It is important to splitting the system that several transitions can occur simultaneously an independently. The ability to deal with concurrent processes is an important extension to ESD method with probabilistic dynamics too [4-8, 11]. Illatively all kinds of graph elements all can present the relevant mathematical formulations.

3. Systematic Structure of ESD Modeling

3.1 Systematic Structure

Through the ESD modeling and the analysis, find from the initial event to each kinds of result which causes possibly, carries on the representing of accident process and the qualitative/quantitative processing. The ESD visualization modeling system can be divided into following five modules. The whole systematic structure in Fig.2:

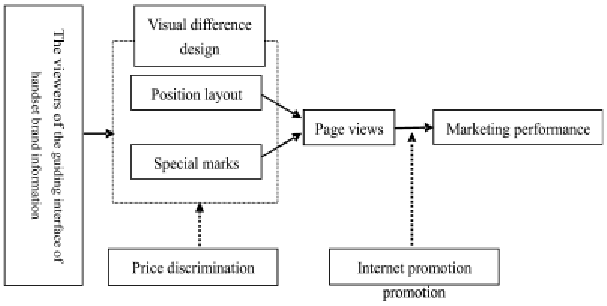

Fig. 2 Structure of ESD modeling system

1) Design of graph element base in ESD modeling: According to the characters of ESD modeling, designed the graph element template based on which has used in specially the ESD modeling. Including the basic general events, the logical gates and so on, moreover according to the need of different project model, can design the special graph element according to the situation independently.
2) Graph modeling based on ESD: Use the graph element base of modeling, choose the corresponding the graph element of modeling, according to actual system model diagram or functional block diagram plan system ESD model diagram. When each cartography operation of added events, deleted events, connected events order etc, its graph element information of corresponding operation read in the database, and the preserved final graph and the data of various graph element form the ESD model.
3) Maintenance of the data property: According to the property information of various graph elements in the graph element based on modeling, show the maintenance frame of graph element property. Mainly include two parts,

which the property data of each modeling graph element and the data of quantitative analysis. Its property frame can show and modify the own unique information data of choosing graph element in the database.
4) Analysis engine of the ESD model: Transfer analysis counting subroutine, produce the result of analysis. Its algorithm is improved on according to the method of the event tree.
5) The analysis result show: The data of analysis result stores to the database, after pass through the transformation to form the display of table form data, click on the single event in the form, will form the display of graph.

3.2 Hierarchy of ESD Model

Toward the simple system, each kind of state in the system parts can define ESD event, this establishes the corresponding relations between the ESD event and the state of system part. However toward the large-scale complex dynamic system, want to realize this kind of corresponding mapping is difficult extremely. On the one hand the accurate definition of the dynamic system as well as the state of part is very difficult; on the other hand it can greatly cause the scale of ESD model to control difficulty. Therefore there is a definition of level structure marking in the 7-tupleΣ, the utilization has followed the level principle of the complex dynamic system in constitution, the method of hierarchy solve the modeling of large-scale complex system. The hierarchy of system model in Fig.3.

Taking the function subsystem as the smallest unit, each state of each function subsystem is defined as the ESD event, thus establishing the corresponding relations between the ESD event and the state of function subsystem. Through this way, it may establish the ESD model of function subsystem in the dynamic complex system thus directly reflects the state of function subsystem through the ESD model and direct accurately produces the hidden danger of function subsystem in the system design. After the established ESD model of the function subsystem, if also have to further study some function subsystem, may take this function subsystem as the object of research, each state of equipment in this function subsystem define as the ESD event, thus establishes the corresponding relations between the ESD event and the state of equipment. Through this way, may take the state of each equipment in this function subsystem as well as the state of other related function subsystems as the basic ESD event, certain state of this function subsystem above this level of ESD model takes as the final state, establishes the ESD model of the equipment class function subsystem. Through the ESD model of the equipment class, can reflect directly the state of equipment in this function subsystem, and direct accurately produce the hidden danger of function subsystem in the system design. Similarly, but also may obtain each level ESD model of the stand-alone class, the parts class, the equipment class as well as the element class and so on about the same dynamic complex system, thus finally establishes corresponding relations of the system part and the ESD event, reflects the state of system part from the ESD model directly.

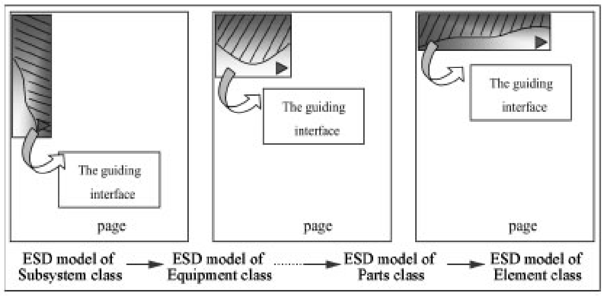

Fig. 3 Hierarchy of ESD model

3.3 Database Structure of ESD Model

The ESD framework is established in a unified foundation of data logical organization [10]. Establishing model with the method of object-oriented visualization should be consistent with the object-oriented database system, therefore the logic relation analyses between the system model and the relational database, establish some fundamental catalogues, and produce some table of the data structure, in Table 1-2.

Using the data maintenance window and the text frame of property, user's input data is saved to the corresponding data item in the database, after the transfer function which will be auto-transferred the data in the database as the input form the ESD request, satisfied the translation request by the analysis subroutine. Speak of the users, only need to choose certain graph element, pop up the property data window of the graph element, according to the content of text frame inputted or modified the corresponding data.

Table 1: Listing of part tables in database

Table abbreviation	*Brief introduction of table*
ESD-ESD	ESD description table
ESD-Data	Related datasheet of event, gate etc
ESD-Datatemp	Temporary datasheet of event, gate etc
ESD-ESDSeq	Event sequence table of ESD
ESD-Temp	Interim table of calculated probability

Pla-Event	Relational event table
Pla-EventProbType	Probability type table of event

Table 2: Data structure of ESD-data

Field name	***Data type***	***Brief introduction***
ID	Auto no.	
PrjID	int	Project id
EsdID	int	ESD model id
TaskID	int	Task node id
EsdName	text	ESD model name
EsdDate	date/time	ESD model date
EsdVersion	int	Version number
Remark	text	ESD model remark
Esdnodeid	int	Node id
Esdparentid	int	Father node id
Esdnodelevel	int	Hierarchy
ISeof	yes/no	Result or not
Nodetype	int	Node type
Eventid	long	Event id
Happentype	yes/no	Relation(yes/no)
Eventprobtype	long	Probability of type
Eventprob	double	Probability of event

4. Analytical Algorithm of ESD Model

Due to the most of logical gates can be transformed the combination of the AND gate and the OR gate, therefore the model may be simplified to the oriented graph of $\deg(x) \le 2$. To certain initial event, if there are N kind of limit events, each kind of event takes the state which YES (Y) or NO (N), then the number of event sequence is 2^N which this initial event result in the accident, but acts according to the character of depend on each other, many sequences cannot appear or have not any significance, the number of such event sequence is greatly smaller than 2^N. Therefore the algorithm of depth first search in the graph theory and the disjoint of graph model combined to obtain the algorithm of improved ESD and realize the quantificational processing of ESD on the computer. The event reliability probability algorithm of ESD model as follows:

First establish the ESD model, and inspect regularity. Suppose that start to search the initial event which the marking is 1, take k as its serial number, v for the event which inspects, w is the event which will be processed, $N(i)$ for gives the marking of the i th node, its the level marking.

Step1 $v := 1$, $k := 1$, $N(1) := 1$, $H := 1$

Step2 With recursion method, reduce branch [11] and depth first search, seek the related events which have not been examined and their relations, search all ways from the initial event to the final event.

1) Take the first examined event which relate with v, supposes for $\{v, w\}$, arrive the event w after the relations, the direction of stipulation relations $\{v, w\}$ is from v to w. Go to Step3.

2) If there isn't such event relation, namely the event relation with the event v all had examined, go to Step4.

Step3 1) If the event w has not been visited, namely $N(w)$ still was not the determination, make $v := w$, $K := k+1$, $N(w) := k$, go to Step2.

2) If the event w already has been visited, namely $N(w) \ne 0$, return to the event v, go to Step2.

Step4 Determine all way L from the initial event to the final event. The way of a certain final event is l, its probability formula show as follows:

$$R = \sum_{j=1}^{l} (R_1 \prod_{i=2}^{n_j} P_i) \quad , n_j \ge i \ge 2, n_j \in Z, i \in Z$$

Where $P_i = \begin{cases} R_i \ , \ success\ of\ event \\ 1 - R_i \ , \ failure\ of\ event \end{cases}$

5. Application and Illustrating

In the NASA projects, safety system of propellant distribution in the spacecraft is very important. There are two independent and redundant sets of thrusters in the spacecraft. The propellant distribution system associated with one set of thrusters. The relevant portions are a hydrazine tank, two propellant distribution lines leading to thrusters, a normally-open isolation valve in each line, a pressure sensor in each line, and control circuitry capable of actuating the isolation valves based on pressure sensed in the distribution lines. When the attitude-control system signals for thruster operation, the controller opens the solenoid valves to allow hydrazine to flow. Part of the design intent of this system is that in the event of a leak in the distribution lines, the leak should be detected by the pressure sensors (the leak should cause a pressure reduction) and thereafter should be isolated by closure of both isolation valves. The scenarios analyzed in this system are those leading to loss of vehicle or loss of scientific data as a result of a hydrazine leak. They are also the final events in ESD model after the hydrazine leak probability of 1.0E-2 happen. Use safety modeling and analysis method of dynamic system based on event sequence diagram, simplify and build the ESD model of hydrazine leak shown in Fig.4.

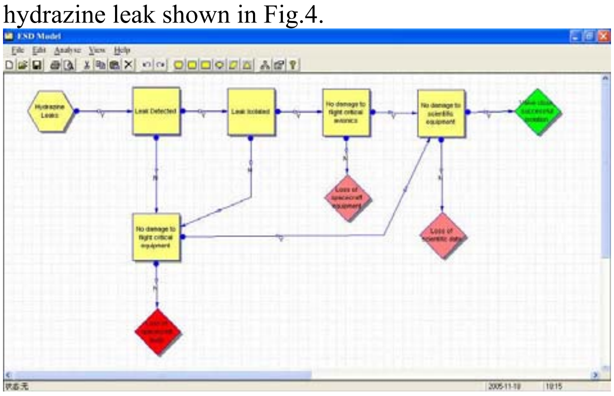

Fig. 4 ESD for the hydrazine leak

Analyzing and calculating with above arithmetic, worked out each state's probability of the final event in this ESD model shown in Table 3. Accordingly may reflect directly the probability of final event as well as the hidden danger of process state in the system, offer other analysis work the info-gist. The conclusion from the table of analytical result: After the initial event of "Hydrazine leak" happen, the successful probability of "Valve close after successful isolation" is 99.989%, the probability of "Loss of scientific data" is 0.00099%, the probability of "Loss of spacecraft equipment" is 0.0099%, the probability of "Loss of spacecraft body" is less. Using the analysis of DFTA, the associated frequencies of all kinds of scenarios leading to "Loss of Vehicle" is 1.02E-4, viz. the successful probability of "successful isolation" is 99.9898%. It is obvious that the expanded ESD is a valid method.

Table 3: Analytical result of final events

The state of final events	***Probability***
Valve close, successful isolation	.999890001
Loss of scientific data	9.99899999995449E-06
Loss of spacecraft equipment	9.9980000999989E-05
Loss of spacecraft body	1.99989999999956E-08

The other example is the safety analysis of driver distance motoring with tiredness shown in Fig. 5. There are one initial event "Driver distance motoring with tiredness", seven link events of "No peccancy actions of driver", "Good state of Road surface", "Good state of Weather", " Good state of Vehicle", " Good state of illumination", " Failure of Vehicle safeguard", one conditional event "Traffic flowing heavy", five end events of "No accident", "Slight accident", "General accident", "Big accident", "Fatal accident" and one "in N take K" gate. Their correlation is shown in Fig.5 too.

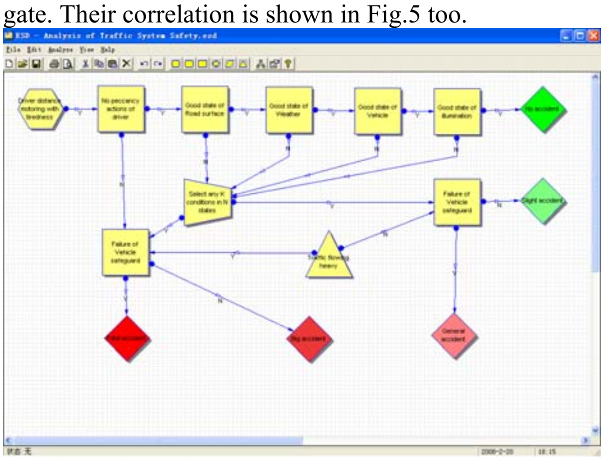

Fig. 5 ESD for the driver distance motoring with tiredness

The initial event probability of 1.0E-1 happen, other data of traffic accidents happened on 107 Chinese national road marked 1741 km are adopted to prove this method [11-13]. We analyzed and calculated with above ESD model and arithmetic, the five final event probabilities shown in Table 4.

Table 4: Analytical result of final events

The state of final events	***Probability***
No accident	.897999000
Slight accident	4.30992100992065E-02
General accident	2.89998999456990E-02
Big accident	1.99989900000998E-02
Fatal accident	9.99118999549947E-03

6. Conclusions

The safety analysis of dynamic system is a complex work extremely. Traditional analysis methods (for example FTA/ETA etc) are mostly the analysis methods based on the static logic or the static fault mechanism [14, 15], which are helpless to the fault-tolerant system with the dynamic random fault, the repair system with the redundancy (or cold, hot backup), the system with the storehouse of public resources, as well as the system of safety analysis with the ordinal pertinence. Based on the research and analysis of domestic and foreign dynamic systems safety modeling and analysis in recent years, this paper proposes one kind of improved ESD method theoretically. Not only the definition of ESD has been given, but also the dynamic logical diagram formulation and its mathematics description for the ESD framework are produced. The foundations have been built for the work of qualitative and quantitative analysis, dynamic probability risk assessment and so on in the dynamic system. In the project application, this paper presented the expansion of the dynamic logical graph element and the hierarchy strategy to enhance the modeling ability of ESD and the correlative ability of system structure, designed a new algorithm of ESD, at last gave a set of modeling and analysis software based on ESD in order to solve a probabilistic safety risk problem in the dynamic systems. The results of two application examples have show the feasibility and effectiveness of the extended ESD model and algorithm.

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