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BAYESIAN-NETWORK-BASED HYDRO-POWER FAULT DIAGNOSIS SYSTEM DEVELOPMENT BY FAULT TREE TRANSFORMATION

Chaur-Gong Jong
Department of Construction Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, R.O.C.Water Resources Agency, Ministry of Economic Affairs, Taichung City,Taiwan, R.O.C, wra.jhong@gmail.com

Sou-Sen Leu
Department of Construction Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, R.O.C.

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BAYESIAN-NETWORK-BASED HYDRO-POWER FAULT DIAGNOSIS SYSTEM DEVELOPMENT BY FAULT TREE TRANSFORMATION

Chaur-Gong Jong[1, 2] and Sou-Sen Leu[1]

Key words: fault tree, Bayesian Network, system reliability, Weibull distribution.

ABSTRACT

Currently, fault diagnosis of reservoir facilities relies mostly on check-list evaluation. The results and qualities of evaluation are limited by experience and ability of the evaluators, which may not achieve the goal of systematic assessment in a consistent manner. To overcome the limitation of the traditional approach, this research develops a fault diagnosis and evaluation system for reservoir facility by utilizing multi-state Fault-Tree Analysis (FTA) technique, in conjunction with Bayesian Networks (BN) which incorporate expert experiences through lateral linkages among BN nodes and weighting factors. The system has been used to analyze and verify against three hydro-power systems currently in operation. It was found that through BN analysis the fault trend is consistent to that from historical data analysis via Weibull distribution. This indicates that the transformation of a multi-state Fault-Tree (FT) and BN is reasonable and practical. Based upon the analysis of BN by inputting prior information of the hydro-power systems, the probabilities of fault occurrences are effectively computed based on which proper preventive maintenance strategies can be established.

I. INTRODUCTION

All reservoir facilities become aged over time which result in degradation of total performance [27]. Due to limited suitable sites for new reservoirs in Taiwan, high quality maintenance of existing reservoir facilities, such as spillways, outlet structures and power generation systems, becomes one of the main concerns in the reservoir management. Recently, periodic inspection and maintenance are carried out to maintain the facilities in normal operation. However, the goal of fault prevention and economic maintenance costs cannot be effectively achieved by the simple periodic maintenance and inspection through check-list evaluation. To achieve the goal of the preventive maintenance, an effective fault diagnosis system is required. In recent years, fault diagnosis receives a lot of attention and emphasis for the maintenance and the safety evaluation of reservoir facilities [27].

Currently, faults diagnosis methods of reservoir facilities include three types: qualitative analysis, semi-quantitative analysis, and quantitative analysis. Due to the complexity, uncertainty and variability of the hydro-power system, limited maintenance data are collected for quantitative analysis. Qualitative analysis only provides rough maintenance status and cannot support the sound maintenance plan. Therefore, several hybrid approaches are developed for the fault diagnosis that combine limited objective data and experts' experiences. Some popular hybrid approaches are Event-Tree Analysis (ETA), Fault-Tree Analysis (FTA) and Bayesian Networks (BN).

FTA is a common diagnostic tool used to assess the reliability of a system. However, FTA has some limitations in modeling, such as lack of lateral links and limited definition of event states and logic gates. To overcome the limitations of FTA, BN has been proposed and widely applied for uncertainty analysis. However, the establishment of BN for practical applications could be quite difficult and tedious, especially for complicated ones. This study combines the advantage of FTA and BN to propose a more effective BN development process by transforming a multi-state FT into a BN framework. The process was then used to build a hydro-power plant fault diagnosis system. Model validation and sensitivity analysis are performed to further assess the applicability of the diagnosis system.

II. LITERATURE REVIEW

Hydro-power systems in Taiwan utilize the operation, maintenance and surveillance manuals as the basis for maintenance and inspection. In practice, a periodic interval (i.e., week, month, season, or year) is selected for the inspection

Paper submitted 11/10/11; accepted 05/08/12. Author for correspondence: Chaur-Gong Jong (e-mail: wra.jhong@gmail.com).
[1] *Department of Construction Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, R.O.C.*
[2] *Water Resources Agency, Ministry of Economic Affairs, Taichung City, Taiwan, R.O.C.*

and the regular maintenance, based on the system types, component characteristics and operational environments [25]. Since facilities are only regularly maintained or replaced, the desire of early fault prevention cannot be achieved without prior diagnosis of the faulty states and fragile conditions. That may lead to unnecessary waste of manpower and resources in maintenance.

Since 1990, risk and fault diagnosis evaluation have been included in dam safety assessment and hydro-power system management programs around the world. US Federal Energy Regulatory Commission (FERC) implemented Potential-Failure-Mode Analysis by adopting core-group discussion to conduct qualitative evaluation [9]. Failure Mode Effects and Criticality Analysis (FMECA), a semi-quantitative analysis, is also widely applied in fault diagnosis. Furthermore, several quantitative probability analysis models were developed for risk and fault diagnosis, such as statistical deduction, reliability analysis and model simulation. For statistical deduction, common techniques used are the relative frequency method and BN [14]. Reliability analysis makes use of probability density function (PDF) to deduce the requirement and the probability for the system to stay within safety margin. Monitoring data over the years are used to determine parameters for the model. Nevertheless, limited maintenance data can be collected during the life cycle of the dam facilities. The life time of the dam facilities is generally much longer than that of electronic facilities and rarely maintenance data are collected for the fault diagnosis. Because of that, some semi-quantitative analysis methods were proposed for the system diagnosis, such as FTA [7, 15, 20, 22].

FTA assumes an event to be either fault or normal state (i.e., two states). In FTA two logic gates are commonly used to link the events in hierarchy and they are “OR Gate” and “AND Gate”. Due to the limited expression only for two states of the original FTA, multi-state fault-tree quantification technique is proposed to transform FT into BN for fault analysis [13]. The use of BN allows incorporating expert knowledge with Bayesian probability theory for more effective fault diagnosis. The main techniques make use of “OR Gate” and “AND Gate” logic transform into BN to perform probabilistic analysis of event occurrence [2-4, 6, 12, 17, 18]. Most of the transformation methods convert both event nodes and logic gates in FT into corresponding physical nodes in BN. However, logic gates are used to describe the relationship between events in sequence. It is meaningless to convert the logic gates into physical BN nodes. Moreover, under the multi-state situation, it is difficult to define its conditional probability by using FTA [1, 8, 11, 24].

In this research, a more reasonable transformation process from FT to BN is proposed and investigated. A systematic BN-based reservoir facility fault diagnostic system was then developed for a more objective diagnosis and evaluation. Three hydro-power systems currently in operation were used to analyze and verify the applicability of the BN-based fault diagnostic system.

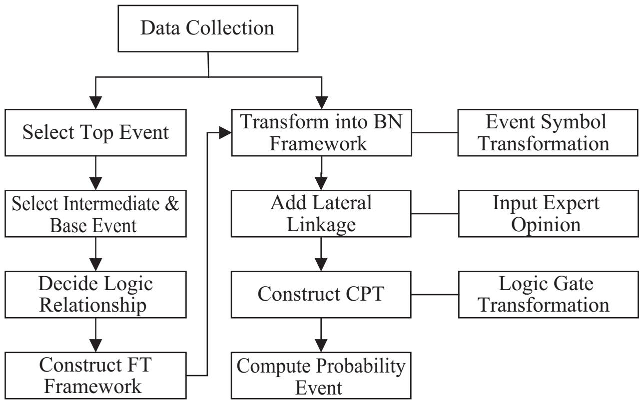

Fig. 1. Flow Chart for Transformation from FT to BN.

III. RESEARCH APPROACH AND PROCESS

The construction of BN could be quite complicated and its network structure is problem specific. It is more advantageous to construct BN hierarchy by following the concept of FTA and then transforming basic FT into BN framework. Finally, lateral links among BN nodes and conditional probability table (CPT) were introduced to incorporate experts’ experiences. Fig. 1 depicts the proposed transformation process. In the following, FTA, BN and the transformation processes are explained in detail.

1. Fault Tree Analysis (FTA)

FTA is graphical deduction method by selecting an event which a system does not wish to occur as the top event and from top-down searches for intermediate events till the very bottom events. FTA generally uses “OR Gate” and “AND Gate” logic to link basic events, intermediate events and top event in an inverted tree diagram called FT diagram. Through a logic tracing of the developed tree diagram, FTA qualitatively or quantitatively analyzes defect and weaknesses of a system. It is a common analytical tool for system and mechanical reliability and for safety and fault diagnosis [7, 15, 20, 22]. With the popular application of FTA software packages, FTA has been widely applied to fault analysis and risk evaluation of large systems. However, Generally FTA defines only two states (either fault or normal) in the events, and two logic gates (OR Gate and AND Gate) to link the events in a hierarchy. It is not powerful to handle the situation of complicated multi-state systems. FTA is more applicable to a system analysis problem in which fault mechanism and logic relationship are clearly defined. For complex and uncertain systems, probabilistic network approach should be a better choice.

2. Bayesian Network (BN)

BN combines probability theory with graphic theory and is consisted of tree major parts: node, connecting arrow and CPT. It is a directed acyclic graph (DAG) and can display interrelated variables in a network by means of their cause and effect

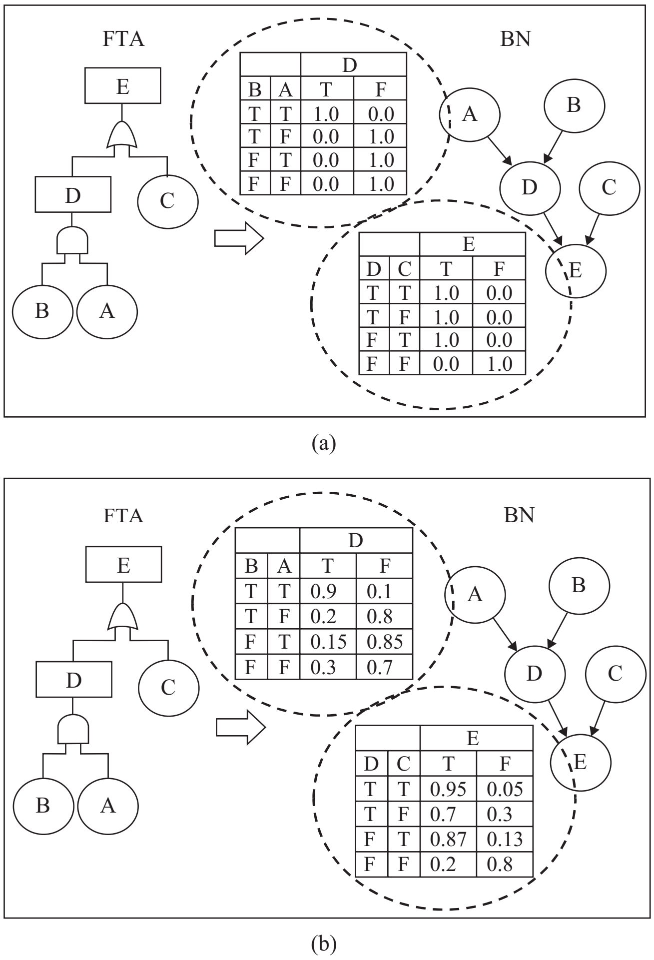

Fig. 2. Conventional Transformation Process from FT to BN: (a) Condition with Certainty, and (b) Condition with Uncertainty.

relationships. The technique can make qualitative and quantitative deduction for uncertain outcomes by inferring the conditional probabilities in BN. BN has a higher efficiency and accuracy in uncertain inference, especially for complicated systems with highly correlated elements [2, 17, 18, 21]. In recent years, BN has been widely applied in various fields, such as medical diagnosis, industrial design, financial investment, ecology, etc.

However, it is generally difficult to establish mutual relationship among nodes in the network by directly incorporating the views of experts. Therefore, several transformation processes from FT to BN have been proposed [2-4, 6, 12, 17, 18]. In general, the transformation of logic gates in FT into BN is also one-to-one; i.e., logic gates in FT are converted into corresponding physical nodes in BN (shown in Fig. 2). However, there are differences in meanings of an event node in BN and a logic gate in FT. An event node is used to represent a variable in the problem domain, whereas a logic gate is to describe the logical relationship between the nodes. For the transformation between FT and BN, the event nodes and the logic gates should be treated differently. In the transformation process of logic gates, CPT in BN, which corresponds to logic gate, should be analyzed under two states or multi-state by probability value.

3. Transformation from FT to BN

The proposed transformation process consists of two main steps: 1) structure transformation from FT to BN; and 2) CPT determination (see Fig. 1). Each step is explained in detail in the following:

- Structure transformation from FT to BN
  Some researchers proposed previously were used as a foundation for the proposed method of transformation to BN structure [4, 8, 10, 17, 18, 21]. Top event, intermediate events, and basic events are directly mapped into the nodes in BN. The arrows among BN nodes follow the definition of event relationships in FT. Furthermore, some meaningful auxiliary arrows can be inserted into fundamental BN based upon the opinions of experts. In summary, the transformation process of BN structure from FT is described below (see Fig. 1):

  1. All FT events are transformed into BN base nodes. Repeated events in FT are represented only by a BN base node.
  2. The probability of occurrence of basic event in FT can be directly applied as the prior probability of a BN base node.
  3. The arrows among BN nodes follow the definition of event relationships in FT.
  4. If there are some meaningful relationships among basic BN nodes that are not well defined in FT, arcs and arrows should be inserted into basic BN to indicate the mutual influences among the nodes. Those arcs can be defined by experts based on the problem scope.

- CPT Determination
  In a BN framework, if a node has several parent nodes, or if each parent node and child node has several states, the CPT structure will become complicated. In addition, the values of CPT are generally defined by experts based on their experience, the probability values could be inconsistent especially under the condition of complicated CPT stated above. In this study the software, AgenaRisk, was used to eliminate the above-mentioned difficulties (Agena 2008). Through parameters defined in the software, coupled with weighting factors filled by experts among nodes, one can calculate probability values in CPT rapidly.

When AgenaRisk is used to define CPT, the definition of the expression function in the software is a key step. As stated above, there are two main logic gates in FT: “AND” and “OR”. In the selection of the expression function items, minimum is selected if the corresponding logic gate in FT is “AND”, whereas maximum is selected if the logic gate is “OR”.

Table 1. Background Information of Experts.

Affiliation	Group	Title	Experience (yr.)
Power Production Department, Taipower	Commercial Group	Group Leader	38
Power Production Department, Taipower	Maintenance Group	Supervisor	19
Power Production Department, Taipower	Operation Group	Specialist	6
Shihmen Power Plant, Taipower	Shihmen Plant	Superintendent	29
Shihmen Power Plant, Taipower	Shihmen Plant	Superintendent	29
Shihmen Power Plant, Taipower	Electrical-Mechanical Group	Manger	20
Shihmen Power Plant, Taipower	Mechanical Department	Department Head	38
Shihmen Power Plant, Taipower	Control Department	Department Head	19
Shihmen Power Plant, Taipower	Electrical Department	Department Head	34
Shihmen Power Plant, Taipower	Mechanical Department	Specialist	32

Through deduction, it can be proven that the fault probabilities of top event by FTA and BN are identical. For simplicity, assuming that there are two independent events: A and B, and their top event C, they have two states: A_1 and B_1 belong to normal states, A_2 and B_2 fault states, as well as C_1 normal states, C_2 fault states.

Based on the logic of AND gate, the fault probability can be calculated as

$$P(C_2) = P(A_2 \cap B_2) = P(A_2) \times P(B_2) \tag{1}$$

Based upon the concept of BN, the fault probability can be derived as

$$\begin{aligned} P(C_2) &= C_2A_1B_1 \times A_1 \times B_1 + C_2A_1B_2 \times A_1 \times B_2 \\ &\quad + C_2A_2B_1 \times A_2 \times B_1 + C_2A_2B_2 \times A_2 \times B_2 \\ &= 0 \times A_1 \times B_1 + 0 \times A_1 \times B_2 + 0 \times A_2 \times B_1 \\ &\quad + 1 \times A_2 \times B_2 \\ &= A_2 \times B_2 \end{aligned} \tag{2}$$

Based upon the logic of OR gate, the fault probability can be defined as:

$$\begin{aligned} P(C_2) &= P(A_2 \cup B_2) = P(A_2) + P(B_2) - P(A_2 \cap B_2) \\ &= 1 - [(1 - P(A_2)) \bullet (1 - P(B_2))] = 1 - P(A_1) \bullet P(B_1) \end{aligned} \tag{3}$$

Based upon the concept of BN, the fault probability can be derived as

$$\begin{aligned} P(C_2) &= C_2A_1B_1 \times A_1 \times B_1 + C_2A_1B_2 \times A_1 \times B_2 \\ &\quad + C_2A_2B_1 \times A_2 \times B_1 + C_2A_2B_2 \times A_2 \times B_2 \\ &= 0 \times A_1 \times B_1 + 1 \times A_1 \times B_2 + 1 \times A_2 \times B_1 \\ &\quad + 1 \times A_2 \times B_2 \\ &= A_1 \times B_2 + A_2 \times B_1 + A_2 \times B_2 \\ &= 1 - A_1 \times B_1 \end{aligned} \tag{4}$$

It is seen that the fault probabilities of top event by FTA and BN are identical. Furthermore, in AgenaRisk, the output is identical to the "AND" logic gate in FT if the minimum value of the expression function item is selected. Also, the output is identical to the "OR" logic gate in FT if the maximum value of the expression function item is selected. After the minimum or maximum value has been selected in function types, the weighting factors should then be selected in the software. The weighting factors can be determined through the opinion poll of experts based on the contribution of parent nodes to the subsequent nodes. The score ranges from 1 to 5 in which 1 means that the parent node has the least effect on child node and 5 means the most effect. Based upon the above-mentioned inputs, CPT can be calculated by AgenaRisk.

IV. BN-BASED HYDRO-POWER DIAGNOSIS SYSTEM

Based upon the proposed BN construction process, a BN-based hydro-power diagnosis system was developed. In order to obtain the sound knowledge support, nine experts were invited to construct BN. Their background information is listed in Table 1. The detail of the system development is explained below.

1. Construction of FT Framework

First, a top event indicating the condition that the hydro-power system fails to produce power is defined. Based upon the components of the hydro-power system and their conditions, eight intermediate events in the second level; 27 intermediate events in the third level; and 84 basic events were further defined. Based upon the discussion with the experts (as shown in Table 1) and the examination of past maintenance records, it was found that the occurrences of any intermediate or basic event can disable power production. Therefore "OR Gate" is used as logic linkage among the events. The FT frameworks after careful deliberation with the experts are shown in Figs. 3-6 each of which, respectively, are FT diagrams describing the causes making the system unable to produce power, disabled turbine, malfunction generator, and failed transmission system for delivering power.

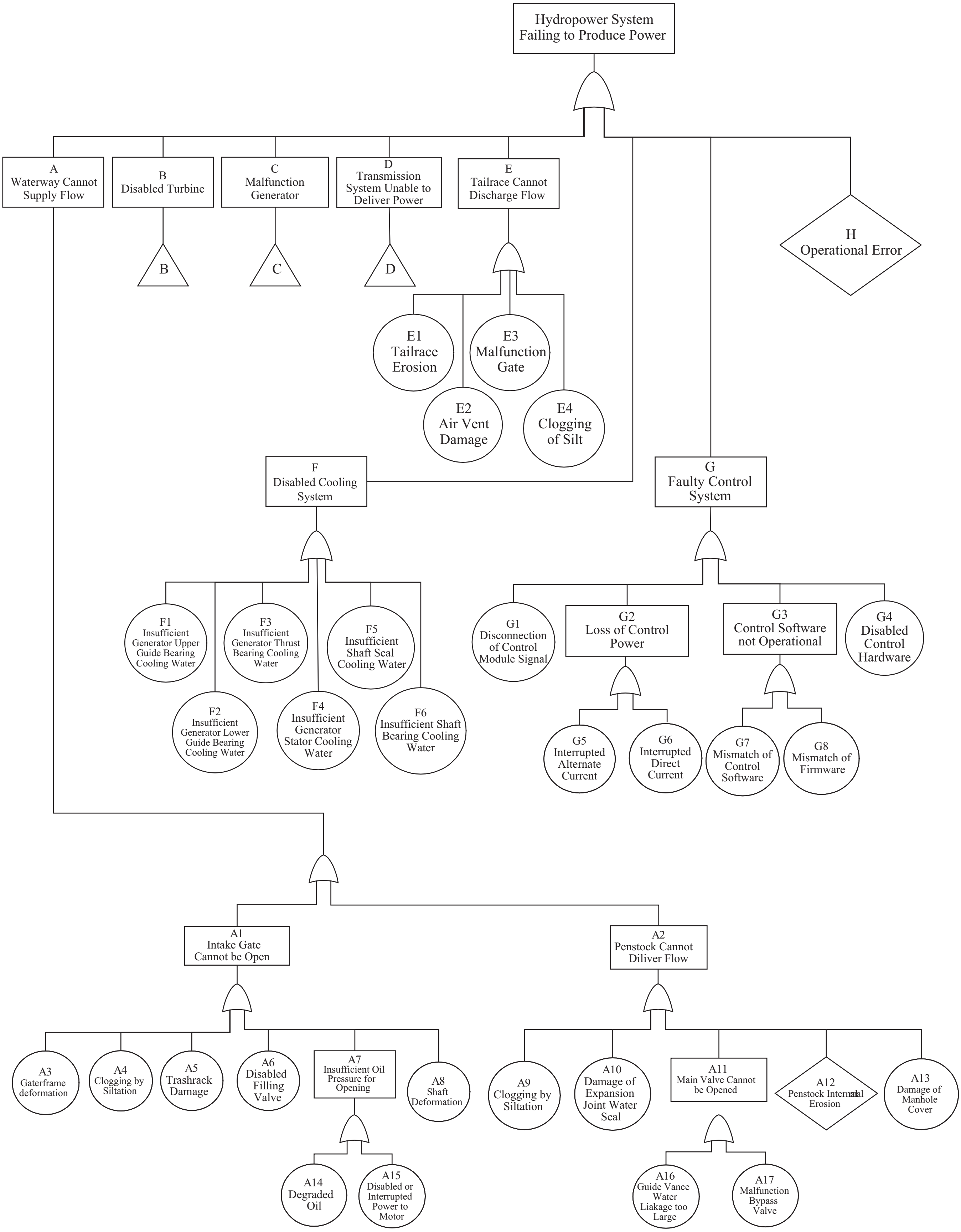

Fig. 3. Fault-Tree Diagram of System Failing to Produce Power.

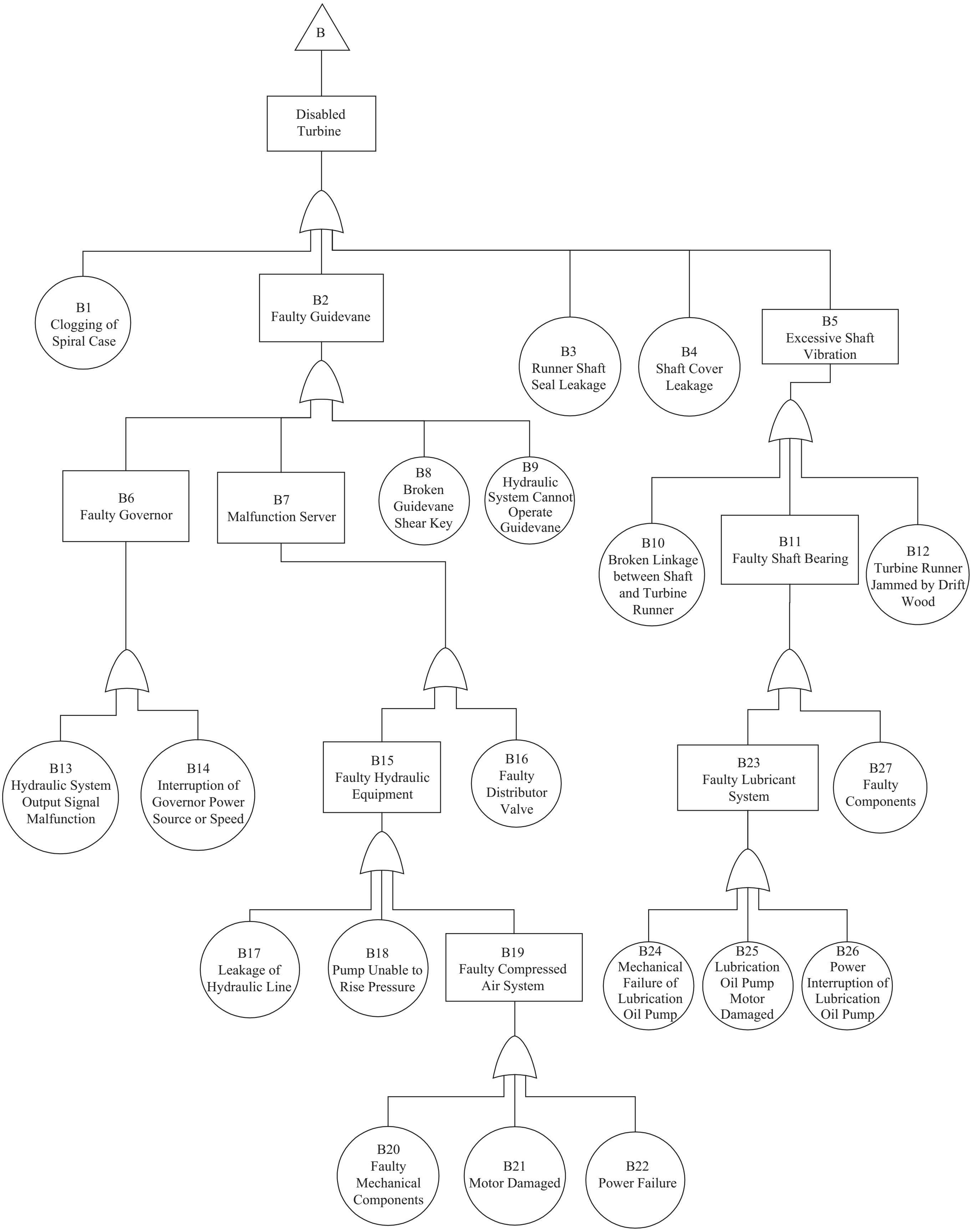

Fig. 4. Fault-Tree Diagram of Disabled Turbine.

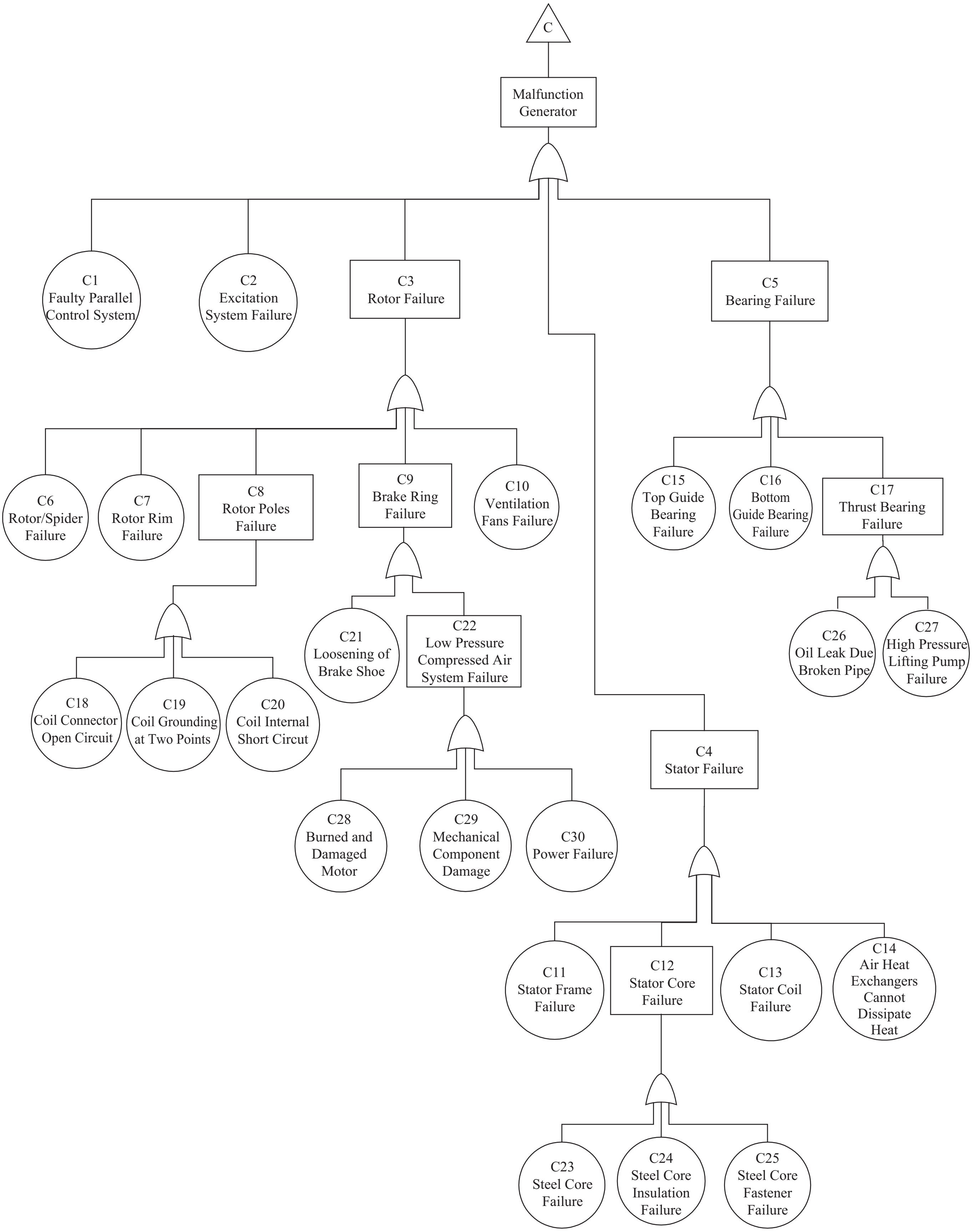

Fig. 5. Fault-Tree Diagram of Malfunction Generator.

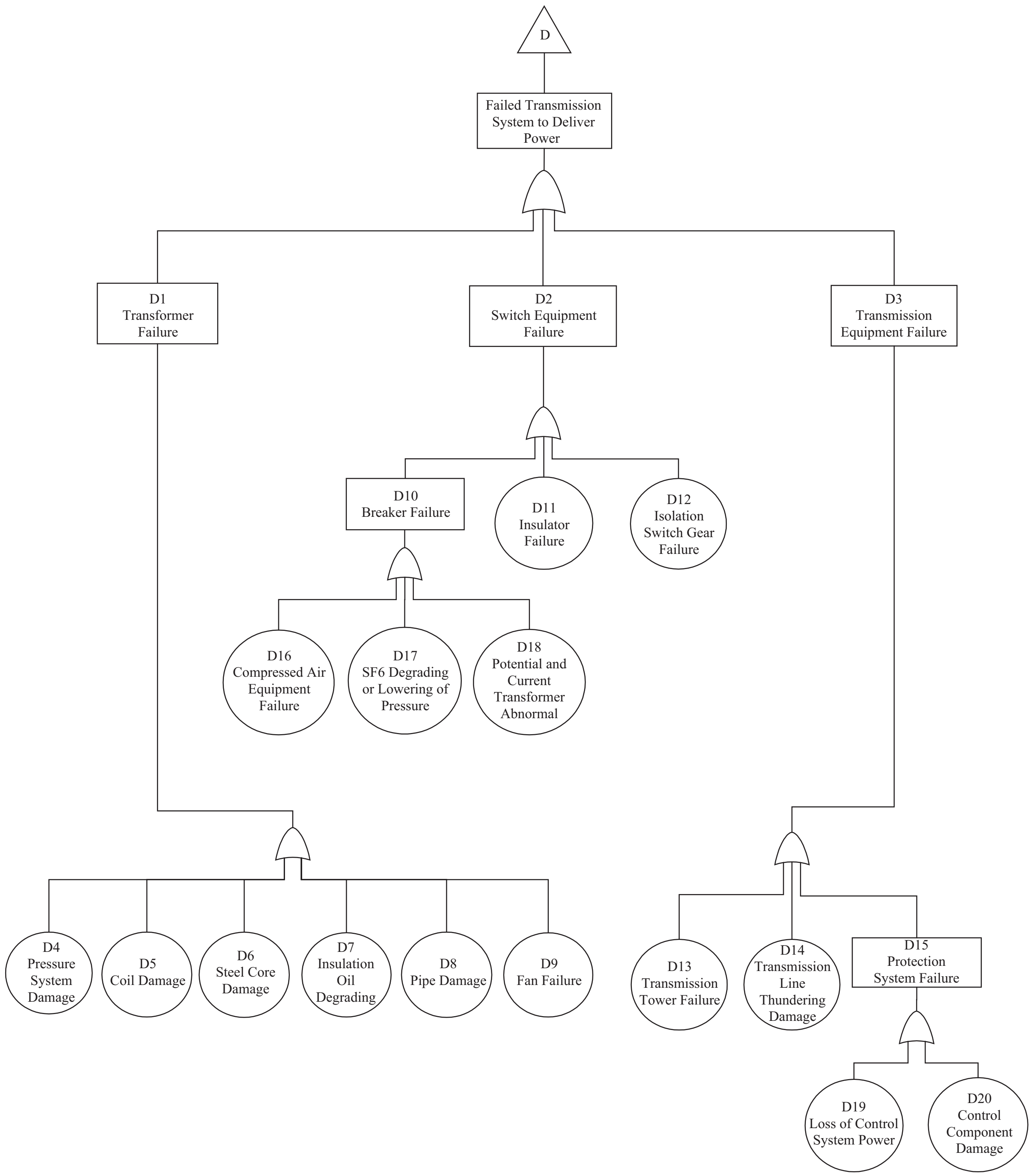

Fig. 6. Fault-Tree Diagram of Failed Transmission System to Deliver Power.

After the completion of FT frameworks, a total of 18-year fault and maintenance data are analyzed statistically for Shihmen units 1 & 2 and Yihsin unit, excluding the period from 2004 to September 2007 during which typhoon had caused severe interruption of the system operation. The total analysis periods are 126,312 and 131,400 hours, respectively. The analysis was performed on an hourly basis for three separate states. The state classifications are made in accor dance with FMEA fault rate occurrence scoring standard ranking 3 (see Table 2). The fault duration of 1/15,000 of the total period of analysis, that is 8 hrs, is used as a state classification interval. Thus, the system has three states: (1) normal

Table 2. Scoring standard for fault frequencies.

Disabled Duration	Disabled Probability	Ranking
Extremely Long: Extremely long disabled duration. Almost daily occurrence	>1 in 2	10
	1 in 3	9
Very Long: Very long disabled duration. From past experience or data, the event caused a long disabled duration	1 in 8	8
	1 in 20	7
Long: Intermediate disabled duration. From past experience or data, disabled duration caused by the event is not very long	1 in 80	6
	1 in 400	5
	1 in 2,000	4
Short: Short disabled duration	1 in 15,000	3
	1 in 150,000	2
Extremely Short: Disabled duration extremely short	1 in 1,500,000	1

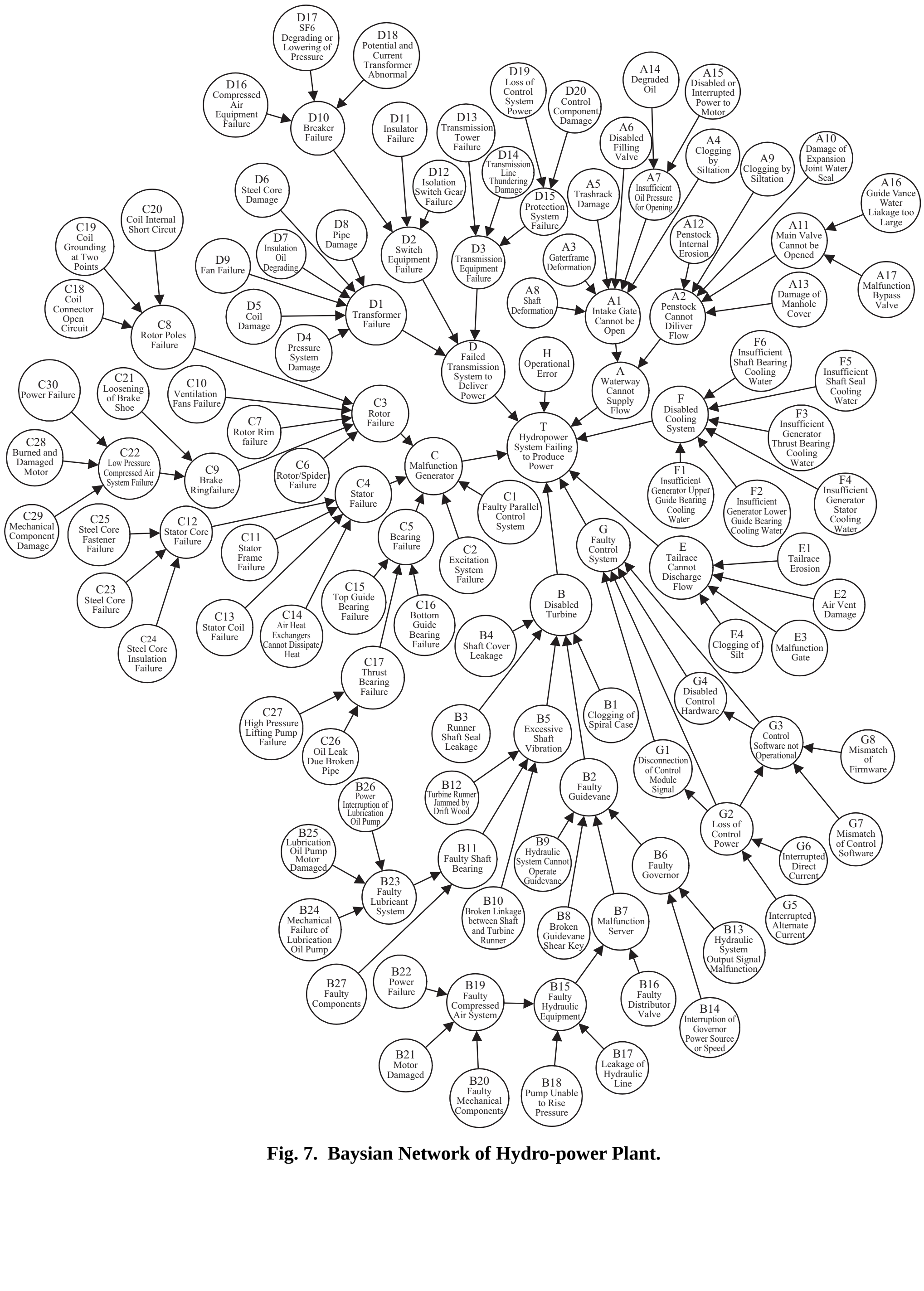

Fig. 7. Baysian Network of Hydro-power Plant.

condition - the state is ″0″; (2) faulty state with duration less than 8 hrs - the state is ″1″; and (3) faulty state with duration longer than 8 hrs - the state is ″2″. Through discussions with a panel of the site experts (as shown in Table 1), it was concluded that the state classification matches the 8 hrs daily work requirement. Based upon the state classification, the fault durations of all basic events over the years were analyzed. The ratios of the fault duration over the total operation duration are used for the prior probabilities of basic events.

2. Construction of BN from FT

Based upon the transformation process described in Section 3, all the FT diagrams were transformed to BN. Overlapping nodes were combined into one. Furthermore, some lateral arcs among the BN nodes were added based upon the experts' experiences. The complete BN framework is shown on Fig. 7 which will be used in the follow-up analysis and in-depth investigation.

3. CPT Development

AgenaRisk was used to calculate CPT based on the constructed BN framework. Since FT logic gates are all "OR Gate", maximum values were selected in the expression function types. The relative weighting factors of parent nodes to their child nodes were discussed and defined in the panel of nine experts. Based upon the above-mentioned input data, the CPTs for all the arcs in the BN were then calculated. Finally, the posterior probabilities of the BN nodes (including both top event and the intermediate events) were inferred along BN. The sum of probabilities in states ″1″ and ″2″ yields the fault probability of the system.

V. MODEL VERIFICATION AND SENSITIVITY ANALYSIS

The results of BN inferences were validated by comparing with the reliability analysis of historical data. The sensitivity analysis was further performed to identify key subsystems and components for system fault diagnosis. The results from the sensitivity analysis may be used as an important reference in future diagnostic analysis and maintenance strategies.

1. Background Data of the Systems

The Shihmen Reservoir, located in Northern Taiwan, is formed by an embankment Dam. Since reservoir filling in May, 1963, it has been in operation for 47 year. It is a multipurpose reservoir for irrigation, power generation, water supply, flood control and recreation. Unit 1 and 2 hydro-power units are located at right bank downstream from the dam. Each installed capacity is 45 MW, with average annual output of about 1.1×10^8 KWH. The Yihsin hydro-power unit is located 12km upstream from the dam and has an installed capacity of 40 MW with an average annual output of 1.80×10^8 KWH. Vertical type Francis turbines are installed for all three units. Thus the flow direction is perpendicular to the axis of rotation. The type of turbine is suitable for head in the range of 30 to 500 m, and is referred to as medium head turbine. The basic features of the three hydro-power units are summarized in Table 3.

Table 3. Key features of three hydro-power plants.

Item \ Plant	Yihsin	Shihmen 1	Shihmen 2
Storage Facility	Regulation Pool Type	Reservoir Type	Reservoir Type
Turbine type	Francis	Francis	Francis
Head	146.8 m	59~109 m	59~109 m
Installed Capacity	40 mw	45 mw	45 mw
Annual Output	1.80×10^8 kwh	1.10×10^8 kwh	1.10×10^8 kwh
Location	12 km upstream from Reservoir	Downstream from Reservoir on Right Bank	Downstream from Reservoir on Right Bank
Main Facilities	Waterway, Turbine, Generator, Transmission and Transformer Facility, Cooling Facility, Control System and Tailrace, etc.		

2. System Reliability Analysis

In this research, actual fault and maintenance records of Shihmen Unit 1 and 2 (1965~2008) and Yihsin Unit (1991~2008) were collected and analyzed. The goodness-of-fit test by Chi-Square test indicates that the historical failure data reveals that time-to-failure of the three turbines fits the Weibull distribution. The Weibull distribution is a commonly used probability distribution in reliability analysis and may be used to model both increasing and decreasing failure rates [7, 8, 10, 12, 13]. The three parameters are: shape parameter β, scale parameter θ (characteristic life) and location parameter τ. If there existed faulty condition at the beginning of the system use, the location parameter can be set to zero [7, 8, 10]. Because faulty conditions had occurred to all three hydro-power units, location parameter is not considered in Weibull distribution.

Based on the available maintenance data, Weibull distribution parameters β and θ were estimated by the least square method and the resulting coefficient of determination (R^2) were greater than 0.9. Table 4 shows the statistic data and the good-of-fit test results. As can be seen that β values for Shihmen Unit 1 and 2 range between 1 and 3 and the corresponding probability density function (PDF) are skewed. For Yihsin unit, β is larger than 3 and its PDF is close to the normal distribution and is symmetrical. Fig. 8 depicts the PDF curves for the time-to-failure of the three turbine units. From Table 4 it is observed that all three systems shape parameter $\beta > 1$ have a trend of increasing failure rate and exhibit wear-out failure period in a form of bathtub curve. Increased inspection, monitoring and maintenance are needed for these three hydro-power units.

Table 4. Chi-Square goodness-of-fit test for weibull distribution and parameter estimation.

Item \ System	Yihsin	Shihmen 1	Shihmen 2	Shihmen 1 & 2
Sample size	33	60	64	124
χ^2 Goodness-of-fit Test on H0: Weibull Distribution				
Equally Spaced Intervals K	7	7	7	8
Length of Interval (hr)	1200	1700	2300	2000
Freedom	4	4	4	5
Critical values @5%	9.5	9.5	9.5	11
Test statistic values	9.31	9.08	7.26	10.69
H_0: Weibull distribution	accepted	accepted	accepted	accepted
Weibull Parameter Estimation				
Regression Line	4.885*x*-41.716	1.637*x*-14.24	2.373*x*-20.535	1.959*x*-16.994
Critical values @5%	9.5	9.5	9.5	11
Test statistic values	9.31	9.08	7.26	10.69
H_0: Weibull distribution	accepted	accepted	accepted	accepted
Weibull Parameter Estimation				
Regression Line	4.885*x*-41.716	1.637*x*-14.24	2.373*x*-20.535	1.959*x*-16.994
β	4.885	1.637	2.373	1.959
θ	5115 hr	5986 hr	5727 hr	5859 hr
R^2	0.943	0.937	0.946	0.944

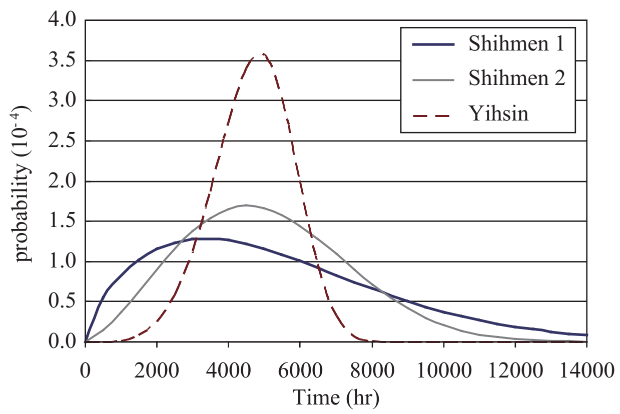

Fig. 8. Probability Density Function Curves for Time-to-Failure of Three Hydro-power Plants.

3. Model Verification

From the results of the reliability function (shown in Table 5) and the posterior probabilities of top event in BN, the results from the developed BN model was verified. Table 6 shows the comparison between the results of BN model and the reliability analysis. It can be observed that the trend of the top event fault probabilities in the BN model is consistent with those obtained from the reliability analysis. Shihmen Unit 1 and 2 and Yihsin unit has the lowest variance based upon reliability and BN analysis. The corresponding time at which 1.17~3.44 percent of the variance will have calculated. This means that three hydro-power units median time to failure, mean time between failure and fault probability of top event will face a same result and fault possibility during its life time after each repair. From the above-mentioned discussion, it can be concluded that the BN-based hydro-power fault diagnosis system can be used as a tool for the fault assessment of hydro-power systems in practice.

4. Sensitivity Analysis

To further look into the key fault events which would affect the occurrence probability of top event, a sensitivity analysis was performed in this study. Table 7 summarizes key events of each hydro-power system based upon their own prior information. Because of their different prior conditions, the key faulty events and components of each hydro-power system are slightly varying. In summary, top five key faulty events are: malfunction generator (C); faulty control system (G); transmission system unable to deliver power (D); disabled turbine (B); and waterway cannot supply flow (A). That the trend of the Key fault events is consistent with those obtained from the BN analysis. Especially malfunction generator (C) is the most important event that can easily trigger the disabled system in power production. In practice, to lower the malfunction probability of the hydro-power system, there is a need to focus on the weakness of these critical subsystems and components to enhance the safe and productivity of power generation. More intensive in-situ on-line monitoring and thorough inspection are suggested to these sensitive components.

Table 5. Weibull reliability functions of three hydro-power systems.

Item \ Plant	Yihsin	Shihmen 1	Shihmen 2	Shihmen 1&2
Cumulative distribution function $F(t)$	$1-e^{-\left(\frac{t}{5115}\right)^{4.885}}$	$1-e^{-\left(\frac{t}{5986}\right)^{1.637}}$	$1-e^{-\left(\frac{t}{5727}\right)^{2.373}}$	$1-e^{-\left(\frac{t}{5859}\right)^{1.959}}$
Failure Rate Function $\lambda(t)$	$\frac{4.885}{5115}\left(\frac{t}{5115}\right)^{3.885}$	$\frac{1.637}{5986}\left(\frac{t}{5986}\right)^{0.637}$	$\frac{2.373}{5727}\left(\frac{t}{5727}\right)^{1.373}$	$\frac{1.959}{5859}\left(\frac{t}{5859}\right)^{0.959}$
Probability density function $f(t)$	$\lambda(t)\cdot e^{-\left(\frac{t}{5115}\right)^{4.885}}$	$\lambda(t)\cdot e^{-\left(\frac{t}{5986}\right)^{1.637}}$	$\lambda(t)\cdot e^{-\left(\frac{t}{5727}\right)^{2.373}}$	$\lambda(t)\cdot e^{-\left(\frac{t}{5859}\right)^{1.959}}$
Mean-time-to-failure (MTTF)	4,692 hrs	5,358 hrs	5,248 hrs	5,308 hrs
Characteristic Life (θ)	5,115 hrs	5,986 hrs	5,727 hrs	5,859 hrs
Median time-to-failure (R = 0.5)	4,745 hrs	4,787 hrs	4,908 hrs	4,859 hrs

Table 6. Comparison of BN and reliability analysis.

Plant \ Method	Weibull-based Reliability Analysis			Fault Probability of Top Event in BN
	Median Time To Failure (R = 0.5)	Mean Time Between Failure from Records After Each Repair	Fault Probability of Top Event from Mean Time Between Failure	
Yihsin	4,745 hrs	3,873 hrs	0.2267	0.1817
Shihmen 1	4,787 hrs	2,463 hrs	0.2084	0.1875
Shihmen 2	4,908 hrs	3,214 hrs	0.2242	0.1870
Average	4,813 hrs	3,183 hrs	0.2198	0.1854
variance	1.17%	–	3.44%	1.34%

Table 7. Summary results of sensitivity analysis.

Rank \ Plant	Yihsin	Shihmen-1	Shihmen-2
1	Malfunction Generator (C)	Malfunction Generator (C)	Malfunction Generator (C)
2	Faulty Control System (G)	Faulty Control System (G)	Faulty Control System (G)
3	Faulty Protection System (D15)	Transmission System Unable to Deliver Power (D)	Transmission System Unable to Deliver Power (D)
4	Transmission System Unable to Deliver Power (D)	Faulty Protection System (D15)	Faulty Protection System (D15)
5	Faulty Transmission Equipment (D3)	Waterway cannot supply flow (A)	Disabled Turbine (B)
6	Waterway cannot supply flow (A)	Disabled Turbine (B)	Waterway cannot supply flow (A)
7	Disabled Turbine (B)	Loss of Control Power (G2)	Loss of Control Power (G2)
8	Loss of Control Power (G2)	Faulty Transmission Equipment (D3)	Faulty Transmission Equipment (D3)
9	Disabled Cooling System (F)	Disabled Cooling System (F)	Penstock cannot Deliver Flow (A2)
10	Penstock cannot Deliver Flow (A2)	Penstock cannot Deliver Flow (A2)	Faulty Exciter System (C2)

VI. CONCLUSIONS AND RECOMMENDATIONS

This paper developed an effective process to build BN-based hydro-power diagnosis system. The diagnosis system starts with the formation of FT based upon the problem domain, followed by. The transform from multi-state FT to BN is performed to obtain basic BN. Furthermore, based upon experts' inputs lateral arcs among nodes are inserted into BN to derive a more sound BN. Finally, a logical transformation approach was developed in the study to convert the logic gates in FT into CPT in BN. The results of BN inferences were validated by a comparison with the reliability analysis based upon historical data of three hydro-power systems in Taiwan. Through the analysis and comparison, it is found that the results of BN analysis are consistent with Weibull distribution-based reliability analysis and sensitivity analysis. This indicates that transformation process from multi-state FT to BN can effectively set up a realistic and accurate diagnosis system.

Although the mechanism of transformation from FT to BN has been well examined, the use of BN, nevertheless, relies on the inputs of expert experiences for the linkages and CPTs. Data provided by different experts will directly affect the accuracy and the assessment quality of BN. Special attention should be paid to expert elicitation in the future study. In addition, BN can be learnt from raw data. If complete and sound maintenance data are available, an objective BN can be established. Finally, there are other important facilities in a reservoir, such as spillway, water intake structure and silt-sluiceway. There is a need to extend the reliability analysis of this type to these systems and make use of BN for faulty diagnosis to enhance the reliability of the entire reservoir system.

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