IJRRS
International Journal of Reliability, Risk Saftey: Theory and Application

DOI : 10.30699/IJRRS.3.1.5

Vol. 3/ Issue 1/ 2020
pp. 45-53

Development of an Efficient Approach for Reliability Analysis Using the Comparative Study of Several Static and Dynamic Methods; Case Study of an Unmanned Aerial Vehicle

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Abstract

Unmanned Aerial Vehicles (UAV) are increasingly being popular in many applications. Their operation requires a high level of safety and reliability to accomplish successful missions. In this study, their reliability is comparatively analyzed by different available approaches to select the efficient method. Firstly, the failure model of the system is developed. Then, three different scenarios are considered to study the effect of redundancies on the reliability of the system. In the first scenario, there is no redundancy, whereas in the second scenario there is one redundant component and in the third scenario, there are three redundant components. Static reliability analysis implemented on the proposed scenarios using methods of Fault Tree Analysis (FTA), Reliability Block Diagram (RBD), Markov Chain (MC), and Bayesian Networks (BN) and the results are obtained. Also, regarding the time dependencies between redundant components, a dynamic-based methodology is developed by applying Dynamic Fault Tree (DFT) analysis. Then, the proposed static and dynamic approaches are applied to a UAV as a case study and the results are discussed. Finally, the characteristics of each methodology and the related conditions are clarified for selecting the efficient reliability analysis approach.

Keywords: UAV, Reliability, Bayesian Networks, Dynamic Fault Tree, Redundancy.

Nomenclature

BN	Bayesian Networks
DFT	Dynamic Fault Tree
FTA	Fault Tree Analysis
MC	Markov Chain
N	Number of variables
n	Time Granularity
RBD	Reliability Block Diagram
SRS	Social Responsiveness Scale
t	Mission Time
UAV	Unmanned Aerial Vehicles
λ	Failure rate
Δ	Length of a Time Interval

Introduction

Nowadays, reliability analysis has become an integral part of system design. System designers rely on commercially available dependability tools in order to assess the reliability of their systems. During recent years, reliability assessments have gained widespread attention in many technological areas such as nuclear, aerospace, and other industries [1-3]. In this work, reliability analysis is done comparatively by Reliability Block Diagram (RBD), Markov Chain (MC), and Bayesian Networks (BN) to select the efficient method. Fault Tree Analysis (FTA) is utilized to demonstrate the behaviours and interactions between system components of a UAV as a case study.

UAV system environments are socio-economic, regulatory, physical in operations, and maintenance. Challenges in hardware, software, and human factors in the environments have interactions that lead to big differences in precise SRS assessment.

However, it is extremely difficult to accurately assess the reliability of a UAV due to some reasons such as the confidentiality and limitation of the data which caused to suppose hypothetical samples to provide comparative analysis.

UAV is typically a complex system that adopts redundancy techniques to ensure higher reliability. To achieve the goal, some assumptions are adopted as follows:

(i) Failure rates are constant,

(ii) Probabilistic distribution is exponential,

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Received: 2020.05.20, Accepted: 2020.10.04

(iii) Subsystems are independent of each other,
(iv) Any subsystem has a state of success or failure, and
(v) All subsystems are initially in success state.

We considered three scenarios with different structures in modelling by enhancement of the redundancy between defined components. Three mentioned methodologies are applied to the proposed scenarios. A UAV is considered as a case study which is assumed to be an unrepairable system to avoid the complexity of the problem. In the modelling procedure, two static and dynamic approaches are employed. In the static analysis, three methods are applied to a case study, however, in the dynamic one, due to the characteristics of the preferred methods, only the BN method is taken into account. In BN modelling, at first, DFT is provided and then mapped into the BN model.

A Review on Previous Studies

In a NASA report, Hanks et al. [4] studied on the reliability of the flight control system of a Boeing, using RBD and MC methods. In this study, the component with the greatest impact on the reliability of the flight control system is identified.

Ackart [5] in his MS thesis implemented Markov Chain modeling for an aircraft. In this research, the system is modeled with MC method for various flight conditions which led to the availability estimation of the system in its mission.

Nanda et al. [6] compared system algebra with other popular approaches such as RBD and FTA on the flight control system of Boeing 777 and Airbus A380 aircraft.

Pourgol-Mohammad et al. [7] developed a Hybrid Fault Tree-Markov Chain (HFT-MC) methodology in the framework of dynamic and hybrid PRA methods as a new generation of probabilistic risk assessment methodologies. This methodology is applied to the simulation of the emergency power system of the Bushehr Nuclear Power Plant with a combined design of two different technologies (Western KWU PWR design and Russian WWER PWR design).

Xing et al. [8] analyzed the phased-mission systems (PMS) that propose a binary decision diagram (BDD) based method for the reliability evaluation of non-repairable binary-state PMS along with common-cause failures and modeling with the FTA method in different scenarios.

Mi et al. [9] investigated a two-axis positioning mechanism for assessment of a multi-state system with common-cause failure by employing graphical representation and uncertainty reasoning of Bayesian Network (BN) method.

Asghari and Pourgol-Mohammad [10] examined the differences between the dynamic and static FTA by modeling a wind turbine as a case study. DFTA model is solved with Monte Carlo simulation. The results were compared and the analysis is provided.

Kang et al. [11] studied a Bayesian Network based probabilistic safety model according to the state relationship between flight control system with multi-state property and its constituting components.

Duan et al. [12] evaluated a data communication system (DCS) using DFT method based on fuzzy set theory for handling uncertainty. They also adopted BN for the inference of reliability results. Moreover, some reliability parameters are calculated by mapping DFT into an equivalent BN.

Garoarsdottir [13] did a reliability analysis of RB-211 jet engine using RBD method.

Okafor et al. [14] studied a UAV flight control system using Markov analysis to determine system failures. In this paper, the UAV is modeled in Markov states for the availability calculation of the system.

This paper aims to evaluate the efficiency of reliability analysis approaches for UAVs and other emerging technologies with a critical mission. In this work, the reliability is comparatively analyzed by utilizing RBD, MC, and BN to select the efficient method. FTA is also included in the analysis to demonstrate the behaviors and interaction between system components. Finally, a typical UAV is used as a case study.

Static Analysis Approach

Reliability Block Diagram (RBD), Markov Chain (MC), and Bayesian Networks (BN) models are implemented on a case study to calculate the reliability rate in three scenarios which are explained in the following sections.

RBDs are frequently used to model the effect of the failure items on system performance. It often corresponds to the physical arrangement of items in the system. However, in certain cases, it may be different. In implementation of the RBD approach, the Blocks in software is utilized as well [1].

The system reliability, R_s (t) is obtained for independent blocks in series configuration from equation 1. For parallel configuration, it is obtained from equation 2 [1]:

$$R_s(t) = \prod_{i=1}^{N} R_i(t) \quad (1)$$

$$R_s(t) = 1 - \prod_{i=1}^{N} \left[1 - R_i(t)\right] \quad (2)$$

Markov chain is a type of effective Markovian method to evaluate the availability of a system with multiple states. They have been extensively used for the dependability analysis of systems. The main limitation of this approach is the state space explosion problem [1]. In the MC process, after modeling the system and solving the differential equations for any state, MATLAB software is employed to evaluate and compute the availability of the considered case.

For any state differential equation, equation (5) is developed and solved by using the Laplace transformation as well as determining its respective inverse Laplace transformation [1].

$$\Pr_i(t) = \Pr(\text{system is in state i at time t}), \sum_{i=1}^{N} \Pr_i(t) = 1 \quad (3)$$

$$\rho_{ij} = \text{transition rate from state i to state j}, \quad (4)$$

(i, j = 1, 2,..., N)

$$\frac{d\Pr_i(t)}{dt} = -\Pr_i(t)\left(\sum_j \rho_{ij}\right) + \left(\sum_j \rho_{ji} \Pr_j(t)\right) \quad (5)$$

A Bayesian network is a directed acyclic graph (DAG) comprised of nodes and arcs. Nodes represent random variables (RV) and directed arcs between pairs of nodes are present dependencies between the RVs. Nodes without parent nodes are called root nodes and possess a prior probability distribution table. All other nodes are intermediate nodes possessing a conditional probability table (CPT). Nodes without children nodes are also called leaf nodes. A Network uniquely defines a joint probability distribution for all the RVs of the graph [15]. In the BN approach, GeNIe and BayesiaLab software is utilized for system modeling and numerical analysis. GeNIe has a straightforward structure showing the graphical connection between nodes and the probability of system success. However, BayesiaLab is popular in modeling and assessing the reliability of systems due to characteristics such as defining joint probability distribution for all random variables and updating the probability distributions of all nodes. Also obtaining conditional probability and Total Probability Law that the main process in BN is Bayesian theory.

The joint probability distribution of a set of variables shown as $\{X_1, X_2, ..., X_N\}$ is defined as [16,17]:

$$\Pr(X) = \Pr(x_1, x_2, ..., x_N) = \prod_{i=1}^{N} \Pr\left(x_i \,\middle|\, Parents(x_i)\right) \quad (6)$$

The Bayesian formula is represented with the following equation [1]:

$$\Pr(H|D) = \frac{\Pr(D|H)\Pr(H)}{\int \Pr(D,H)\,dH} \quad (7)$$

Then, conditional probability and total probability law are respectively introduced with equations (8) and (9):

$$\Pr(H|D) = \frac{\Pr(D,H)}{\Pr(D)} \quad (8)$$

$$\Pr(H) = \int_y \Pr(H|D)\Pr(D)\,dD = \sum_{i=1}^{N} \Pr(H|D_i)\Pr(D_i) \quad (9)$$

For C-SPARE gate, equation (10) is used, where Δ=t/n, t is the mission time, and n is the time granularity and Δ is length of a time interval [18].

Pr {B failing in y | A failing in x} = (10)

$$= \frac{\int_{(x-1)\Delta}^{x\Delta} \int_{(y-1)\Delta}^{y\Delta} \lambda e^{-\lambda(b-a)} \lambda e^{-\lambda a}\, da\, db}{\int_{(x-1)\Delta}^{x\Delta} \lambda e^{-\lambda a}\, da}$$

$$= \frac{\lambda\Delta \int_{(y-1)\Delta}^{y\Delta} \lambda e^{-\lambda b}\, db}{\int_{(x-1)\Delta}^{x\Delta} \lambda e^{-\lambda a}\, da} = \lambda\Delta e^{\lambda x\Delta} e^{-\lambda y\Delta}$$

For W-SPARE gate, equations (11) and (12) are used [18].

$$\Pr_1(t) = \Pr(A=1 \mid S=0) = \frac{\Pr(S=0, A=1)}{\Pr(S=0)} = 1 - e^{-\lambda_A \alpha t} \quad (11)$$

$$\Pr_2(t) = \Pr(A=1 \mid S=1) = \frac{\Pr(S=1, A=1)}{\Pr(S=1)}$$

$$= \frac{\Pr(<P, A^S>)(t) + \Pr(<A, S>)(t)}{F_S(t)} \quad (12)$$

$\Pr_1(t)$ and $\Pr_2(t)$ are the failure probabilities in nodes of success and failure states.

P(< P, AS >)(t) and P(< A,S >)(t) are sequence probabilities calculated by equation (13):

$$\Pr(<\Pr, A^S>)(t) + \Pr(<A, S>)(t) =$$

$$= 1 - e^{-\lambda t} + \frac{e^{-(\lambda+\alpha\lambda)t} - e^{-\lambda t}}{\alpha} \quad (13)$$

The First Scenario

In the framework of this scenario, it is supposed that the components of the system are arranged in a series configuration. It means that the failure of any block leads to the failure of the, RBD is developed based on the failure mode of each item. This scenario shows that the simplest type of components is placed in any system. While it has low cost, no assurance in mission success is seen.

As mentioned earlier, we applied RBD, MC and BN approaches on this case study.

The research has some assumptions as follows:

- Probabilistic distributions are of exponential type and the failure rate is constant.
- The components are independent of each other.
- Each component has two states (success and failure) and at a specified time, the system cannot be in more than one state and condition.
- In the initial state, all components are in success and active mode.
- The components are non-repairable.

In this paper, generic data is adopted from standard databases, namely, Mil-HDBK-217F, OREDA, and Typical Equipment MTBF Value System Reliability

Center to numerical evaluating. Table 1 shows the definitions of UAV's components and the related failure rates.

Table 1. Subsystems and Failure Rates of Unmanned Aerial Vehicle

Subsystem	Failure Rate λ
FUEL SYSTEM (F)	$13.6 \times 10^{-6}\ h^{-1}$
ENGINE (E)	$1 \times 10^{-6}\ h^{-1}$
PROPPELER (P)	$167 \times 10^{-6}\ h^{-1}$
GENERATORE (G)	$0.669 \times 10^{-6}\ h^{-1}$
COMMUNICATION RECIEVER (R)	$16.7 \times 10^{-6}\ h^{-1}$
FLIGHT CONTROL COMPUTER (FC)	$25 \times 10^{-6}\ h^{-1}$
HYDRAULIC SYSTEM (H)	$20 \times 10^{-6}\ h^{-1}$
ACTUATOR (A)	$0.19 \times 10^{-6}\ h^{-1}$

The mission time for supposed UAV is 60 flight hours for a week. It means that an approximate value of 3000 flight hours occurs in a year leading to the mission time of 3000 hours.

Figure 1 shows the modeling of UAV with RBD method.

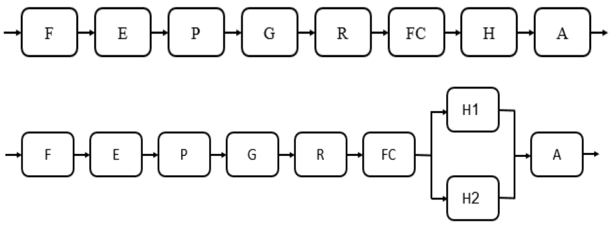
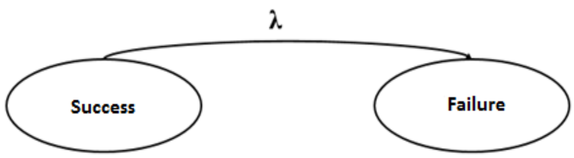


Fig.1. RBD Model for UAV in the First Scenario

In this model, by considering the failure rate for each component and mission time, the reliability of UAV can be calculated.

Figure 2 shows the modeling of UAV with Markov Chain method.



$$\lambda = \lambda_F, \lambda_E, \lambda_P, \lambda_G, \lambda_R, \lambda_{FC}, \lambda_H, \lambda_A$$

Fig.2. MC Model for UAV in the First Scenario

The Utilization of MC modeling for this configuration shows that the UAV has only one successful state. It means the reliability of UAV equals the probability of success of the state. This is achieved when only all modules work in a proper manner.

Figure 3 shows the modeling of UAV with Bayesian networks method.

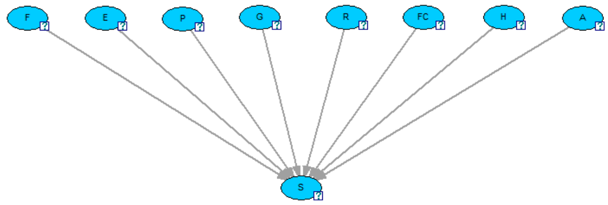


Fig.3. BN Model for UAV in the First Scenario

In Figure 3, we can see the graphical model with root and leaf nodes as well as their arcs defining their dependability in the system.

The Second Scenario

In this scenario, the former configuration is examined with one redundant component in the hydraulic subsystem. It is commonly known that the redundancies in these aerial systems have limitations due to the cost and weight characteristics. However, to achieve an adequate rate of safety and reliability of system missions, redundant subsystems should be set in some critical of them.

Since static analysis is done, the redundant component is active simultaneously in sync with the main member in a parallel manner. If a module fails, then the other one can keep the system in an active state.

Figure 4 shows the modeling of UAV with the RBD method. As shown in the figure, all subsystems are in series configuration except the hydraulic one.

In this model, by employing the failure rate of each component, and the mission time, the reliability of UAV can be calculated. It is substantial that the main and redundant modules are the same and have the same failure rates.

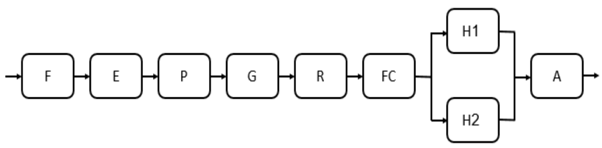
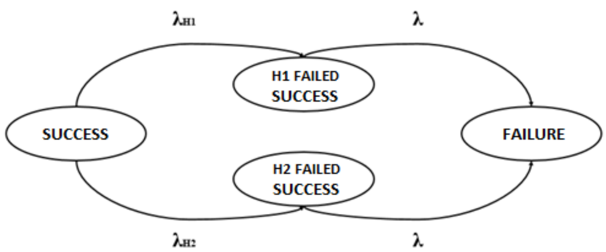


Fig.4. RBD Model for UAV in Second Scenario

Figure 5 shows the modeling of UAV with Markov Chain approach.



$$\lambda = \lambda_F, \lambda_E, \lambda_P, \lambda_G, \lambda_R, \lambda_{FC}, \lambda_{H1}, \lambda_{H2}, \lambda_A$$

Fig.5. MC Model for UAV in the Second Scenario

As mentioned above, it is seen that a redundant module in one of the components has three success states for the case study.

Figure 6 shows the modeling of the UAV with Bayesian Networks method.

The Third Scenario

At this stage, the number of redundancies is increased in some critical components of the UAV to reach a high reliability in their mission. Redundancy is applied for hydraulic (H), receiver (R) and flight control computer (FC) modules due to their significance in proper functioning of the mission. Because of the importance of the communication during flight of the UAV, two redundant modules are considered for this component.

Figure 7 shows the modeling of UAV with RBD method.

Figure 7 shows a system in series-parallel configuration. By using the relevant functions, we can compute the reliability of the UAV.

Figure 8 shows the modeling of UAV with Markov Chain approach.

In this model, 63 success states are present. In other words, the reliability of the UAV is much higher than the previous scenarios. Figure 8 represents the complexity of the system modeling. Also, to estimate the value of reliability rate, it is required to calculate the probability of success of all 63 states by summation.

Figure 9 shows the modeling of the UAV with Bayesian Networks method.

All previous modeling is related to the static analysis. In this approach, there is no time dependency in functions of UAV components. In the following section, the dynamic approach is analyzed for the considered UAV.

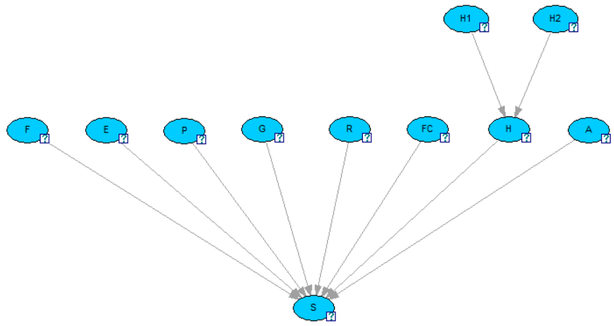


Fig.6. BN Model for UAV in the Second Scenario

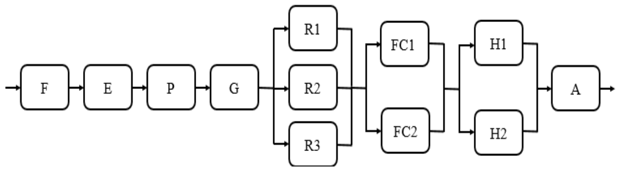
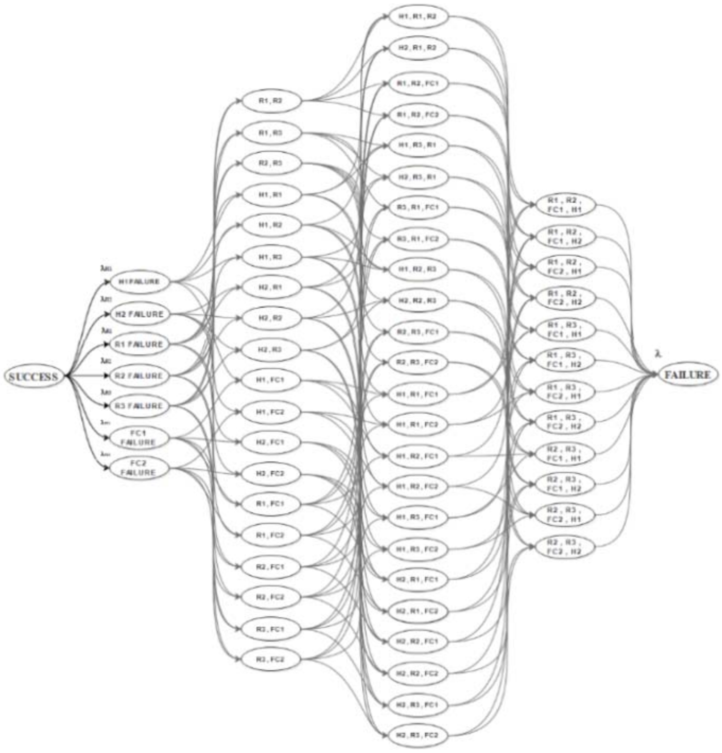


Fig.7. RBD Model for UAV in the Third Scenario



$\lambda = \lambda_F, \lambda_E, \lambda_P, \lambda_G, \lambda_{R1}, \lambda_{R2}, \lambda_{R3}, \lambda_{FC1}, \lambda_{FC2}, \lambda_{H1}, \lambda_{H2}, \lambda_A$

Fig.8. MC Model for UAV in the Third Scenario

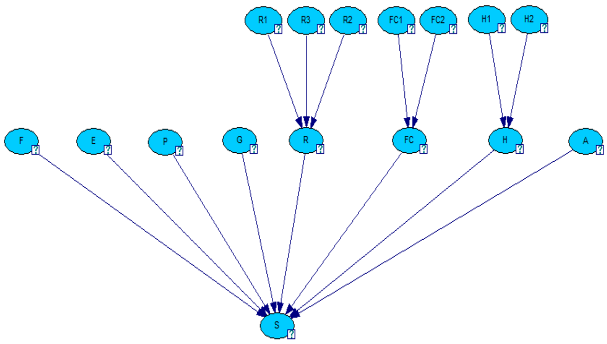


Fig.9. BN Model for UAV in the Third Scenario

Dynamic Analysis Approach

Static analysis is usually done in a faster way than the dynamic one, yet it has lower accuracy. Dynamic analysis is related to the time dependency between components of a system and it aims to find errors in a program during its implementation. Typically, in dynamic systems, the reliability is less than the real rate due to the complexity of behaviors, interactions, and time dependencies. Therefore, these systems should be analyzed with dynamic approaches. Since the RBD and MC methods have some defects in the modeling of dynamic systems such as the expression of dependencies and the order of the function of the components, not only the combination of the failed components matters but also the order in which those components fail is of high importance. In this study, only the BN method is applied to the three scenarios.

For modeling dynamic systems, DFT approach is more popular among researchers and analyzers due to graphical representation of various combinations of basic failures leading to the occurrence of the undesirable top event. DFT extends traditional FT by defining additional gates called dynamic gates to model complex interactions. After modeling the system, it is required to do numerical analysis for reliability calculations. As a result, the DFT is mapped to an equivalent BN method. Also, in constructing DFT, the basic event is the failure of the overall system [18,19].

The First scenario

Figure 10 shows the Fault Tree (FT) of the system for the first scenario. As mentioned earlier, in this scenario, there is no time for dependent redundant.

Hence, the analysis of this configuration is classified under static analysis. Now is feasible to model the system with the BN model.

Figure 11 shows the translated FT model to the BN graphical model.

Figure 11indicates that the model is similar to the first scenario in static analysis, which is due to the absence of redundancy in components. Thus, the system is considered as a static system.

The Second Scenario

In this scenario, due to the presence of redundant module, a dynamic gate is used in FT. By considering the function of the redundant component for hydraulic subsystem, the C-SPARE gate is used in DFT. The DFT for this type of UAV is modeled in figure 12.

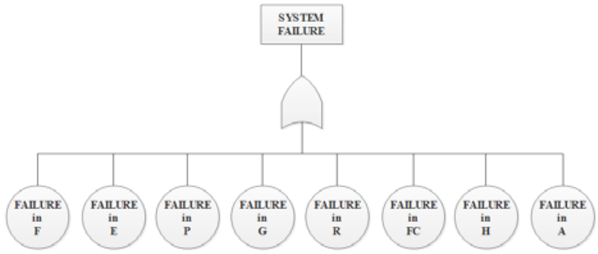


Fig.10. FT Model for UAV in the First Scenario

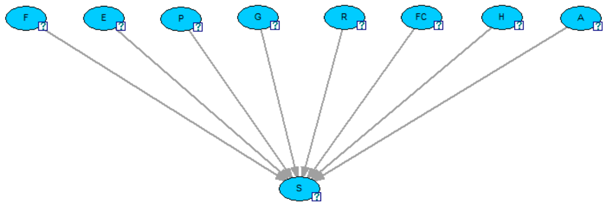


Fig.11. Equivalent BN Model for FT Model in the First Scenario

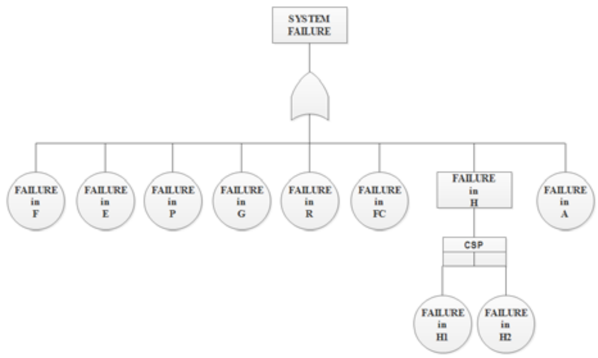


Fig.12. DFT Model for UAV in the Second Scenario

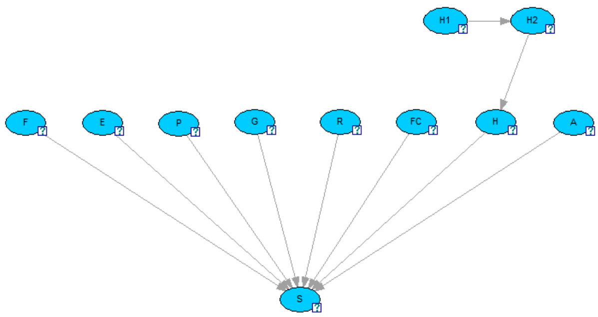


Fig. 13. shows the translated DFT model to the BN graphical model.

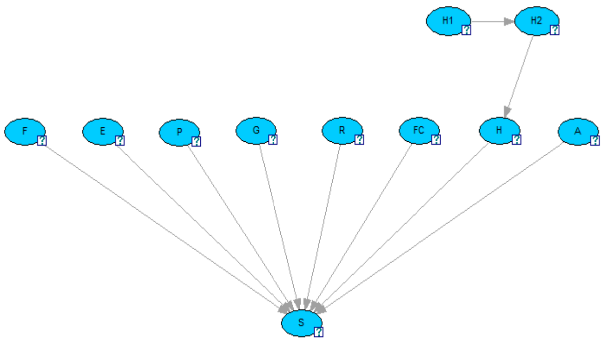


Fig.13. Equivalent BN Model for DFT Model in the Second Scenario

The Third Scenario

In this scenario, DFT is more complicated because of the increasing number of redundant components. Figure 14 represents that the UAV has two redundancies in receivers with C-SPARE gate as a hydraulic system that has one redundant with C-SPARE gate and flight control computer has one redundant with W-SPARE gate due to the urgent need for the member to be ready to work during the failure of the main member. W-SPARE gate has dormancy factor of α=0.5.

Then, the translated DFT model to the BN graphical one is provided in figure 15.

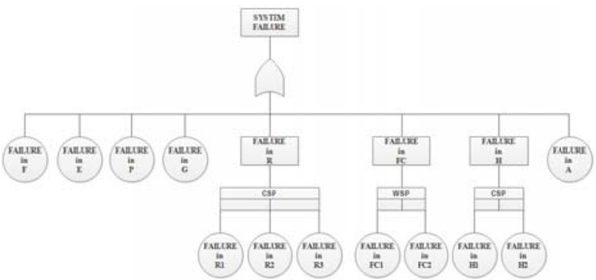


Fig. 14.DFT Model for UAV in the Third Scenario

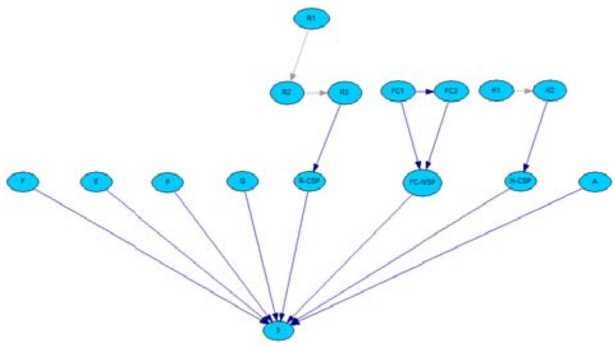


Fig.15. Equivalent BN Model for DFT Model in the Third Scenario

Results and Discussion

After modeling and analysis of the static and dynamic approaches, their results are examined for the considered UAV.

Static Analysis

The resulted values from reliability analysis of the system using the static approach is depicted in table 2.

Table 2. Numerical Results of Static Approach

Title	RBD (Blocksim)	MC (MATLAB)	BN (GeNIe & BayesiaLab)
1st scenario	0.4807	0.4807	0.4807
2nd scenario	0.5087	0.5087	0.5087
3rd scenario	0.5734	0.5734	0.5034

Figure 16 shows the comparative chart for the obtained results of this approach. It is seen that the results of the three models are equal for all scenarios. As the redundant components in the UAV increases, the rate of reliability is raised.

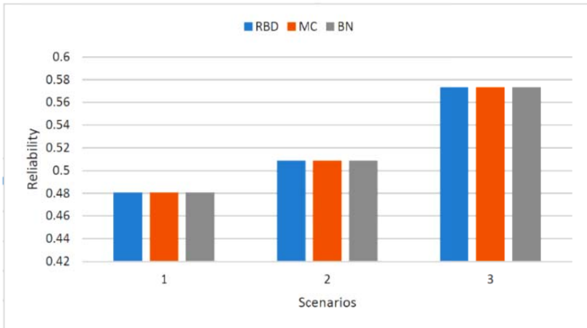


Fig.16. Relative Reliability Comparison Diagram of Static Analysis

Dynamic Analysis

In this approach, as mentioned earlier in the first scenario, we don't have dynamic analysis. Hence, the results of the second and third scenarios are illustrated in table 3.

Table 3. Numerical Results of Dynamic Approach

Title	BAYESIAN NETWORKS	
	BayesiaLab	GeNIe
2nd scenario	0.5104	0.5104
3rd scenario	0.5104	0.5104

Figure 17 shows the comparative chart for the obtained results of this approach.

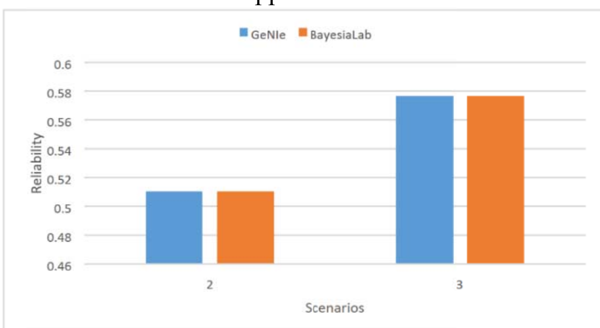


Fig.17. Relative Reliability Comparison Diagram of Dynamic Analysis

By examining the results, it is seen that the time dependency between the considered components and the rate of reliability has increased. Numerical analysis of two programs leads to the same results, but GeNIe is the simplest software. It is capable of calculating the probability of defining modes. As mentioned above, regarding the BN method four main characteristics were pointed out which is not available in this program. Therefore, to overcome this weakness, the analysis is done in BayesiaLab software. It has good features in displaying the capabilities of the BN method. It can also represent the evidential reasoning, predictive reasoning, and diagnostic reasoning.

Recently, BayesiaLab software is used in BN modeling for complex and multi-state systems.

Figure 18 shows us that the rate of reliability of UAV in a static approach with no redundancy in subsystems is less than the dynamic approach with supposed redundant components.

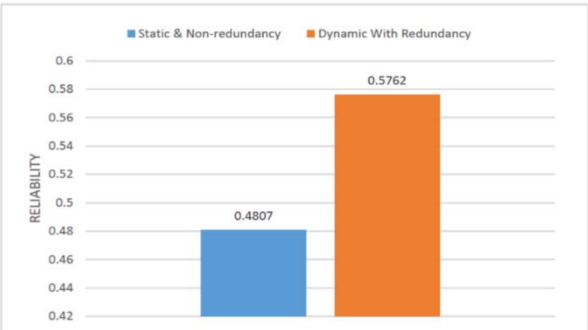


Fig.18. The Effect of Redundancy and Dynamic Analysis on Reliability of the System

Conclusion

The main achievement of this research is the comparative evaluation of three well known approaches in modeling and analyzing system reliability. A case study is also considered in this work. As discussed in previous sections, it is possible to study the reliability of a UAV with two approaches, namely, statically and dynamically. By applying those methods, it is seen that the dynamic approach has high reliability than the static one. Besides, it is commonly known that the UAVs are highly complicated systems, and as the complexity of the system increases, the modeling and analysis become more complicated. By comparing the referred methods, it is concluded that the appropriate and efficient method in reliability evaluations of these systems is Bayesian Networks. With more complexity of systems, it is required to decrease the faults in modeling and analysis by programmable methods. BN approach is supported by some programs, but BayesiaLab software is very powerful in this regard. Finally, the characteristics of methodologies and the related conditions convince us that the choice of the BN method leads to the most efficient reliability analysis approach in this study.

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