Reliability analysis of $k$-out-of-$n$ Phased-Mission systems with Phase-AND requirement

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Abstract. In this paper, the reliability of a non-repairable phased-mission system (PMS) with $k$-out-of-$n$ structure and phase-AND requirements is modeled and analyzed, where the required number of working components $k$ and available components $n$ may vary in different phases. The phase-AND requirement implies that the mission fails only when it fails in all the phases. In other words, the success in any one phase would lead to the successful execution of the entire mission. A new multi-valued decision diagram (MDD)-based method is suggested for reliability analysis of the considered PMS. Different from the existing methods that generate the PMS reliability model phase by phase, the proposed MDD method encompasses a fast model generation procedure that considers behaviors of all the mission phases together. The proposed MDD-based method is combinatorial and thus applicable to any types of component time-to-failure distributions. The application and advantage of the proposed method are demonstrated using an example.

1. Introduction

Phased-mission systems (PMSs) are systems, which perform their missions in multiple consecutive and non-overlapped phases [1]. Many systems in real-world applications such as cluster computing [2, 3], wireless sensor networks [4, 5], and aerospace [6, 7] are PMSs.

Since PMSs are often required to complete different tasks under different environmental conditions during different phases, the system configuration, success criteria and component failure behavior may vary from phase to phase. Such dynamics have brought great challenges to reliability analysis of PMSs. In addition, for a particular component in non-repairable PMSs, the state at the beginning of a new phase has to be the same as its state at the end of the previous phase, such statistical dependencies across phases also has to be considered, which further complicates the PMS analysis [1].

There have been considerable research works expending on the reliability analysis of PMSs. These techniques can be classified into two categories: simulation methods [7] and analytical modeling methods [8-12]. Simulation methods can often offer great generality and flexibility in modeling system and component behaviors. However, they can only provide approximate reliability results, which may not be sufficient or suitable for mission-critical systems [1]. Comparing with simulation methods, analytical modeling methods can provide accurate results (given sufficient computing resources are available). There are three types of analytical modeling methods: combinatorial
methods [8-10], state-space-oriented methods [11-13], integrated methods [6], and recursive methods [14, 15]. As one combinatorial method, the multi-valued decision diagram (MDD)-based methods [10, 16, 17] have been proved to offer lower computational complexity than other analytical modeling methods.

This paper extends the MDD-based method for efficient reliability analysis of dynamic k-out-of-n PMSs with the phase-AND requirement, where the entire PMS succeeds if the mission succeeds in any phase. In each phase, the number of available components n and the required number of working components k may vary from phase to phase. In [14, 15, 18], recursive methods and MDD-based methods were proposed for reliability analysis of k-out-of-n PMSs, but these methods are only applicable to systems with s-identical components or a fixed number of available components (i.e., fixed n). Besides, these methods are limited to the phase-OR requirement, that is, the PMS fails if the mission fails in any phase. In this work, we extend MDDs for reliability analysis of dynamic k-out-of-n PMSs with the phase-AND requirement and dynamic k and n in different phases. The suggested method encompasses a new and fast MDD generation method, enabling analyzing large-scale k-out-of-n PMSs.

The remainder of the paper is organized as follows. Section 2 describes the system studied in this paper. Section 3 proposes the new MDD-based method for reliability analysis of dynamic k-out-of-n PMSs with the phase-AND requirement. Section 4 studies the reliability of a 2-phase PMS applying the proposed method. Section 5 gives conclusions and future work.

2. System description
Consider a PMS with the phase-AND requirement and M phases. The structure of each phase is k-out-of-n. The values of k and n are not necessarily the same in different phases. Let the number of available components be n_i and the required number of working components be k_i for phase i. The structure of phase i is k_i-out-of-n_i, denoted by k_i/n_i in this paper. Let X_i be the set of components that affect the system function in phase i and X be the set of all available components, then X = ∪_{i=1}^{M} X_i, |X_i| = n_i, and |X| = N. Note that X includes X_i, meaning that components belonging to X do not necessarily exist in X_i. The states of components that are not in X_i have no contributions to mission status in phase i. The mission in phase i succeeds when at least k_i components in set X_i do not fail in phase i and the entire mission succeeds when the mission succeeds in any of the M phases.

3. MDD-based analysis method
The proposed MDD-based analysis method involves three main tasks, which are described in detail below.

3.1. MDD modelling for Components
In the proposed MDD method, each system component is modelled by a node, which is labelled by a multi-valued variable. In particular, component C_x in the PMS with M phases is modelled by a multi-valued variable x with (M + 1) different values 0, 1, ..., M. Each value corresponds to a different state of the component. Specifically, a value of 0 indicates that the component does not fail during all M phases; a value of j (1 ≤ j ≤ M) indicates that the component does not fail before phase j, and the first failure occurs in phase j.

As shown in figure 1, node x is a non-sink node with (M + 1) output edges and each of the edges corresponds to one of the (M + 1) different values. The two constant values ‘1’ and ‘0’ indicate that the component is in or not in a specific state, respectively. In figure 1, only the value of edge j is constant ‘1’, which means that the component is in state j, that is, component x fails for the first time at phase j.
3.2. MDD generation method for PMS with phase-AND requirement

The MDD generation method is proposed as the following 6-step procedure.

Step 1: assign a different index to each input component variable, and then set the node/component with the smallest index as the root node of the MDD model to be built. Then label this root node using \((k_1/n_1, k_2/n_2, \ldots, k_6/n_6)\), where \(k_i\) is the required number of operating components in phase \(i\), and \(n_i\) is the number of components in set \(X_i\).

Note that different indexing/ordering of component variables lead to different MDD models for the same system. The reliability analysis based on these MDD models however provides the same result [19].

Step 2: according to the label of its parent node, add a label in the form of \((v_1/w_1, v_2/w_2, \ldots, v_n/w_n)\) for each unlabeled non-sink node, where \(v_i\) denotes the required number of operating components in phase \(i\) and \(w_i\) denotes the remaining number of components in phase \(i\) (excluding components already involved in the parent nodes based on success criteria of phase \(i\)).

Since \(v_i > w_i\) indicates that the success criteria of the phase \(i\) could not be satisfied with the remaining components, the mission must fail in phase \(i\). Thus, the \(v_i/w_i\) with \(v_i > w_i\) in the label is replaced with ‘F’, which implies that the mission has failed in phase \(i\) with the failure of components involved in the node and its parent nodes.

Consider non-sink node \(y\), which is connected to its parent node \(x\) through edge-\(j\). The label of node \(y\) is denoted by \((v_1^{(y)}/w_1^{(y)}, v_2^{(y)}/w_2^{(y)}, \ldots, v_i^{(y)}/w_i^{(y)}, \ldots, v_n^{(y)}/w_n^{(y)})\) and the label of its parent node \(x\) is denoted by \((v_1^{(x)}/w_1^{(x)}, v_2^{(x)}/w_2^{(x)}, \ldots, v_i^{(x)}/w_i^{(x)}, \ldots, v_n^{(x)}/w_n^{(x)})\).

Based on the label of the parent node \(x\), the rules for determining the label of node \(y\) are as follows.

Case 1: \((C_x \notin X_i)\) or \((v_i^{(x)}/w_i^{(x)} = F)\).

Under this case, the state of component \(C_x\) (modeled by node \(x\) in MDD) makes no contribution to mission’s status in phase \(i\). Hence, the required number of operating components and the remaining number of components in phase \(i\) (excluding node \(x\) and its parent nodes) stay the same: \(v_i^{(y)}/w_i^{(y)} = v_i^{(x)}/w_i^{(x)}\).

Case 2: \((C_x \in X_i)\) and \((v_i^{(x)}/w_i^{(x)} \neq F)\).

In the case of \(j = 0\), node \(y\) is connected to its parent node \(x\) via edge-0 (meaning component \(C_x\) is not failed during the whole mission). Since \(C_x\) has survived phase \(i\), both the required number of operating components and the remaining number of components in phase \(i\) decrease by 1: \(v_i^{(y)} = v_i^{(x)} - 1\) and \(w_i^{(y)} = w_i^{(x)} - 1\).

In the case of \(j \neq 0\), \(C_x\) fails in phase \(j\) for the first time (having survived the previous \((j - 1)\) phases).

- For \(i < j\), \(C_x\) is operating in phase \(i\), thus both the required number of operating components and the remaining number of components decrease by 1: \(v_i^{(y)} = v_i^{(x)} - 1\) and \(w_i^{(y)} = w_i^{(x)} - 1\).
- For \(j \leq i \leq M\), \(C_x\) fails in phase \(j\) and remains the failed state for all phases following phase \(j\). Hence, the required number of operating components stays the same as that for its parent component.
node \( x \): \( v_i^{(y)} = v_i^{(x)} \). But the remaining number of components decreases by 1: \( w_i^{(y)} = w_i^{(x)} - 1 \). If \( v_i^{(y)} > w_i^{(y)} \), \( v_i^{(x)}/w_i^{(x)} = F \).

**Step 3**: merge non-sink nodes with identical indexes and identical labels. These nodes are essentially the same variable with the same child nodes. Merging them reduces the MDD size, leading to less time for the subsequent MDD model evaluation.

**Step 4**: for each non-sink node (e.g. \( y \) with index \( h \)), based on the labeling in Step 2, add its \((M + 1)\) edges and connect them to child nodes using the following three steps.

**Step A**: analyze edge-0 from node \( y \) (implying that component \( C_y \) is not failed during the whole mission). Two scenarios A1, A2 are considered.

A1: at least one \( v \) in the label of node \( y \) satisfies \( v_i^{(y)} = 1 \) and \( C_y \in X_i \).

In this scenario, for phases with \( v = 1 \), if \( C_y \) is operating, the entire mission succeeds because the required number of operating components in those phases has been met and the mission succeeds in those phases. Thus, edge-0 from node \( y \) leads to sink node ‘0’ directly. Note that component \( C_y \) first fails after phase \( i \) with \( v_i^{(y)} = 1 \) and \( C_y \in X_i \) implies that the component does not fail in phase \( i \), all edges from edge-\((i+1)\) to edge-M should be connected to sink node ‘0’. Assume there are \( m \) phases in the label of node \( y \) having \( v_i^{(y)} = v_i^{(y)} = \cdots = v_m^{(y)} = 1 \), \((1 \leq m \leq M)\) and \( C_y \in X_i \) for all \( i \in \{i_1, i_2, \ldots, i_m\} \), the first phase satisfies the pattern is phase \( i_1 \). The first failure from component \( C_y \) happening after phase \( i_1 \) indicates that the mission succeeds in phase \( i_1 \) with the working of component \( C_y \) and the components involved in the parent nodes of node \( y \). Therefore, edge-\((i_1 < l \leq M)\) is connected to sink node ‘0’. In this case, edges from edge-\((i_1+1)\) to edge-M are not needed analyzed any more. Starting from edge-\(i_1\), following steps will applied to analyze remaining edges.

A2: the condition under A1 is not met.

The child nodes must be analyzed to decide the mission state. Hence, a new non-sink node with index \((h+1)\) is added as child node connected by edge-0 of node \( y \).

**Step B**: analyze edge-M from node \( y \) (implying that \( C_y \) has survived the first \((M-1)\) phases and fails at the last phase \( M \)). Three scenarios B1-B3 are considered.

B1: \( C_y \notin X_M \) or \( v_M^{(y)}/w_M^{(y)} = F \).

In this case, \( C_y \) failing at phase \( M \) has no impact on the mission status in phase \( M \), \( C_y \) can be considered as operating during the whole mission. Thus, edge-M of node \( y \) is connected to the same child node connected by edge-0 of node \( y \).

B2: \( C_y \in X_M \) and \( v_M^{(y)} = w_M^{(y)} \) and \( v_s^{(y)}/w_s^{(y)} = F \) for all \( 1 \leq s < M \).

\( C_y \in X_M \) and \( v_M^{(y)} = w_M^{(y)} \) implies that failure of component \( C_y \) at phase \( M \) will lead mission to fail in the phase. In addition, \( v_s^{(y)}/w_s^{(y)} = F \) for all \( 1 \leq s < M \) implies that the mission has failed in all phases before \( M \). Therefore, the mission would fail in all phases with failure of \( C_y \) in phase \( M \). For a PMS with the phase-AND requirement, the entire mission fails when the mission fails in all phases. Therefore, edge-M from node \( y \) is connected to sink node ‘1’ in this case. Note that the failure of \( C_y \) before phase \( M \) also causes the failure in phase \( M \), edge-\((1 \leq l \leq M)\) from node \( y \) is connected to sink node ‘1’.

B3: conditions of B1 and B2 are not met.

In this scenario, a new non-sink node with index \((h+1)\) is added as a child node connected by edge-M of node \( y \).

In the case of \( M = 1 \), all edges are analyzed (Step 4 is completed); otherwise, Step C is performed to determine the remaining child nodes.

**Step C**: analyze edge-\(j \) \((0 < j < M, M > 1)\) of node \( y \) (implying that \( C_y \) has survived the first \((j-1)\) phases and fails for the first time in phase \( j \)). The child node is added for each edge one by one starting from edge-\((M-1)\) to edge-1. Three scenarios C1-C3 are considered.
C1: \((C_y \notin X_j)\) or \((v_j^{(y)}/w_j^{(y)} = F)\).

This case is similar to B1. In this scenario, \(C_y\) failing in phase \(j\) has no impact on the mission status in phase \(j\). \(C_y\) can be considered as operating in phase \(j\) but being failed in the later phase \((j + 1)\). Thus, edge-\(j\) of node \(y\) leads to the same child node as that of edge-\((j+1)\).

C2: \((C_y \in X_j)\) and \((v_j^{(y)} = F)\) for all \(1 \leq s < j\) and \((v_t^{(y)}/w_t^{(y)} = F)\) for all \(j < t \leq M\).

\(C_y \notin X_j\) and \(v_j^{(y)} = F\) implies that failure of component \(C_y\) at phase \(j\) will cause the mission to fail in the phase. In addition, \(v_s^{(y)}/w_s^{(y)} = F\) for all \(1 \leq s < j\) implies that mission has failed in all phases before \(j\). For all \(j < t \leq M\), \((v_t^{(y)}/w_t^{(y)} = F)\) or \((v_t^{(y)} = w_t^{(y)} \text{ and } C_y \in X_t)\) for all \(j < t \leq M\).

C3: conditions of C1 and C2 are not met.

A new non-sink node with index \((h+1)\) is added as child node connected by edge-\(M\) of node \(y\).

Step 5: repeat steps 2-4 until sink node ‘0’ or ‘1’ is reached.

Step 6: apply reduction rule of merging isomorphic structures to generate a compact PMS MDD.

The flow chart of the proposed method is shown in figure 2.

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**Figure 2.** Reliability analysis flowchart for dynamic k/n PMS with the phase-AND requirement.
3.3. PMS MDD evaluation
The final PMS MDD has two sink nodes, ‘0’ and ‘1’, denoting the mission is successful or failed, respectively. Each path from the root node of the PMS MDD to sink node ‘0’ (‘1’) corresponds to a disjoint combination of component states in certain phases leading to the overall mission success (failure). Thus, the mission reliability (unreliability) is obtained as summation of probabilities of all paths from the root node to sink node ‘0’ (‘1’). The probability of each path is the product of probabilities of all edges appearing on the path. Specifically, per the MDD modelling in Section 3.1, edge-0 is associated with the probability that the corresponding component has survived all the phases; edge-$j$ ($j \neq 0$) is associated with the probability that the corresponding component has its first failure in phase $j$. As demonstrated in Section 4, the edge probabilities are computed based on input component failure parameters in each phase.

4. Case study
Consider a PMS with the phase-AND requirement having two phases ($M = 2$) and three components ($N = 3$). The set of system components is $X = \{C_1, C_2, C_3\}$. In phase 1, the set of components that have contribution to mission failure is $X_1 = \{C_1, C_3\}$ and the system structure of phase 1 is 1/2, which means that when at least one of the two components $C_1$ and $C_3$ is working, the mission succeeds in phase 1. In phase 2, the set of components that have contribution to mission failure is $X_2 = \{C_1, C_2, C_3\}$ and the system structure of phase 2 is 2/3, which means that when at least two of the three components $C_1$, $C_2$ and $C_3$ are working, the mission succeeds in phase 2. If the mission fails in both phases, that is, the phase-AND requirement is satisfied, the entire mission fails.

Table 1 presents phase durations and conditional failure parameters of the three components in each phase (conditioned on the component having survived the previous phase).

| Component | Phase 1 (20 hours) | Phase 2 (40 hours) |
|-----------|--------------------|--------------------|
| $C_1$     | $\lambda = 0.004$  | $\lambda = 0.003$  |
| $C_2$     | $\lambda = 0.001$  | $\hat{q} = 0.035$ |
| $C_3$     | $(\lambda_W = 0.004, \alpha_W = 2)$ | $\lambda = 0.002$ |

Three types of time-to-failure distributions are illustrated: 1) component fails with a fixed probability $\hat{q}$; 2) component fails exponentially with constant failure rate $\lambda$ (failure probability is $1 - e^{-\lambda t}$); and 3) component fails following the Weibull distribution with scale parameter $\lambda_W$, and shape parameter $\alpha_W$ (failure probability is $1 - e^{-(\lambda_W t)^{\alpha_W}}$).

Since there are two phases, each component is associated with a three-valued variable, modelled by a non-sink node in MDD with three outgoing edges labelled by 0, 1, and 2. Thus there are three three-valued variables: 1, 2, 3. The ordering used for MDD generation is 1 < 2 < 3. Node 1 is the root node since it has the smallest index.

Figure 3 shows the process of generating the entire PMS MDD for the example 2-phase PMS.
Figure 3. Process of generating the MDD for the example 2-phase PMS.
Specifically, according to Step 2, the label $(1/2, 2/3)$ for root node 1 is added as figure 3 (a) shows. According to the label of node 1, three edges and connected child nodes are added to node 1 by Step 4 as figure 3 (b) shows. Then the rules in Step 2 are applied to add a label for node 2 based on the label of its parent node (i.e. node 1). Based on the label of node 2, the rules in Step 4 are applied to add child node for each edge of node 2, which is shown in figure 3 (c). figure 3 (d) shows MDD after
adding child nodes for node 3. By merging isomorphic structures in Step 6, the final PMS MDD is shown in figure 3 (e).

Using parameters in table 1, the three edge probabilities for each node/component are calculated and summarized in table 2. Consider node 3 as an example. Its edge-1 probability (i.e., the probability that component $C_3$ fails at phase 1) is calculated as $1 - e^{-(0.004 \times 20)^2} = 0.00638$; its edge-2 probability (the probability that component $C_3$ fails at phase 2 for the first time) is calculated as $e^{-(0.004 \times 20)^2} (1 - e^{-0.002 \times 40}) = 0.076393$; its edge-0 probability (the probability that component $C_3$ does not fail during the entire mission) is calculated as $1 - 0.00638 - 0.07693 = 0.917227$.

| Node | Edge-1   | Edge-2   | Edge-0   |
|------|----------|----------|----------|
| 1    | 0.076884 | 0.104386 | 0.81873  |
| 2    | 0.019801 | 0.034307 | 0.945892 |
| 3    | 0.00638  | 0.076393 | 0.917227 |

Using the edge probabilities computed in table 2, we evaluate the PMS MDD in figure 3(e) to obtain the system unreliability at the end of the entire mission (i.e., 60 hours). There is only one path from the root node to sink node ‘1’. The probability of this path is the product of node 1’s edge-1 probability and node 3’s edge-1 probability, that is, $0.076884 \times 0.00638 = 0.000491$. Thus the mission unreliability is 0.000491.

5. Conclusions and future work

In this paper, a new MDD-based combinatorial method is proposed for reliability analysis of a dynamic $k/n$ PMS with the phase-AND requirement. Based on node labeling, the proposed method can construct the PMS MDD model by considering all the mission phases together (instead of one by one in the traditional PMS analysis methods), facilitating fast system model generation and thus analyzing large-scale PMSs. The proposed method is applicable to PMSs where both the number of available components $n$ and the required number of working components $k$ may vary from phase to phase. As illustrated by the example, the proposed method has no limitation on the type of component time-to-failure distributions.

In the future, the proposed method will be implemented and applied to analyze large-scale PMSs. Both space and time complexity will be studied and compared with the existing method [10]. Another direction is to study the dynamic $k/n$ PMS with more general combinatorial phase requirements [20].

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