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Complex Satellite Lifetime Optimization Based on Bayesian Network Reliability Compression Inference Algorithm

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ABSTRACT In the satellite lifetime optimization, reliability is a critical issue. For the complex satellite system, Bayesian network (BN) is an important method for reliability modeling and inference. As the number of system's components increases dramatically, the memory storage requirements of the system's node probability table (NPT) will exceed the computer's random access memory (RAM). To solve this challenge, compression methods have been proposed to reduce the memory storage requirements of NPT. However, for the complex satellite system with extreme large number of components and the explosion of probable state combination, the existing methods still face big challenge in compression efficiency. Therefore, an improved encoding compression algorithm is proposed to further enhance the NPT compression effect in this paper. For the hierarchical complex satellite system that has multiple subsystems which are further composed of multiple components, the multilevel BN reliability model is first constructed based on the proposed encoding compression algorithm. By the variable elimination algorithm, a multilevel BN reliability inference algorithm is proposed to perform the inference of the multilevel BN reliability model. Based on the basis of the reliability model above, further considering system mass, power and cost requirement, the satellite lifetime is properly designed by optimizing the system component configuration, including component model/type selection and number determination for redundancy. Finally, two cases are studied to demonstrate and validate the proposed algorithms.

INDEX TERMS Bayesian network, complex satellite system, compression algorithm, lifetime optimization, reliability.

NOMENCLATURE

τ	the number of subsystems to be designed.
$\tilde{i}$	the subsystem index, $\tilde{i} = 1, 2, \cdots, \tau$.
$\delta_{\tilde{i}}$	the number of the $\tilde{i}$ th subsystem's components.
$\tilde{j}$	the component index, $\tilde{j} = 1, 2, \cdots, \delta_{\tilde{i}}$.
$\gamma_{\tilde{i}}^{\tilde{j}}$	the number of the $\tilde{j}$ th component's models.
$\tilde{k}$	the model index, $\tilde{k} = 1, 2, \cdots, \gamma_{\tilde{i}}^{\tilde{j}}$.
$MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$	the number of the $\tilde{k}$ th model of the $\tilde{j}$ th component.
S	a complex satellite system.
$S_{\tilde{i}}$	the $\tilde{i}$th subsystem of the system S.
$C_{\tilde{i}}^{\tilde{j}}$	the $\tilde{j}$th component of the subsystem $S_{\tilde{i}}$.
Ψ_S	the structure function of system.
$\Psi_{S_{\tilde{i}}}$	the structure function of subsystem.
$\Psi_{C_{\tilde{i}}^{\tilde{j}}}$	the structure function of component.
$Mo_{\tilde{i}}^{\tilde{j}}$	parent nodes of the root node $C_{\tilde{i}}^{\tilde{j}}$.
i	the parent node index, $i = 1, 2, \cdots, n$.
C_i	the i th parent node of the child node Ch.
P_{Ch}	the NPT's normal conditional probability column of the child node Ch.
k	the row index of NPT, $k = 1, 2, \cdots, 2^n$.
$ceil(x)$	the function that returns the smallest integer which is no less than the value of x.
s_i^k	the state of the i th binary parent node in the k th row of NPT.

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cP_{Ch}	the compressed column P_{Ch}.
P_{Ch}^{k}	the k th row of the column P_{Ch}.
j	the row index of cP_{Ch}.
d_r	the run accompanying dictionary.
q^j	the run number in d_r.
n_r^j	the repeated number of a run in the column cP_{Ch}.
r^j	the numerical value that composes a run.
L_r^j	the number of r^j.
d_p	the phrase accompanying dictionary.
p^j	the phrase number in d_p.
n_p^j	the repeated number of a phrase in the column P_{Ch}.
v_1^j	the first numerical value that composes a phrase.
v_2^j	the second numerical value that composes a phrase.
L_p^j	the number of v_1^j and v_2^j.
RP	the row start number sets of run and phrase.
S^{all}	the row start number set.
λ_i	the intermediate factor after eliminating the parent node C_i.
$c\lambda_i$	the compressed intermediate factor λ_i.
$c\lambda_i^j$	the j th row of $c\lambda_i$.
d_{r_i}	the corresponding run accompanying dictionary of $c\lambda_i$.
d_{p_i}	the corresponding phrase accompanying dictionary of $c\lambda_i$.
q_i^j	the run number in d_{r_i} .
r_i^j	the numerical value that composes a run in λ_i.
$L_{r_i}^j$	the number of r_i^j .
$n_{r_i}^j$	the repeated number of a run in λ_i .
$n_{p_i}^j$	the repeated number of a phrase in λ_i.
$v_{1_i}^j$	the first numerical value that composes a phrase in λ_i.
$v_{2_i}^j$	the second numerical value that composes a phrase in λ_i.
$L_{p_i}^j$	the number of $v_{1_i}^j$ and $v_{2_i}^j$.
d_{ri}^j	the q_i^j th row of d_{r_i}.
d_{pi}^j	the p_i^j th row of d_{p_i}.
N	the number of a complex satellite system's levels.
l	the level index of a complex satellite system, $l = 1, 2, \cdots, N$.
K_l	the number of the nodes in the l th level.
m_l	the node index in the l th level ($l \geq 2$), $m_l = 1, 2, \cdots, K_l$.
Ch_{m_l}	the m_l th node.
$cBN_{m_l}^{l}$	a child-BN.
$\Psi_{Ch}^{m_l}$	the structure function of node Ch_{m_l}.
R_{sat}	the complex satellite system reliability.
$MT_{(\tilde{i},\tilde{j},\tilde{k})}^{\max}$	the maximum bounds of $MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$.
$MT_{(\tilde{i},\tilde{j},\tilde{k})}^{\text{mim}}$	the minimum bounds of $MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$.
$Life$	the satellite design lifetime.
M_{sum}	the overall mass of the satellite.
$M_{(\tilde{i},\tilde{j})}^{\tilde{k}}$	the mass of the $\tilde{k}$th model of the $\tilde{j}$th component of the $\tilde{i}$th subsystem.
$M_{\max}$	the limited maximum mass.
P_{sum}	the overall power of the satellite.
$P_{(\tilde{i},\tilde{j})}^{\tilde{k}}$	the power of the $\tilde{k}$th model of the $\tilde{j}$th component of the $\tilde{i}$th subsystem.
$P_{\max}$	the limited maximum power.
C_{sum}	the overall cost of the satellite.
$C_{(\tilde{i},\tilde{j})}^{\tilde{k}}$	the cost of the $\tilde{k}$th model of the $\tilde{j}$th component of the $\tilde{i}$th subsystem.
$C_{\max}$	the cost budget of the satellite.
R_{sat}^{EOL}	the system reliability.
$R_{\min^{EOL}}$	the limited minimum reliability requirement.
$Nu_{\tilde{i}}^{\tilde{j}}$	the number of all the selected models for the $\tilde{j}$th component of the $\tilde{i}$th subsystem.

I. INTRODUCTION

In the satellite system engineering, the proper design of satellite lifetime [1]–[3] is an important part. System reliability is one of the main influencing factors to the satellite lifetime design [4]–[6]. As the time for satellite to perform missions in orbit increases, its system reliability is gradually decreasing [7], [8]. In particular, the satellite system reliability at the end of lifetime (EOL) should meet the prescribed requirements so that the satellite can finish its mission successfully [9]. Therefore, the reliability design should be considered in designing the satellite lifetime.

For the studies about the reliability design, Woo and O'Neal [10] proposed a reliability methodology utilizing parametric accelerated life testing to improve the reliability of mechanical systems. Besides, to achieve the fast inference of reliability, Yu *et al.* [11] developed a visual reliability design calculation program for the airport runway soft soil foundation based on Visual Studio 2010. To realize the steady state with duty cycle time 0.3–0.5 of CFETR, Cao *et al.* [12] studied the relations between steady-state operation with duty cycle time 0.3–0.5 and the reliability of divertor. Based on Probabilistic Design and Physics of Failure Analysis, Sharp *et al.* [13] used the reliability design to mitigate the harms of armaments to civilians. By melding multi-source lifetime or failure information, Xu *et al.* [14] proposed a reliability-based design optimization method based on the Bayesian Melding Method. By the researches on the methods (like the above methods) for reliability design, the system reliability can be improved by proper design. The reliability has influence on the system lifetime [8], [15]. For satellite engineering, its components will age as the satellite's on-orbit service time increases [4], which will lead to a gradual decline in the reliability of satellite systems. Therefore, how to apply reliability design to satellite lifetime optimization is a problem worthy of attention and research.

Considering the satellite development cost and the reliability requirements at EOL, Yao *et al.* [16] proposed a satellite lifetime optimization method based on the discrete Cross Entropy optimization algorithm. In Yao's method, the satellite system reliability model is constructed by the reliability function according to the logical relationship between components. However, as the satellite system becomes more complex, e.g. it usually has multiple subsystems which are further composed of multiple components, and the function of each component may be implemented by several component models for redundancy with complex logical relationship, it is difficult to formulate an explicit mathematical expression through the reliability function in constructing the system reliability model. For this situation, Bayesian network (BN) [17]–[20] is a powerful tool for constructing the complex system reliability model.

With the development of aerospace technology, the function of the satellite and the missions it performs are becoming more complicated, which makes the number of satellite's components increases dramatically. In BN, each node has a node probability table (NPT) [21], [22] which reflects the relationship between the child node and its parent nodes. In constructing the system's BN reliability model, with the number of satellite system's components gradually increases, the component state combinations will increase exponentially, which makes the memory storage requirements of NPT increase directly. When the components reach a certain number, it will lead to the memory storage requirements of NPT exceeding the computer's random access memory (RAM). For example, suppose that a binary child node has 31 binary parent nodes. Therefore, a $2^{31} \times 2$ matrix needs to be created to store the NPT of this child node. If the $2^{31} \times 2$ matrix is created by the MATLAB software on a 16GB RAM computer with 2.5 GHz Intel(R) Core(TM) i7-4710MQ processor, an error arises because the $2^{31} \times 2$ matrix needs 32 GB memory to store while the computer only has 16 GB RAM. Therefore, how to reduce the memory storage requirements of NPT becomes a problem that needs to be solved.

Based on the run length encoding compression technique [23], [24] and Lempel-Ziv encoding compression technique [25], Tien and Kiureghian [26], [27] and Tong and Tien [28] proposed the compression algorithm to reduce the memory storage requirements of NPT for the BN reliability modelling and applied to infrastructure system. However, this compression algorithm does not consider some special binary system situations, which greatly limits its universal application. To remedy these defects, Zheng *et al.* [29] proposed the improved compression and inference algorithm which can be applied to any complex binary system. In Zheng's method, NPT is compressed to be two zip files to reduce the memory storage requirements of NPT. However, for the complex satellite system with extreme large number of components and the explosion of probable state combination, the existing methods still face big challenge in compression efficiency. In this paper, an encoding compression algorithm combined with the study of Zheng *et al.* [30] is propose d to enhance the NPT compression effect by adding an accompanying dictionary.

Combined with the proposed encoding compression algorithm, a multilevel BN reliability inference algorithm is proposed to perform the inference of the multilevel BN reliability model by the variable elimination algorithm in this paper. On the basis of the above researches, to optimize the satellite lifetime, this paper proposed an efficient satellite lifetime optimization method that can properly design the system component configuration, including component model/type selection and number determination for redundancy. In this efficient satellite lifetime optimization method, the complex satellite reliability model is constructed by the proposed two algorithms of this paper, based on which the satellite lifetime optimization model is established according to several constraints like system reliability, mass, power and cost. To solve this life optimization problem, genetic algorithm (GA) [31], [32] is used to search the optimum design scheme so that the satellite lifetime is as long as possible under meeting several constraints. Combine with the actual engineering conditions and the historical engineering experience, the optimum scheme can be used as a reference for the engineers.

The rest of this paper is structured as follows. In section II, the encoding compression algorithm and the multilevel BN reliability inference algorithm are proposed. The satellite lifetime optimization problem is formulated in section III, wherein the optimization variables, the optimization objective, and the constraints are described in detail. Two case studies are demonstrated in section IV. Case 1 is used to demonstrate the usage of the proposed reliability compression modelling and inference algorithms with a simple two-level problem. In Case 2, the lifetime design problem of a satellite with 59 components is investigated. The effectiveness of the proposed method is summarized in section V.

II. COMPLEX SATELLITE SYSTEM MULTILEVEL BN RELIABILITY MODELLING AND INFERENCE

A. COMPLEX SATELLITE SYSTEM HIERARCHICAL STRUCTURE MODELLING

Hierarchical systems [33] are ubiquitous in engineering systems, and their obvious feature is that the output (response) of the low-level component is the input to the high-level subsystem. For the satellite system, it is composed of several subsystems and each subsystem is composed of multiple components. To implement each component's function, there are several optional types of models for selection (e.g. the model data in Appendix B for Case 2). Either one single model or a combination of different models can be chosen to fulfill the specific task. The type and number of models to be selected should be properly defined for both redundancy and cost/mass effectiveness considerations. For the $\tilde{i}$th subsystem, denote the number of its components as $\delta_{\tilde{i}}$ ($\tilde{i} = 1, 2, \cdots, \tau$), where τ is the number of subsystems to be designed. For the $\tilde{j}$th component of the $\tilde{i}$th subsystem,

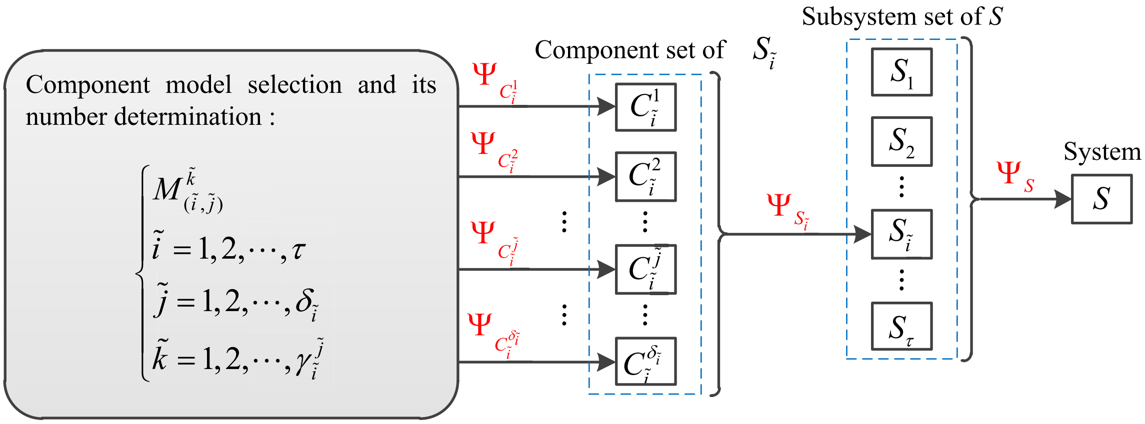


FIGURE 1. Complex satellite system hierarchical structure modelling.

denote the number of alternative models as $\gamma_{\tilde{i}}^{\tilde{j}}$, where $\tilde{j} = 1, 2, \cdots, \delta_{\tilde{i}}$. According to the performance requirements of the $\tilde{i}$th subsystem, the number of the $\tilde{k}$th model of the $\tilde{j}$th component should be carefully defined and denoted as $MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$, where $\tilde{k} = 1, 2, \cdots, \gamma_{\tilde{i}}^{\tilde{j}}$. If $MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$ is zero, it means the corresponding model is not selected. For each component, at least one model should be selected to implement the required function. Then, the satellite system design problem can be decomposed to the bottom level of the hierarchy as the model/type and number selection for all the components of all the subsystems, which is formulated as

$$\begin{cases} MT_{(\tilde{i},\tilde{j})}^{\tilde{k}} \\ \tilde{i} = 1, 2, \cdots, \tau \\ \tilde{j} = 1, 2, \cdots, \delta_{\tilde{i}} \\ \tilde{k} = 1, 2, \cdots, \gamma_{\tilde{i}}^{\tilde{j}} \end{cases} \tag{1}$$

With the proper design of $MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$, the complex satellite system hierarchical structure can be constructed as shown in FIGURE 1.

In FIGURE 1, S means the complex satellite system, $S_{\tilde{i}}$ is the $\tilde{i}$th subsystem of the system S, and $C_{\tilde{i}}^{\tilde{j}}$ is the $\tilde{j}$th component of the subsystem $S_{\tilde{i}}$. Ψ_S, $\Psi_{S_{\tilde{i}}}$ and $\Psi_{C_{\tilde{i}}^{\tilde{j}}}$ are the structure functions which reflect the parallel, series, or mixed relationship between these parts (compose a part in the higher level) in the low level.

B. COMPLEX SATELLITE SYSTEM MULTILEVEL BN RELIABILITY MODELLING

1) BN MODEL CONSTRUCTING

According to the multilevel BN modeling method [29] and the complex satellite system hierarchical structure in FIGURE 1, the four-level BN reliability model is constructed as show in FIGURE 2. For the root node $C_{\tilde{i}}^{\tilde{j}}$ in FIGURE 2, its parent nodes $Mo_{\tilde{i}}^{\tilde{j}}$ can be determined after

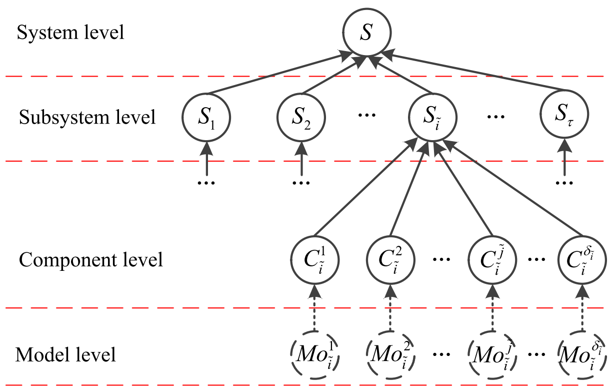


FIGURE 2. Four-level BN reliability model of the hierarchical system.

choosing the component's model and the corresponding number.

According to the state combination of binary parent nodes, each state's probability of the child node in FIGURE 2 is calculated according to the structure function defined by Ψ_S, $\Psi_{S_{\tilde{i}}}$ and $\Psi_{C_{\tilde{i}}^{\tilde{j}}}$. In this paper, the normal probability column of the NPT is compressed by the encoding compression algorithm as shown in section II-B based on the run length encoding compression technique [23], [24] and Lempel-Ziv encoding compression technique [25].

2) ENCODING COMPRESSION ALGORITHM

Suppose that a binary child node Ch has n binary parent nodes $\{C_i | i = 1, 2, \cdots, n\}$. Thus, the NPT's normal conditional probability column of the child node is

$$P(Ch = 1 | C_1, C_2, \cdots, C_n),$$

denoted as P_{Ch}. For the NPT of Ch, the state of each binary parent node in NPT's each row is calculated by the rules [27], [29] as shown in equation (2). k $(k = 1, 2, \cdots, 2^n)$ is the row number of NPT, $ceil(x)$ is the function that returns the smallest integer which is no less than the value of x. s_i^k $(i = 1, 2, \cdots, n)$ is the state of the ith binary parent node in the k th row of NPT. 0 means the parent node is false, and 1 means the parent node is normal.

$$s_i^k = \begin{cases} 0 & \text{if } ceil\left(\frac{k}{2^{n-i}}\right) \in \text{odd} \\ 1 & \text{if } ceil\left(\frac{k}{2^{n-i}}\right) \in \text{even} \end{cases} \quad (2)$$

The compressed column P_{Ch} (denoted as cP_{Ch}) is composed of run and phrase [29], [30], where run like "0.1 0.1 0.1" is composed of only one numerical value, and phrase like "0.3 0.2 0.2 0.2" of which the second numerical value is different from the first numerical value but is the same with the numerical value from the third to the last. Denote that the k th row of the column P_{Ch} is P_{Ch}^k. The compression process of the column P_{Ch} is as follows. For $k = 1, 2, \cdots, 2^n$, both the values of s_i^k and s_i^{k+1} are calculated by equation (2), respectively. Then, the values of P_{Ch}^k and P_{Ch}^{k+1} can be determined by the structure function Ψ_{Ch}. Compare that whether the values of P_{Ch}^k and P_{Ch}^{k+1} are equal or not:

If P_{Ch}^k and P_{Ch}^{k+1} are equal, the k th row is a run start position. Then, continue to query the next row's value of P_{Ch}. If the next row is different from P_{Ch}^k, the current querying run is end. Once a run is queried, the run accompanying dictionary (denoted as d_r) will be constructed. The queried run is stored in cP_{Ch} in the form of $\{run, q^j, n_r^j\}$, where j is the row number of cP_{Ch}, q^j is the run number in d_r, and n_r^j is the repeated number of this run in the column P_{Ch}. Besides, the queried run is added into d_r in the form of $\{q^j, r^j, L_r^j\}$, where $r^j = P_{Ch}^k$ is the numerical value that composes the run, and L_r^j is the number of r^j. In the subsequent querying process, if a run is queried again, this run needs to be judged whether it is the same with the run in the q^j th row of d_r according to the rules in [30]. If the q^j th row's run of d_r is the same with this run, the value of n_r^j is updated, i.e. $n_r^j = n_r^j + 1$. Otherwise, this run is added into cP_{Ch} and d_r in the form of $\{run, q^j, n_r^j\}$ and $\{q^j, r^j, L_r^j\}$, respectively.

If P_{Ch}^k and P_{Ch}^{k+1} are not equal, the k th row is a phrase start position. Then, continue to query the next row's value of P_{Ch}. If the next row is different from P_{Ch}^{k+1}, the current querying phrase is end. Once a phrase is queried, the phrase accompanying dictionary (denoted as d_p) will be constructed. The queried phrase is stored in cP_{Ch} in the form of $\{phrase, p^j, n_p^j\}$, where p^j is the phrase number in d_p, and n_p^j is the repeated number of this phrase in the column P_{Ch}. Besides, the queried phrase is added into d_p in the form of $\{p^j, v_1^j, v_2^j, L_p^j\}$, where $v_1^j = P_{Ch}^k$ and $v_2^j = P_{Ch}^{k+1}$ are the first and the second numerical values that compose the phrase, and L_p^j are the number of v_1^j and v_2^j. In the subsequent querying process, if a phrase is queried again, this phrase needs to be judged whether it is the same with the phrase in the p^j th row of d_p according to the rules in [30]. If the p^j th row's phrase of d_p is the same with this phrase, the value of n_p^j is updated, i.e. $n_p^j = n_p^j + 1$. Otherwise, this phrase is added into cP_{Ch} and d_p in the form of $\{phrase, p^j, n_p^j\}$ and $\{p^j, v_1^j, v_2^j, L_p^j\}$, respectively.

TABLE 1. A NPT of child node *Ch* with three parent nodes.

C_1	C_2	C_3	$p(Ch\|C_1, C_2, C_3)$	
			$Ch = 0$	$Ch = 1$
0	0	0	1	0
0	0	1	1	0
0	1	0	0	1
0	1	1	0	1
1	0	0	1	0
1	0	1	1	0
1	1	0	0	1
1	1	1	1	0

TABLE 2. Compressed column $p(Ch = 1|C_1, C_2, C_3)$ by the proposed encoding compression algorithm.

run or $phrase$	p_4^j or q_4^j	n_{p4}^j or n_{r4}^j
run	1	2
run	2	1
$phrase$	1	1

TABLE 3. Run accompanying dictionary of TABLE 2.

q_4^j	r_4^j	L_{r4}^j
1	0	2
2	1	2

TABLE 4. Phrase accompanying dictionary of TABLE 2.

p_4^j	v_{14}^j	v_{24}^j	L_{p4}^j
1	1	0	2

In addition to cP_{Ch}, d_r and d_p, both the row start number sets RP and S^{all} of run and phrase are also needed to be calculated, the detailed calculation methods are the same with the methods in [30]. In summary, the flowchart of the encoding compression algorithm is shown in FIGURE 3.

According to the description of Introduction in section I, the improved compression algorithm [29] is also used to compress the NPT. Therefore, in order to show the difference between the proposed encoding compression algorithm and the improved compression algorithm [29], the column $\Pr(Ch = 1|C_1, C_2, C_3)$ as shown in TABLE 1 is compressed respectively by the above two compression algorithms.

Firstly, the column $p(Ch = 1|C_1, C_2, C_3)$ is compressed by the encoding compression algorithm, and the results are shown in TABLE 2, TABLE 3 and TABLE 4. Besides, $S_4^{all} = \{1, 3, 5, 7\}$ and $RP_4 = \{[1, 5], [3], [7]\}$.

Secondly, the column $p(Ch = 1|C_1, C_2, C_3)$ is compressed by the encoding compression algorithm, and the results are shown in TABLE 5 and TABLE 6. Besides, $S_4^{all} = \{1, 3, 5, 7\}$ and $RP_4 = \{[1], [3], [5], [7]\}$.

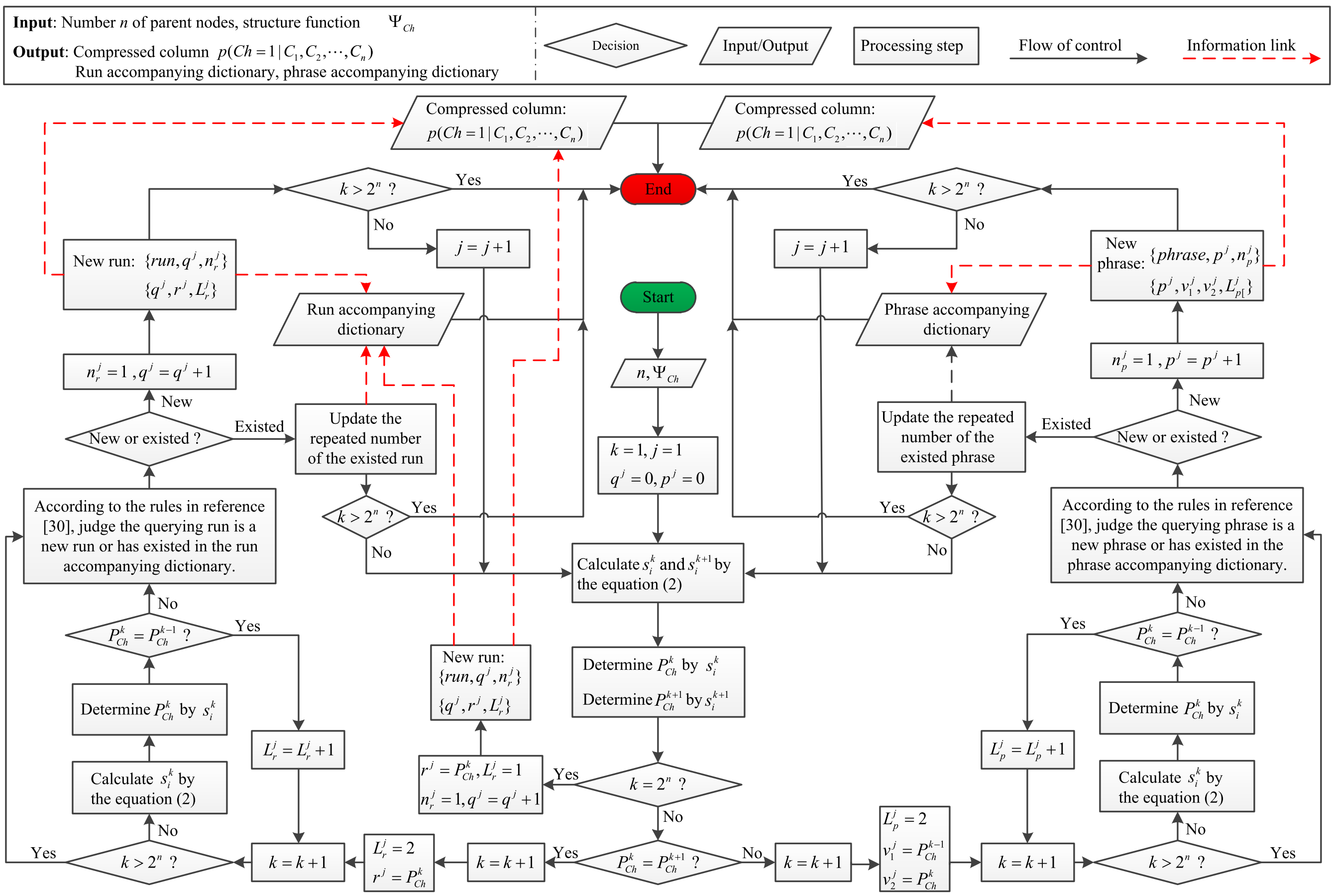


FIGURE 3. The flowchart of the proposed encoding compression algorithm.

TABLE 5. Compressed column $p(Ch=1|C_1,C_2,C_3)$ by the improved compression algorithm [29].

run or $phrase$	p_4^j or r_4^j	$n_{p_4}^j$ or $L_{r_4}^j$
run	0	2
run	1	2
run	0	2
$phrase$	1	1

TABLE 6. Phrase accompanying dictionary of TABLE 5.

p_4^j	v_{14}^j	v_{24}^j	L_{p4}^j
1	1	0	2

According to the above results, the run in the first row of TABLE 2 repeats twice in the column $p(Ch=1|C_1,C_2,C_3)$. For this two runs, they are located in the first and third rows of TABLE 5, respectively. Different from the improved compression algorithm, the results of the encoding compression algorithm add a run accompanying dictionary as shown in TABLE 3. Besides, the RP_4 of two algorithms are also different with each other. Compared with the improved compression algorithm, the compression effectiveness of the encoding compression algorithm is more obvious, and this will be discussed in Case 1 of section IV-A in detail.

C. COMPLEX SATELLITE SYSTEM MULTILEVEL BN RELIABILITY INFERENCE

1) CHILD-BN INFERENCE

In multilevel BN, each child node and its parent nodes are equivalent to a child-BN. Based on the variable elimination algorithm (VE) [34], the inference of each child-BN is performed by eliminating parent nodes $\{C_i|i=1,2,\cdots,n\}$ one by one, i.e.

$$\begin{aligned} p(Ch) &= \sum_{C_1,\cdots,C_n} p(C_1)\cdots p(C_n)p(Ch|C_1,\cdots,C_n) \\ &= \sum_{C_1} p(C_1)\cdots \sum_{C_{n-1}} p(C_{n-1}) \sum_{C_n} p(C_n)\lambda_{n+1} \\ &= \sum_{C_1} p(C_1)\cdots \sum_{C_{n-1}} p(C_{n-1})\lambda_n \\ &= \cdots = \sum_{C_1} p(C_1)\cdots \sum_{C_i} p(C_i)\lambda_{i+1} \\ &= \cdots = \sum_{C_1} p(C_1)\lambda_2 = \lambda_1, \end{aligned} \quad (3)$$

where $\lambda_{i+1} = p(Ch|C_1,\cdots,C_i)$ is the intermediate factor, $p(C_1),\cdots,p(C_n)$ are the marginal probability distributions of parent nodes. The inference process is performed based on the compressed column $p(Ch|C_1,\cdots,C_n)$.

TABLE 7. Rules for constructing $d^j_{r_i}$.

Switch	Conditions			r^j_i	$L^j_{r_i}$
run	$S^j_{i+1} \in$ odd	$L^j_{r_{i+1}} \in$ odd		r^j_{i+1}	$(L^j_{r_{i+1}} - 1)/2$
		$L^j_{r_{i+1}} \in$ even		r^j_{i+1}	$L^j_{r_{i+1}}/2$
	$S^j_{i+1} \in$ even	$L^j_{r_{i+1}} \in$ odd	$L^j_{r_{i+1}} = 1$	$r^j_{i+1} \times p(C_i = 1) + R^{all}_{I-1}$	1
			$L^j_{r_{i+1}} > 1$	$r^j_{i+1} \times p(C_i = 1) + R^{all}_{I-1}$ (also $r^{j+1}_i = r^j_{i+1}$)	1 (also $L^{j+1}_{r_i} = (L^j_{r_{i+1}} - 1)/2$)
		$L^j_{r_{i+1}} \in$ even	$L^j_{r_{i+1}} = 2$	$r^j_{i+1} \times p(C_i = 1) + R^{all}_{I-1}$	1
			$L^j_{r_{i+1}} > 2$	$r^j_{i+1} \times p(C_i = 1) + R^{all}_{I-1}$ (also $r^{j+1}_i = r^j_{i+1}$)	1 (also $L^{j+1}_{r_i} = (L^j_{r_{i+1}} - 2)/2$)

TABLE 8. Rules for constructing $d^j_{p_i}$.

Switch	Conditions			$v^j_{1_i}$	$v^j_{2_i}$	$L^j_{p_i}$
phrase	$S^j_{i+1} \in$ odd	$L^j_{p_{i+1}} \in$ odd	$L^j_{p_{i+1}} = 3$	$[v^j_{1_{i+1}} \times p(C_i = 0)] + [v^j_{2_{i+1}} \times p(C_i = 1)]$	-3	1
			$L^j_{p_{i+1}} > 3$	$[v^j_{1_{i+1}} \times p(C_i = 0)] + [v^j_{2_{i+1}} \times p(C_i = 1)]$	$v^j_{2_{i+1}}$	$(L^j_{p_{i+1}} - 1)/2$
		$L^j_{p_{i+1}} \in$ even	$L^j_{p_{i+1}} = 2$	$[v^j_{1_{i+1}} \times p(C_i = 0)] + [v^j_{2_{i+1}} \times p(C_i = 1)]$	-3	1
			$L^j_{p_{i+1}} > 2$	$[v^j_{1_{i+1}} \times p(C_i = 0)] + [v^j_{2_{i+1}} \times p(C_i = 1)]$	$v^j_{2_{i+1}}$	$L^j_{p_{i+1}}/2$
	$S^j_{i+1} \in$ even	$L^j_{p_{i+1}} \in$ odd		$R^{all}_{I-1} + [v^j_{1_{i+1}} \times p(C_i = 1)]$	$v^j_{2_{i+1}}$	$(L^j_{p_{i+1}} + 1)/2$
		$L^j_{p_{i+1}} \in$ even	$L^j_{p_{i+1}} = 2$	$R^{all}_{I-1} + [v^j_{1_{i+1}} \times p(C_i = 1)]$	-3	1
			$L^j_{p_{i+1}} > 2$	$R^{all}_{I-1} + [v^j_{1_{i+1}} \times p(C_i = 1)]$	$v^j_{2_{i+1}}$	$L^j_{p_{i+1}}/2$

Therefore, the intermediate factor λ_i is stored in the form of compression, i.e. $c\lambda_i$, and the corresponding run and phrase accompanying dictionary are d_{r_i} and d_{p_i}, respectively. For the jth row of $c\lambda_i$ (denoted as $c\lambda^j_i$), if $c\lambda^j_i$ is a run, it is stored in the form of $\{run, q^j_i, n^j_{r_i}\}$ and the q^j_ith row of d_{r_i} (denoted as $d^j_{r_i}$) is $\{q^j_i, r^j_i, L^j_{r_i}\}$. Otherwise, $c\lambda^j_i$ is stored in the form of $\{phrase, p^j_i, n^j_{p_i}\}$ and the p^j_ith row of d_{p_i} (denoted as $d^j_{p_i}$) is $\{p^j_i, v^j_{1_i}, v^j_{2_i}, L^j_{p_i}\}$. After eliminating the parent node C_i, $c\lambda^j_i$, $d^j_{r_i}$ and $d^j_{p_i}$ are constructed by Appendix A, TABLE 7 and TABLE 8, respectively. Before eliminating the next parent node C_{i-1}, $c\lambda^j_i$ needs to be decompressed and then be compressed row by row based on the methods in [30]. The processes of decompression and compression are introduced by the Case 1 in section IV-A.

2) MULTILEVEL BN RELIABILITY INFERENCE

As shown in FIGURE 2, the lower level's parent nodes are the inputs to the upper level child nodes. Suppose that a complex satellite system multilevel BN has N level and the lth ($l = 1, 2, \cdots, N$) level has K_l nodes. From the bottom level to the top level, the level number increases in turn. For example, the model level is level-1 and the system level is level-4 in FIGURE 2. For the m_lth ($m_l = 1, 2, \cdots, K_l$) node Ch_{m_l} in the lth ($l \geq 2$) level, Ch_{m_l} and its parent nodes in the $(l-1)$th level are equivalent to be a child-BN denoted as $cBN^l_{m_l}$. For $l = 2, 3, \cdots, N$, the multilevel BN reliability inference process of the complex satellite system is shown in the following:

For the NPT of the node Ch_{m_l}, it is compressed by the encoding compression algorithm based on the structure function $\Psi^{m_l}_{Ch}$. Then, the inference of $cBN^l_{m_l}$ is performed by eliminating all parent nodes of node Ch_{m_l} based on Appendix A, TABLE 7 and TABLE 8. Finally, the probability distribution $p(Ch_{m_l})$ of the node Ch_{m_l} can be obtained. For $m_l = 1, 2, \cdots, K_l$, all probability distributions $\{p(Ch_{m_l}) | m_l = 1, 2, \cdots, K_l\}$ of these nodes in the lth level can be calculated by the above calculation process. Then, these probability distributions $\{p(Ch_{m_l}) | m_l = 1, 2, \cdots, K_l\}$ become the inputs of the inference of $cBN^{l+1}_{m_{l+1}}$. Finally, the complex satellite system reliability R_{sat} is equal to $p(Ch_{m_N})$. In summary, the pseudo code of the proposed multilevel BN reliability inference algorithm is shown in TABLE 9.

III. SATELLITE LIFETIME OPTIMIZATION MODELLING

A. OPTIMIZATION OBJECTIVE AND CONSTRAINTS

1) DESIGN VARIABLES

In this paper, the design variables are the number of each optional type of all components' models according to section II-A. For the $\tilde{i}$th subsystem, the number of its components is $\delta_{\tilde{i}}$ ($\tilde{i} = 1, 2, \cdots, \tau$), where τ is the number of subsystems to be designed. For the $\tilde{j}$th component of the $\tilde{i}$th subsystem, the number of alternative models is $\gamma^{\tilde{j}}_{\tilde{i}}$, where $\tilde{j} = 1, 2, \cdots, \delta_{\tilde{i}}$. For the $\tilde{i}$th subsystem, the number of the $\tilde{k}$th model of the $\tilde{j}$th component is $MT^{\tilde{k}}_{(\tilde{i},\tilde{j})}$, where $\tilde{k} = 1, 2, \cdots, \gamma^{\tilde{j}}_{\tilde{i}}$. The maximum and minimum bounds of $MT^{\tilde{k}}_{(\tilde{i},\tilde{j})}$

TABLE 9. Pseudo code of the multilevel BN reliability inference algorithm.

Input	(1)All structure functions: $\{\Psi_{Ch}^{m_l} \vert l = 2, \cdots, N;\ m_l = 1, \cdots, K_l\}$; (2)The root node's marginal probability distribution: $\{p(Ch_{m_1}) \vert m_1 = 1, 2, \cdots, K_1\}$.
Output	Complex satellite system reliability R_{sat}.
Step 1	For $l \leftarrow 2$ to N, do Step 2 to Step 4 to obtain $p(Ch_{m_N})$;
Step 2	(1) Given $\{p(Ch_{m_{l-1}}) \vert m_{l-1} = 1, 2, \cdots, K_{l-1}\}$; (2) For $m_l \leftarrow 1$ to K_l, do Step 3 to Step 4 to calculate $\{p(Ch_{m_l}) \vert m_l = 1, 2, \cdots, K_l\}$;
Step 3	According to structure function $\Psi_{Ch}^{m_l}$, compress the NPT of Ch_{m_l} by the proposed encoding compression algorithm;
Step 4	According to Appendix A, TABLE 7 and TABLE 8, eliminate all parent nodes of node Ch_{m_l} to get the probability distribution $p(Ch_{m_l})$based on VE and the compressed NPT;
Step 5	$R_{sat} = p(Ch_{m_N} = 1)$.

are denoted as $MT_{(\tilde{i},\tilde{j},\tilde{k})}^{\max}$ and $MT_{(\tilde{i},\tilde{j},\tilde{k})}^{\mathrm{mim}}$ respectively, which is decided by designers according to the specific task of the satellite system. Thus, the design variable $MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$ of design space is

$$MT_{(\tilde{i},\tilde{j},\tilde{k})}^{\mathrm{mim}} \leq MT_{(\tilde{i},\tilde{j})}^{\tilde{k}} \leq MT_{(\tilde{i},\tilde{j},\tilde{k})}^{\max}. \tag{4}$$

2) OPTIMIZATION OBJECTIVE

With the mass and power resource constraints which dominates the satellite research and development cost (not considering the operational cost), the satellite design lifetime is expected to be longer with larger revenue. Therefore, the optimization objective is

$$\max\ Life, \tag{5}$$

where *Life* means the satellite design lifetime.

3) CONSTRAINTS

In the satellite conceptual design phase, the main constraints to be considered for the satellite lifetime optimization are the overall mass, power, cost, reliability requirement, and component selection of each subsystem for function fulfillment, which are discussed separately as follows.

a: MASS CONSTRAINT

Given the design scheme $MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$ as shown in equation (1), the overall mass M_{sum} of the satellite can be calculated as follows:

$$M_{sum} = \sum_{\substack{\tilde{i}=1,2,\cdots,\tau \\ \tilde{j}=1,2,\cdots,\delta_{\tilde{i}} \\ \tilde{k}=1,2,\cdots,\gamma_{\tilde{i}}^{\tilde{j}}}} \left[M_{(\tilde{i},\tilde{j})}^{\tilde{k}} \times MT_{(\tilde{i},\tilde{j})}^{\tilde{k}} \right], \tag{6}$$

where $M_{(\tilde{i},\tilde{j})}^{\tilde{k}}$ is the mass of the $\tilde{k}$ th model of the $\tilde{j}$ th component of the $\tilde{i}$ th subsystem. The overall mass M_{sum} should not exceed the limited maximum mass $M_{\max}$ of the satellite, i.e.

$$M_{sum} \leq M_{\max}. \tag{7}$$

b: POWER CONSTRAINT

Given the design scheme $MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$ as shown in equation (1), the overall power P_{sum} of the satellite can be calculated as follows:

$$P_{sum} = \sum_{\substack{\tilde{i}=1,2,\cdots,\tau \\ \tilde{j}=1,2,\cdots,\delta_{\tilde{i}} \\ \tilde{k}=1,2,\cdots,\gamma_{\tilde{i}}^{\tilde{j}}}} \left[P_{(\tilde{i},\tilde{j})}^{\tilde{k}} \times MT_{(\tilde{i},\tilde{j})}^{\tilde{k}} \right], \tag{8}$$

where $P_{(\tilde{i},\tilde{j})}^{\tilde{k}}$ is the power of the $\tilde{k}$ th model of the $\tilde{j}$ th component of the $\tilde{i}$ th subsystem. The overall power P_{sum} should be less than the limited maximum power $P_{\max}$ of the satellite, i.e.

$$P_{sum} \leq P_{\max}. \tag{9}$$

c: COST CONSTRAINT

Given the design scheme $MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$ as shown in equation (1), the overall cost C_{sum} of the satellite can be calculated as follows:

$$C_{sum} = \sum_{\substack{\tilde{i}=1,2,\cdots,\tau \\ \tilde{j}=1,2,\cdots,\delta_{\tilde{i}} \\ \tilde{k}=1,2,\cdots,\gamma_{\tilde{i}}^{\tilde{j}}}} \left[C_{(\tilde{i},\tilde{j})}^{\tilde{k}} \times MT_{(\tilde{i},\tilde{j})}^{\tilde{k}} \right], \tag{10}$$

where $C_{(\tilde{i},\tilde{j})}^{\tilde{k}}$ is the cost of the $\tilde{k}$ th model of the $\tilde{j}$ th component of the $\tilde{i}$ th subsystem. The overall cost C_{sum} should not be larger than the cost budget $C_{\max}$ of the satellite, i.e.

$$C_{sum} \leq C_{\max}. \tag{11}$$

d: RELIABILITY REQUIREMENT CONSTRAINT

Given the design scheme $MT_{(\tilde{i},\tilde{j})}^{\tilde{k}}$ as shown in equation (1), the BN reliability model of the satellite system can be constructed by the method in section II-B. Then, the satellite system reliability can be calculated by its multilevel BN reliability model with the inference method. At the end of the satellite lifetime, the system reliability R_{sat}^{EOL} should not be lower than the limited minimum reliability requirement $R_{\min}^{EOL}$, i.e.

$$R_{sat}^{EOL} \geq R_{\min}^{EOL}. \tag{12}$$

e: COMPONENT SELECTION CONSTRAINT

For each component of the satellite subsystem, there are generally several optional models to be selected to implement the component's function. For example, for a data storage component, there may be multiple alternative models for different product suppliers. It is possible to select only one of the models or combine multiple models for redundancy. But the overall requirement is that at least one model is selected to achieve the component's function. Thus, the sum of the selected numbers of all the optional models is not

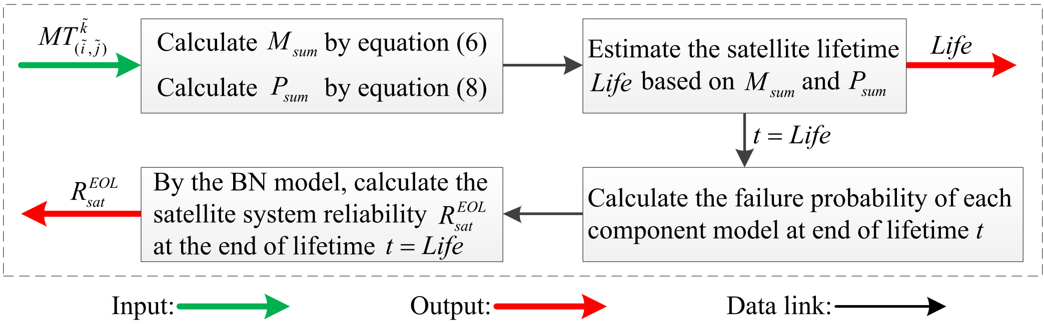


FIGURE 4. **The calculation process of satellite lifetime and system reliability.**

less than 1. For the $\tilde{j}$th component of the $\tilde{i}$th subsystem, the number $Nu^{\tilde{j}}_{\tilde{i}}$ of all the selected models is

$$Nu^{\tilde{j}}_{\tilde{i}} = \sum_{\tilde{k}=1,2,\cdots,\gamma^{\tilde{j}}_{\tilde{i}}} MT^{\tilde{k}}_{(\tilde{i},\tilde{j})}. \tag{13}$$

Therefore, the component selection constraint is $Nu^{\tilde{j}}_{\tilde{i}} \geq 1$.

B. SATELLITE LIFETIME OPTIMIZATION FORMULATION

In the process of satellite lifetime optimization, given the design scheme $MT^{\tilde{k}}_{(\tilde{i},\tilde{j})}$, the overall mass M_{sum}, the overall power P_{sum} and the overall cost C_{sum} are calculated respectively. Then, the design lifetime *Life* is evaluated according to the overall mass M_{sum} and the overall power P_{sum}. Next, at the end of satellite lifetime, i.e. $t = Life$, the failure probability of each optional component model can be calculated by its lifetime distribution. Finally, the satellite reliability at the end of lifetime can be calculated by BN model based on the failure probabilities of optional component models. In summary, the calculation process of satellite lifetime and system reliability is shown in FIGURE 4. It is noteworthy that the BN reliability modelling and inference of satellite system are performed by the proposed encoding compression algorithm and the multilevel BN reliability inference algorithm, respectively.

To sum up, the satellite lifetime optimization problem can be constructed as follows:

$$\text{find} \begin{cases} MT^{\tilde{k}}_{(\tilde{i},\tilde{j})} \\ \tilde{i} = 1, 2, \cdots, \tau \\ \tilde{j} = 1, 2, \cdots, \delta_{\tilde{i}} \\ \tilde{k} = 1, 2, \cdots, \gamma^{\tilde{j}}_{\tilde{i}} \end{cases}$$

$$\max \ Life$$

$$\text{s.t.} \begin{cases} M_{sum} \leq M_{\max} \\ P_{sum} \leq P_{\max} \\ C_{sum} \leq C_{\max} \\ R^{EOL}_{sat} \geq R^{EOL}_{\min} \\ Nu^{\tilde{j}}_{\tilde{i}} \geq 1 \end{cases} \tag{14}$$

Based on the satellite lifetime optimization model, the genetic algorithm (GA) [31], [32] is used to search the optimal solution. The flowchart of satellite lifetime optimization process is shown in FIGURE 5.

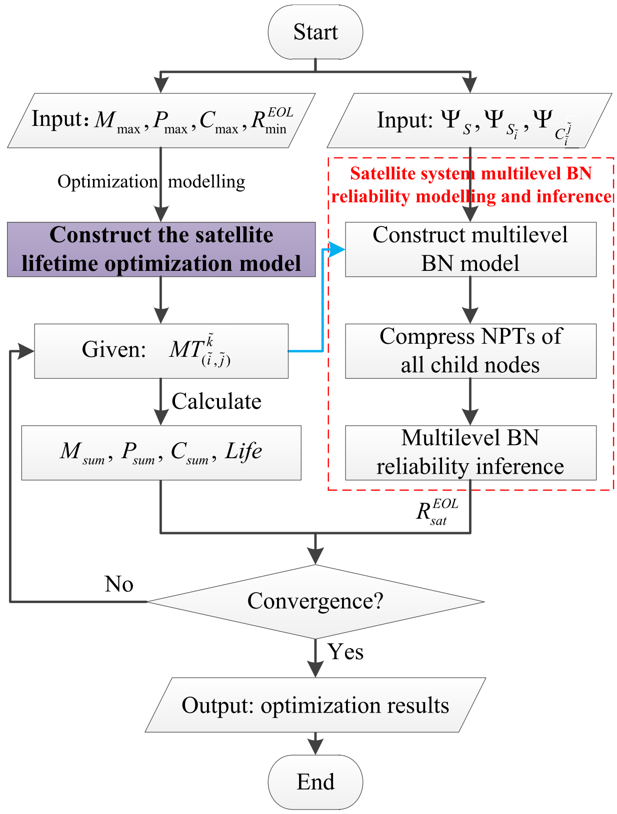


FIGURE 5. **The flowchart of the satellite lifetime optimization process.**

IV. CASE STUDY

A. CASE 1

In this case, a simple two-level satellite subsystem is taken to exemplify the proposed BN reliability compression and inference method. Denote the satellite subsystem node as *Sub*, which has four components denoted as C_1, C_2, C_3 and C_4, respectively. The structure function Ψ_{Sub} between *Sub* and its components indicates that *Sub* will not work normally unless at least two components are normal. Suppose that the normal probability of each component $p(C_i = 1)$ $(i = 1, 2, 3, 4)$ is 0.95.

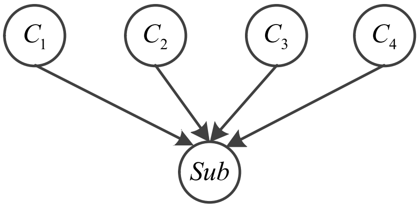


FIGURE 6. BN of the satellite subsystem *Sub*.

TABLE 10. NPT of the satellite subsystem node *Sub*.

C_1	C_2	C_3	C_4	$p(Sub\|C_1, C_2, C_3, C_4)$	
				$Sub = 0$	$Sub = 1$
0	0	0	0	1	0
0	0	0	1	1	0
0	0	1	0	1	0
0	0	1	1	0	1
0	1	0	0	1	0
0	1	0	1	0	1
0	1	1	0	0	1
0	1	1	1	0	1
1	0	0	0	1	0
1	0	0	1	0	1
1	0	1	0	0	1
1	0	1	1	0	1
1	1	0	0	0	1
1	1	0	1	0	1
1	1	1	0	0	1
1	1	1	1	0	1

1) BN RELIABILITY MODELLING AND NPT COMPRESSION

For the satellite subsystem *Sub*, the corresponding BN model can be constructed as shown in FIGURE 6. When the BN model is constructed by the traditional method [21], [35], the NPT of node *Sub* can be obtained as shown in TABLE 10 according to the structure function Ψ_{Sub}. In this paper, the BN model is constructed by the proposed encoding compression algorithm according to the structure function Ψ_{Sub}. The process of compressing the column $p(Sub = 1|C_1, C_2, C_3, C_4)$ is as follows:

Firstly, each parent node's state of *Sub* is calculated by equation (2). Then, the four parent nodes' state combination in the 1st row of NPT is 0 0 0 0, i.e. all components are not normal. Therefore, the 1st row of $p(Sub = 1|C_1, C_2, C_3, C_4)$ is 0 according to the structure function Ψ_{Sub}. As above, both the 2nd row and the 3rd row of $p(Sub = 1|C_1, C_2, C_3, C_4)$ are 0. However, the 4th row is 1 which is different from 0 in the 3rd row. Thus, the first three rows of $p(Sub = 1|C_1, C_2, C_3, C_4)$ constitute a "0" run, i.e. 0 0 0. The "0" run is stored in the form of $\{run, 1, 1\}$ as shown in the first row of TABLE 11, and $\{1, 0, 3\}$ is stored in the run accompanying dictionary as shown in TABLE 12. Besides, the row number 1 is stored in RP_5^1 and S_5^{all}, i.e. $RP_5^1 = [1]$ and $S_5^{all} = \{1\}$. Therefore, $RP_5 = \{RP_5^1\}$.

TABLE 11. Compressed column $p(Sub = 1|C_1, C_2, C_3, C_4)$.

run or $phrase$	p_5^j or q_5^j	n_{p5}^j or n_{r5}^j
run	1	1
$phrase$	1	1
run	2	1
$phrase$	2	1

TABLE 12. Run accompanying dictionary.

q_5^j	r_5^j	L_{r5}^j
1	0	3
2	1	3

TABLE 13. Phrase accompanying dictionary.

p_5^j	v_{15}^j	v_{25}^j	L_{p5}^j
1	1	0	2
2	0	1	8

Repeat the above calculation and query process, the 4th row and the 5th row constitute a phrase, i.e. 1 0. This phrase is stored in the form of $\{phrase, 1, 1\}$ as shown in the second row of Table 3, and $\{1, 1, 0, 2\}$ is stored in the phrase accompanying dictionary as shown in TABLE 13. Similarly, the row number 4 is stored in RP_5^2 and S_5^{all}, i.e. $RP_5^2 = [4]$ and $S_5^{all} = \{1, 4\}$. Therefore, $RP_5 = \{RP_5^1, RP_5^2\}$. The 6th row, the 7th row and the 8th row make up a 1 run, i.e. 1 1 1. Apparently, the "1" run is different from the above "0" run. Thus, "1" run is a new run and it is stored in the third row of TABLE 11 and the second row of TABLE 12. Besides, $RP_5^3 = [6]$, $S_5^{all} = \{1, 4, 6\}$ and $RP_5 = \{RP_5^1, RP_5^2, RP_5^3\}$. In the same way, the last 8 rows of $p(Sub = 1|C_1, C_2, C_3, C_4)$ constitute a new phrase, i.e. 0 1 1 1 1 1 1 1, and it is stored in the fourth row of TABLE 11 and the second row of TABLE 13. Finally, $RP_5^4 = [9]$, $S_5^{all} = \{1, 4, 6, 9\}$ and $RP_5 = \{RP_5^1, RP_5^2, RP_5^3, RP_5^4\}$.

2) INFERENCE PROCESS OF BN RELIABILITY MODEL

Based on TABLE 10, TABLE 11 and TABLE 12, the inference of the BN reliability model as shown in FIGURE 6 is performed according to the methods in section II-C. The inference process is as follows: The parent node C_4 is eliminated firstly. According to Appendix A, TABLE 7 and TABLE 8, the new compressed factor and its two new accompanying dictionaries are shown in TABLE 14, TABLE 15 and TABLE 16, respectively. In particular, for the run in the third row of TABLE 11, its row start number $S_5^3 = 6$ is an even and the run's length $L_{r_5}^3 = 3$ is more than 2. Thus, it is split into two runs as shown in the third row and fourth row of TABLE 14. Besides, RP_5 and S_5^{all} are updated to be $RP_5^{update} = \{[1], [4], [6], [7], [9]\}$ and $S_5^{update} = \{1, 4, 6, 7, 9\}$.

After eliminating C_4, the new compressed intermediate factor $c\lambda_4^{new}$ is decompressed and then compressed

TABLE 14. New compressed intermediate factor $c\lambda_4^{new}$New compressed intermediate factor $c\lambda_4^{new}$.

run or $phrase$	p_4^{j1} or q_4^{j1}	n_{p4}^{j1} or n_{r4}^{j1}
run	1	1
$phrase$	1	1
run	2	1
run	3	1
$phrase$	2	1

TABLE 15. New run accompanying dictionary $d_{r_4}^{new}$.

q_4^{j1}	r_4^{j1}	L_{r4}^{j1}
1	0	1
2	0.95	1
3	1	1

TABLE 16. New phrase accompanying dictionary $d_{p_4}^{new}$.

p_4^{j1}	v_{14}^{j1}	v_{24}^{j1}	L_{p4}^{j1}
1	0.95	-3	1
2	0.95	1	4

TABLE 17. Compressed intermediate factor $c\lambda_4^{new}$.

run or $phrase$	p_4^j or q_4^j or q_4^{j1}	n_{p4}^j or n_{r4}^j
$phrase$	1	1
$phrase$	2	1
run	1	1

synchronously based on $d_{r_4}^{new}$, $d_{p_4}^{new}$, RP_5^{update} and S_5^{update}. The decompression and compression process is as follows:

Querying the first row of TABLE 14, it is a run. According to TABLE 15, the first run is decompressed to be "0". Then, querying the second row of TABLE 14, it is a phrase. According to TABLE 16, the first phrase is decompressed to be "0.95". Apparently, "0.95" is different from "0". Continue to query TABLE 14, the third row is a run. According to TABLE 15, the second row is decompressed to be "0.95". Querying the fourth row of TABLE 14, it is a run. The third row is decompressed to be "1" according to TABLE 15. "1" is different from "0.95". Therefore, the first three rows of the decompressed $c\lambda_4^{new}$ constitute a phrase, i.e. 0 0.95 0.95. This phrase is stored in the form of {*phrase*, 1, 1} as shown in the first row of TABLE 17, and {1, 0, 0.95, 3} is stored in the phrase accompanying dictionary as shown in TABLE 18. Besides, $RP_4^1 = [1]$, $S_5^{all} = \{1\}$ and $RP_4 = \{RP_4^1\}$. It is noteworthy that there is still a remaining "1" here.

Continue to query TABLE 14, the last row is a phrase. According to TABLE 16, this phrase is decompressed to be "0.95 1 1 1". Apparently, "0.95" is different from the above remaining "1". Thus, "1" and "0.95" constitute a phrase, i.e. 1 0.95. This phrase is stored in the form of {*phrase*, 2, 1} as shown in the second row of TABLE 17, and {2, 1, 0.95, 2} is stored in the phrase accompanying dictionary as shown in TABLE 18. The remaining "1 1 1" constitutes a "1" run. This run is stored in the form of {*run*, 1, 1} in the third row of TABLE 17, and {1, 1, 3} is stored in the run accompanying dictionary as shown in TABLE 19.

TABLE 18. Phrase accompanying dictionary d_{p_4}.

p_4^j	v_{14}^j	v_{24}^j	L_{p4}^j
1	0	0.95	3
2	1	0.95	2

TABLE 19. Run accompanying dictionary d_{r_4}.

q_4^j	r_4^j	L_{r4}^j
1	1	3

TABLE 20. Reliability analysis results of Case 1.

Probability	$p(Sub = 0)$	$p(Sub = 1)$
Proposed ECIA	0.00048	0.99952
ICIA by Zheng	0.00048	0.99952
BNT method	0.00048	0.99952
AgenaRisk software	0.00048	0.99952

Based on TABLE 17, TABLE 18 and TABLE 19, the probability distribution of the satellite subsystem can be obtained by eliminating the remaining parent nodes C_3, C_2 and C_1 similarly in the aforementioned way.

3) RESULTS ANALYSIS

The reliability analysis of this two-level subsystem is performed by the proposed encoding compression and inference algorithms (ECIA) in this paper, the improved compression and inference algorithms (ICIA) developed by Zheng *et al.* [29], [36], the Matlab Bayes Net Toolbox (BNT) [35] and the AgenaRisk software [37], respectively. All the methods are run on a 16GB RAM computer with 2.5 GHz Intel(R) Core(TM) i7-4710MQ processor.

a: INFERENCE RESULTS COMPARISON

The reliability analysis results are shown in TABLE 20. Besides, the results of the AgenaRisk software are shown in FIGURE 7. The results of the four methods are exactly the same, which verifies the accuracy of the proposed encoding compression and inference algorithms.

b: MEMORY STORAGE ANALYSIS

For the NPT of binary node *Sub*, its parent nodes have 16 (2^4) state combinations as shown in TABLE 10. Therefore, the BNT method needs 32 cells to store the NPT. By the proposed compression algorithm, the compressed NPT as shown in TABLE 11, TABLE 12 and TABLE 13 needs only $12 + 6 + 8 = 26$ cells to store. Suppose that the satellite subsystem *Sub* has n components as shown in FIGURE 8, and only when the number of normal components is not less

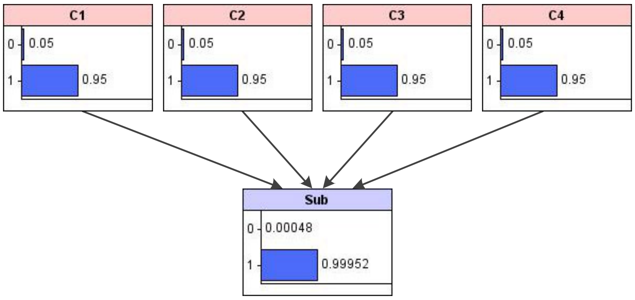


FIGURE 7. Reliability results of Case 1 by the AgenaRisk software.

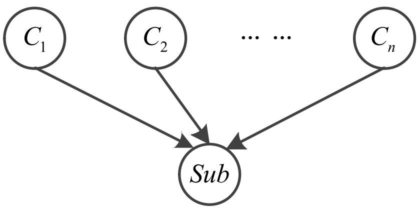


FIGURE 8. BN of the satellite subsystem ***Sub*** with ***n*** components.

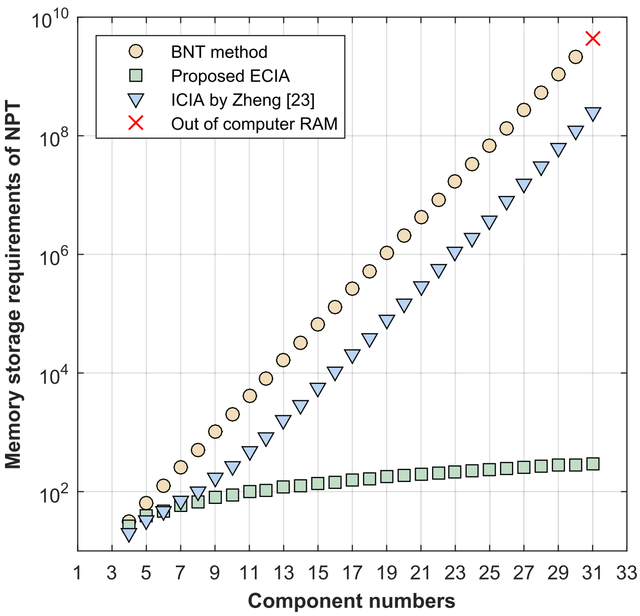


FIGURE 9. The memory storage requirements of the satellite subsystem node's NPT.

than $ceil(n/2)$ can the satellite subsystem *Sub* work normally. With the increase of n, the NPT's memory storage requirements of the BNT method, the proposed ECIA, and the ICIA by Zheng are shown in FIGURE 9, wherein the y-axis uses logarithmic grid. It clearly shows that the NPT's memory storage requirements of both the BNT method and the ICIA by Zheng grow exponentially with the component number. In particular, when the component number is 31, the NPT of the BNT method will need nearly 32 GB RAM to store itself, which excess the computer RAM. But for the proposed ECIA, the need for memory storage remains stable in a low level.

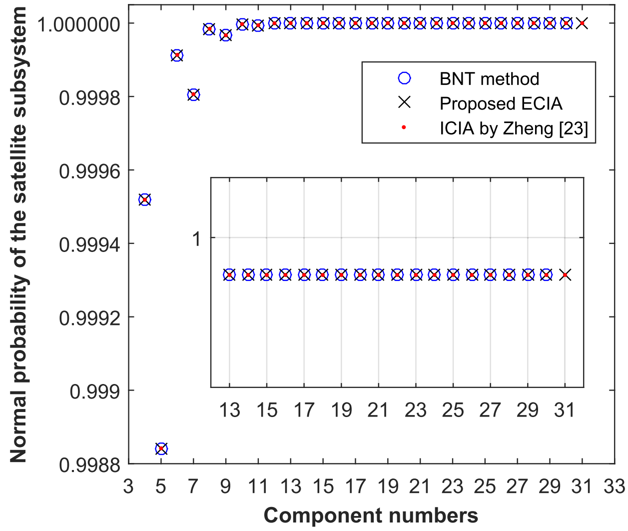


FIGURE 10. The development of the normal probability of the satellite subsystem as the number of components increases.

Besides, as the number of components increases, the normal probabilities of the satellite subsystem calculated by the three methods are shown in FIGURE 10. According to FIGURE 10, the results of the three methods are identical. In particular, when the component number is equal to 31, it is noteworthy that FIGURE 10 does not show the result of the BNT method. This is because the memory requirements of NPT needed by the BNT method have exceeded the computer's RAM in performing the inference of BN. Therefore, the BNT method cannot perform the inference of BN. However, for this situation, both the proposed ECIA and ICIA by Zheng *et al.* [29] still can perform the inference of BN, and the proposed ECIA needs smaller memory requirements of NPT as shown in FIGURE 9.

In summary, the proposed ECIA can reduce the memory storage requirements of NPT effectively and apparently, which greatly enables its wide applicability for extremely large and complex systems.

B. CASE 2

1) BACKGROUND

Suppose a satellite system has twelve main subsystems to be considered, as shown in TABLE 21. The logical relationship between the twelve subsystems is serial. And for each subsystem, its components work in parallel. In total, there are 59 components of the satellite to be defined, and the detailed optional product data is shown in Appendix B. All the models' lifetime distributions are exponential distributions as shown in equation (15), where λ means the failure rate of a component.

$$f(t) = \begin{cases} \lambda e^{-\lambda t}, & t > 0 \\ 0, & \text{other} \end{cases} \tag{15}$$

In designing the satellite, for each component of each subsystem, the optional model or model combination needs to be chosen and the number of each selected model should be

TABLE 21. Twelve subsystems and its components.

Subsystem	Component
Payload subsystem 1	C14, C15
Payload subsystem 2	C16, C17, C18
Avionics subsystem	C19, C20, C21
Antenna subsystem	C22, C23
Data management subsystem	C24, C25, 26, 27, 28
Thermal control subsystem	C29, C30
Propulsion subsystem	C31, C32, C33, C34, C35, C36, C37, C38, C39, C40
Attitude determination subsystem	C41, C42, C43, C44, C45, C46
Solar cell array subsystem	C47, C48, C49, C50, C51
Structure subsystem	C52, C53, C54, C55, C56, C57, C58, C59
Power subsystem	C60, C61, C62, C63, C64, C65, C66
Attitude control subsystem	C67, C68, C69, C70, C71, C72

determined to optimize the satellite lifetime. Set the budget of the max mass, the max power, the max cost, and the minimum reliability at the end of life time to be: $M_{\max} = 3000$kg, $P_{\max} = 1800$W, $C_{sum} = 55$M$ and $R_{\min}^{EOL}$=0.65, respectively.

2) SATELLITE SYSTEM MULTILEVEL BN RELIABILITY MODELLING

According to the satellite structure described in the above section Background, the satellite system multilevel BN reliability model is constructed as shown in FIGURE 11. It is noteworthy that the parent nodes of nodes 14-72 are determined after choosing each component's model or model combination as well as the number of each model. Therefore, from the node 14 to the node 72, each node may have only one parent node or more than one parent nodes. In FIGURE 11, these pending parent nodes, denoted as M14-M72, are represented as dashed circle.

For the root node, its failure probability in the lifetime t can be calculated by

$$F(t) = \int_0^t f(t)dt = \int_0^t \lambda e^{-\lambda t}dt = 1 - e^{-\lambda t}. \quad (16)$$

Therefore, the normal probability is $1 - F(t)$. For the child node, its NPT can be obtained by the logical relationship between the child node and its parent nodes. For example, the payload subsystem 1 (S2) is composed of C14 and C15 in parallel. Thus, the NPT of node 2 is shown in TABLE 22. By the proposed encoding compression algorithm, the column S2 = 1 of TABLE 22 is compressed to be TABLE 23 and TABLE 24.

3) RESULTS ANALYSIS

Embedding the satellite system reliability analysis based on the proposed multilevel BN reliability inference algorithm in the satellite lifetime optimization, and using GA as the optimization solver, the optimization results are shown in TABLE 25 and Appendix C.

TABLE 22. NPT of node 2.

C14	C15	Pr(S2|C14, C15)	
		S2=0	S2=1
0	0	1	0
0	1	0	1
1	0	0	1
1	1	0	1

TABLE 23. Compressed column S2=1.

run or phrase	r^j or p^j	L_r^j or n_p^j
phrase	1	1

TABLE 24. Phrase accompanying dictionary.

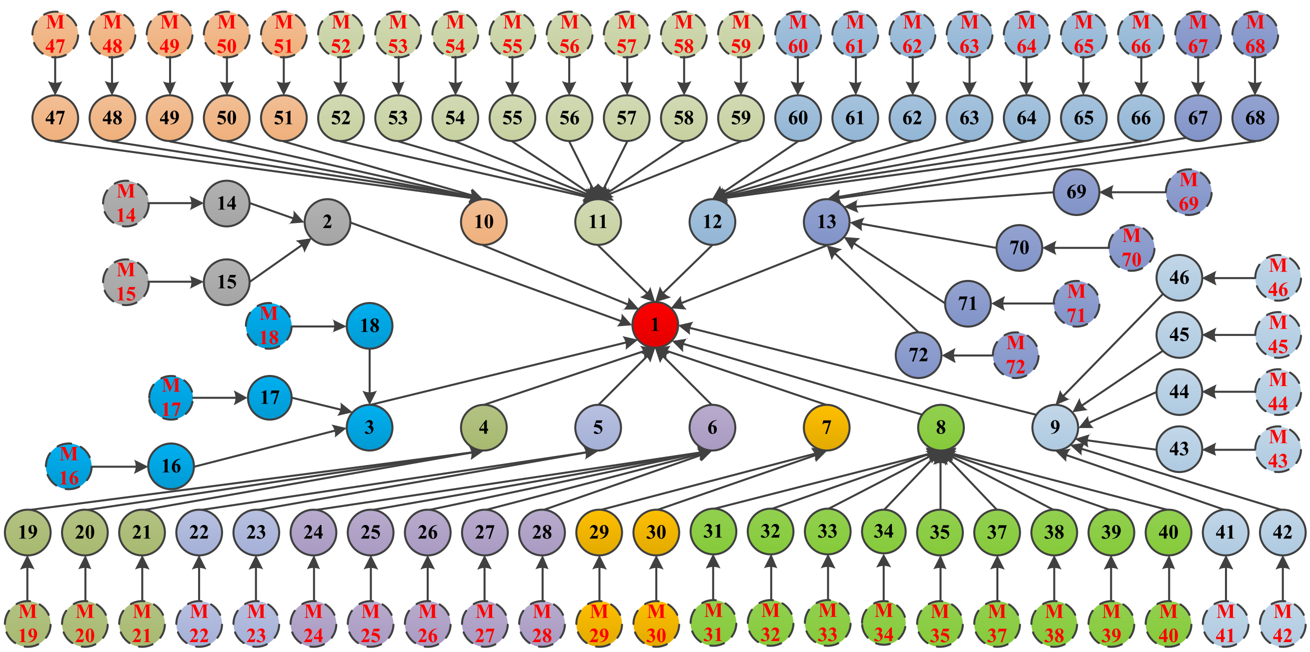
p^j	v_1^j	v_2^j	L_p^j
1	0	1	4

TABLE 25. Satellite system optimization results in Case 2.

	Baseline	Optimization
Design lifetime	5.34 years	7.34 years
Overall mass	2377.0 kg	2763.6 kg
Overall power	1616.9 W	1555.9 W
Overall cost	53.3 M$	54.2 M$
Reliability	0.7732	0.6606

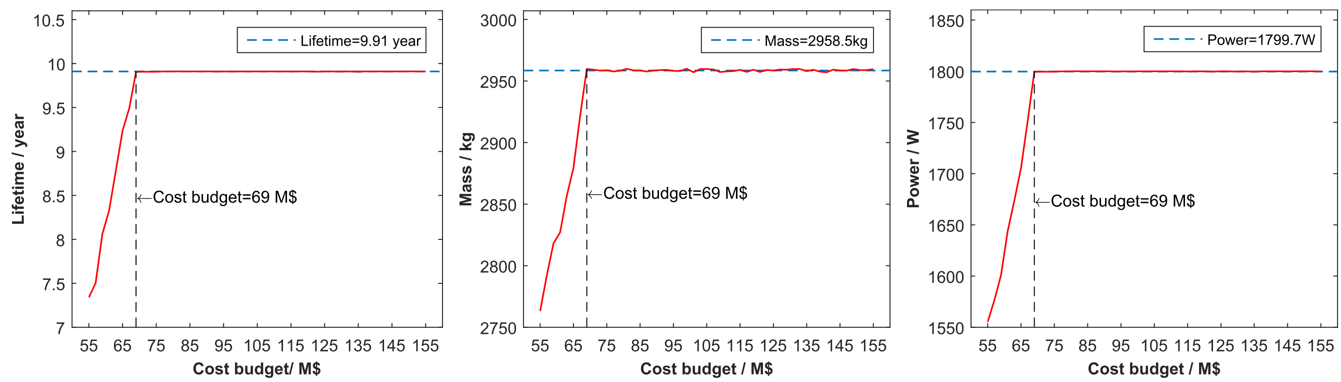
Compared to the baseline scheme, the satellite design lifetime is improved from 5.34 years to 7.34 years after optimization, with only slightly increase of the overall mass, power, and cost which are maintained within the constraint conditions. Especially for the satellite system reliability, under the condition that the satellite design lifetime is extended, the system reliability at EOL still can arrive at 0.6606 (>0.65) by properly optimizing the redundancy allocations of components.

Further study the life optimization effect under different cost budgets by changing the cost budget from 55 M$ to 155 M$ at the step size 2 M$, the optimization results of the satellite design lifetime, overall mass and overall power are shown in (a), (b) and (c) of FIGURE 12, where the x-axis means the cost budget. For the cost budget between 55 M$ and 69 M$, the design lifetime of satellite is improved with the increase of the cost budget according to (a) of FIGURE 12, and the overall mass and the overall power are also improved as shown in (b) and (c) of FIGURE 12. However, as the cost budget increases further, both the overall mass and the overall power remain basically unchanged. At the same time, the satellite design lifetime cannot be improved. Therefore, the mass constraint and the power constraint are the main factors limiting the satellite design lifetime when the cost budget is sufficient.



1-Satellite system; 2-Payload subsystem 1; 3-Payload subsystem 2; 4-Overall circuit subsystem; 5-Antenna subsystem; 6-Data management subsystem; 7-Thermal control subsystem; 8-Propulsion subsystem; 9-Measurement and control subsystem; 10-Solar cell array subsystem; 11-Structure subsystem; 12-Power subsystem; 13-Attitude control subsystem; 14-C14; 15-C15; 16-C16; 17-C17; 18-C18; 19-C19; 20-C20; 21-C21; 22-C22; 23-C23; 24-C24; 25-C25; 26-C26; 27-C27; 28-C28; 29-C29; 30-C30; 31-C31; 32-C32; 33-C33; 34-C34; 35-C35; 36-C36; 37-C37; 38-C38; 39-C39; 40-C40; 41-C41; 42-C42; 43-C43; 44-C44; 45-C45; 46-C46; 47-C47; 48-C48; 49-C49; 50-C50; 51-C51; 52-C52; 53-C53; 54-C54; 55-C55; 56-C56; 57-C57; 58-C58; 59-C59; 60-C60; 61-C61; 62-C62; 63-C63; 64-C64; 65-C65; 66-C66; 67-C67; 68-C68; 69-C69; 70-C70; 71-C71; 72-C72.

FIGURE 11. Satellite system multilevel BN reliability model.



(a) Satellite design lifetime (b) Satellite overall mass (c) Satellite overall power

FIGURE 12. The development trends of the satellite design lifetime, overall mass and overall power.

To further study the effects of the mass constraint and the power constraint on the satellite design lifetime, considering the following three instances:

Instance 1:

$M_{sum} \leq 3000\,\text{kg}$, $P_{sum} \leq 1800\,\text{W}$, $C_{sum} \leq 100$ M$ and $R_{sat}^{EOL} \geq 0.65$.

Instance 2:

$M_{sum} \leq 3000\,\text{kg}$, $P_{sum} \leq 2300\,\text{W}$, $C_{sum} \leq 100$ M$ and $R_{sat}^{EOL} \geq 0.65$.

Instance 3:

$M_{sum} \leq 4000\,\text{kg}$, $P_{sum} \leq 2300\,\text{W}$, $C_{sum} \leq 100$ M$ and $R_{sat}^{EOL} \geq 0.65$.

By the proposed satellite lifetime optimization method, the optimization results of three instances are shown in TABLE 26. The comparison of three instances is shown in FIGURE 13, where the y-axis value for the lifetime, mass and power is the result of normalization based on the baseline scheme.

For **Instance 1** and **Instance 2**, the satellite design lifetime of **Instance 2** is longer than **Instance 1** according to TABLE 26 and FIGURE 13. Compare to the constraints of **Instance 1** and **Instance 2**, only the power constraint of **Instance 2** is more than **Instance 1**. Therefore, under the same conditions of the mass constraint, the cost budget

TABLE 26. Optimization results of three instances.

	Instance 1	Instance 2	Instance 3
Design lifetime	9.91 years	13.31 years	15.17 years
Overall mass	2958.2 kg	2986.9 kg	3591.6 kg
Overall power	1799.6 W	2122.5 W	2299.9 W

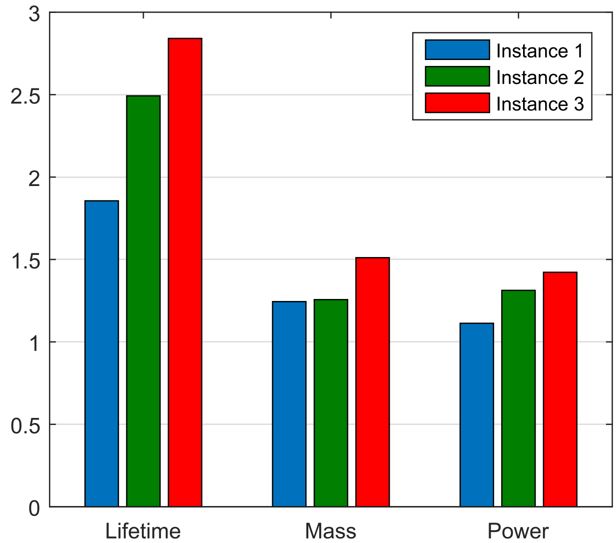


FIGURE 13. Normalization comparison of the satellite design lifetime, mass and power.

constraint and the system reliability constraint, the satellite design lifetime can be improved if the power constraint is relaxed. For **Instance 2** and **Instance 3**, the satellite design lifetime of **Instance 3** is longer than **Instance 2** according to TABLE 26 and FIGURE 13. Compared with the constraints of **Instance 2** and **Instance 3**, only the mass constraint of **Instance 3** is more than **Instance 2**. Therefore, under the same conditions of the power constraint, the cost budget constraint and the system reliability constraint, the satellite design lifetime can be improved if the mass constraint is relaxed.

By the above discussion, the satellite lifetime of the design scheme obtained by the proposed optimization method is longer than the baseline scheme. At the same time, since the satellite system is a complex system with a lot of components which will lead to an exponential increase in the search space size, the obtained optimization design scheme is not necessarily the optimal scheme, such as local optimum scheme. Thus, the obtained optimization design scheme can be used as a reference for engineers. To ensure that the final satellite design scheme is optimal, engineers still need to combine with the actual engineering conditions and the historical engineering experience. Besides, according to the simulation data analysis as shown in FIGURE 12, under the same conditions of the power constraint, the cost budget constraint and the system reliability constraint, the satellite design lifetime can be improved if the mass constraint is relaxed. Therefore, this conclusion also can be a reference for the engineers in designing the satellite.

V. CONCLUSION

In this paper, the satellite lifetime optimization is studied based on the multilevel BN reliability model, wherein the multilevel BN reliability model is constructed by the proposed encoding compression algorithm and the proposed multilevel BN reliability inference algorithm. The proposed encoding compression algorithm can effectively compress the NPT of any binary system with greatly reduced memory storage, which enables its wide applicability for extreme complex systems (e.g. satellite system) with little requirement for computer RAM capability. Based on the compressed NPT, the proposed multilevel BN reliability inference algorithm performs the inference of BN by eliminating parent nodes one by one. Based on the above reliability model, the satellite lifetime optimization model is constructed by considering the constraint conditions of the system reliability, mass, power and cost budget. Two case studies are used to demonstrate and validate the proposed methods of this paper. In Case 1, the reliability analysis of a simple two-level

TABLE 27. Rules for constructing $c\lambda_i^j$.

Switch	Conditions			q_i^j or p_i^j	$n_{r_i}^j$ or $n_{p_i}^j$	R_{i+1}^j	J_{i+1}^j, I and R^{all}
run	$S_{i+1}^j \in$ odd	$L_{r_{i+1}}^j \in$ odd		$q_i^j = q_i^{j-1} + 1$	$n_{r_{i+1}}^j$	$r_{i+1}^j \times p(C_i = 0)$	
			$L_{r_{i+1}}^j \in$ even	$q_i^j = q_i^{j-1} + 1$	$n_{r_{i+1}}^j$	0	
	$S_{i+1}^j \in$ even	$L_{r_{i+1}}^j \in$ odd	$L_{r_{i+1}}^j = 1$	$q_i^j = q_i^{j-1} + 1$	$n_{r_{i+1}}^j$	0	
			$L_{r_{i+1}}^j > 1$	$q_i^j = q_i^{j-1} + 1$ (also $q_i^{j+1} = q_i^{j-1} + 2$)	$n_{r_i}^j = n_{r_{i+1}}^j$ (also $n_{r_i}^{j+1} = n_{r_{i+1}}^j$)	0	$J_{i+1}^j = ism(RP_{i+1}^j, S_{i+1}^{all})$
		$L_{r_{i+1}}^j \in$ even	$L_{r_{i+1}}^j = 2$	$q_i^j = q_i^{j-1} + 1$	$n_{r_{i+1}}^j$	$r_{i+1}^j \times p(C_i = 0)$	
			$L_{r_{i+1}}^j > 2$	$q_i^j = q_i^{j-1} + 1$ (also $q_i^{j+1} = q_i^{j-1} + 2$)	$n_{r_i}^j = n_{r_{i+1}}^j$ (also $n_{r_i}^{j+1} = n_{r_{i+1}}^j$)	$r_{i+1}^j \times p(C_i = 0)$	$I = J_{i+1}^j(1)$
phrase	$S_{i+1}^j \in$ odd	$L_{p_{i+1}}^j \in$ odd	$L_{p_{i+1}}^j = 3$	p_{i+1}^j	$n_{p_{i+1}}^j$	$v_{2_{i+1}}^j \times p(C_i = 0)$	$L_{RP} = length(RP_{i+1}^j)$
			$L_{p_{i+1}}^j > 3$	p_{i+1}^j	$n_{p_{i+1}}^j$	$v_{2_{i+1}}^j \times p(C_i = 0)$	$\begin{cases} \text{for } i_{RP} = 1 : L_{RP}, \text{ do} \\ \quad R^{all}_{J_{i+1}^j(1, i_{RP})} = R_{i+1}^j \\ \text{end} \end{cases}$
		$L_{p_{i+1}}^j \in$ even	$L_{p_{i+1}}^j = 2$	p_{i+1}^j	$n_{p_{i+1}}^j$	0	
			$L_{p_{i+1}}^j > 2$	p_{i+1}^j	$n_{p_{i+1}}^j$	0	
	$S_{i+1}^j \in$ even	$L_{p_{i+1}}^j \in$ odd		p_{i+1}^j	$n_{p_{i+1}}^j$	0	
		$L_{p_{i+1}}^j \in$ even	$L_{p_{i+1}}^j = 2$	p_{i+1}^j	$n_{p_{i+1}}^j$	$v_{2_{i+1}}^j \times p(C_i = 0)$	
			$L_{p_{i+1}}^j > 2$	p_{i+1}^j	$n_{p_{i+1}}^j$	$v_{2_{i+1}}^j \times p(C_i = 0)$	

TABLE 28. Optional component product data:C14-C37.

Component	Model	Mass (Kg)	Power (W)	Cost (M$)	λ	Min-number	Max-number	Baseline	Ψ_i
C14	A	322.5	0	1.200	3.86×10^{-6}	1	1	1	1
C15	A	105	0	0.110	1.43×10^{-6}	1	1	1	1
C16	A	28.4	0	0.310	3.47×10^{-6}	1	3	2	1
C17	A	18.3	5.95	0.200	3.43×10^{-5}	0	4	2	1
	B	17.5	5.21	0.189	3.03×10^{-5}	0	4	0	
	C	19.6	6.33	0.212	2.98×10^{-5}	0	4	0	
	D	20.1	5.86	0.201	3.10×10^{-5}	0	4	1	
C18	A	16.09	10	0.210	5.00×10^{-6}	0	2	1	1
	B	20.31	14	0.231	5.63×10^{-6}	0	2	0	
C19	A	17.35	25.16	0.550	6.58×10^{-5}	1	2	1	1
C20	A	5.44	4.68	0.300	6.58×10^{-7}	1	2	1	1
C21	A	5.22	5.45	0.200	1.43×10^{-6}	1	1	1	1
C22	A	137.6	0	0.500	7.15×10^{-6}	0	2	1	2
	B	140.63	0	0.700	6.87×10^{-6}	0	2	0	
	C	131.4	0	0.561	5.97×10^{-6}	0	2	0	
C23	A	21.24	9.5	0.500	4.32×10^{-5}	2	4	2	1
C24	A	2.8	6.16	0.260	1.04×10^{-6}	1	4	2	1
C25	A	30.18	5.6	0.700	5.72×10^{-6}	2	2	1	1
C26	A	9.11	1.535	0.150	5.72×10^{-6}	2	4	2	1
C27	A	2.3	11	0.350	1.63×10^{-6}	1	4	2	2
C28	A	0.985	0	0.080	1.43×10^{-6}	0	2	1	1
	B	0.896	0	0.065	1.33×10^{-6}	0	2	0	
C29	A	5.45	21.7	0.900	1.43×10^{-6}	1	2	1	1
C30	A	3.58	0	0.080	8.44×10^{-8}	1	2	1	1
C31	A	7	6	0.1025	3.90×10^{-6}	0	8	4	3
	B	8	5.8	0.0983	2.90×10^{-6}	0	8	0	
	C	7.5	5.1	0.110	4.20×10^{-6}	0	8	0	
C32	A	3.5	5.15	0.600	7.32×10^{-6}	0	6	3	1
	B	3.3	4.98	0.580	8.71×10^{-6}	0	6	0	
C33	A	0.54	0.42	0.070	5.83×10^{-6}	1	2	1	1
C34	A	0.103	0	0.028	1.43×10^{-6}	0	10	5	1
	B	0.21	0	0.023	1.11×10^{-6}	0	10	0	
	C	0.18	0	0.032	1.51×10^{-6}	0	10	0	
	D	0.14	0	0.040	1.87×10^{-6}	0	10	0	
C35	A	0.142	0	0.030	1.43×10^{-6}	0	6	3	1
	B	0.231	0	0.025	1.54×10^{-6}	0	6	0	
	C	0.255	0	0.023	1.93×10^{-6}	0	6	0	
C36	A	2	0.7125	0.020	1.43×10^{-6}	0	8	4	3
	B	3	0.812	0.026	1.32×10^{-6}	0	8	0	
	C	4	0.998	0.031	3.23×10^{-6}	0	8	0	
C37	A	5.45	3.29	0.215	1.50×10^{-5}	0	4	2	1
	B	5.98	4.01	0.230	1.20×10^{-5}	0	4	0	

satellite subsystem demonstrates the usage of the proposed encoding compression algorithm and the reliability inference algorithm in detail. Besides, by comparing with the existed methods, the accuracy and compression efficiency of the proposed algorithm are validated. In Case 2, the proposed algorithms are applied to a satellite lifetime optimization problem.

TABLE 29. Optional component product data:C38-C63.

Component	Model	Mass (Kg)	Power (W)	Cost (M$)	λ	Min-number	Max-number	Baseline	Ψ_i
C38	A	8.8	2.37	0.340	1.19×10^{-5}	0	10	5	2
	B	6.9	3.56	0.320	1.31×10^{-5}	0	10	0	
	C	9.1	3.1	0.361	1.09×10^{-5}	0	10	0	
	D	7.2	3.91	0.332	1.35×10^{-5}	0	10	0	
	E	6.3	3.1	0.314	2.29×10^{-5}	0	10	0	
C39	A	8.65	21.4	0.980	1.19×10^{-6}	1	2	1	2
C40	A	10	2.828	0.145	2.88×10^{-5}	2	4	2	1
C41	A	0.35	0	0.025	1.43×10^{-6}	1	4	2	2
C42	A	15.3	35	0.990	3.61×10^{-5}	1	4	2	2
C43	A	1.82	0	0.030	1.43×10^{-7}	0	4	2	2
	B	1.45	0	0.033	1.33×10^{-7}	0	4	0	
	C	1.02	0	0.038	1.21×10^{-7}	0	4	0	
C44	A	1.08	0	0.030	1.43×10^{-7}	1	4	2	2
C45	A	0.1	0	0.025	0	1	2	1	1
C46	A	2	0	0.015	1.43×10^{-9}	1	2	1	1
C47	A	8.78	0	0.100	5.00×10^{-8}	1	4	2	1
C48	A	0.69	0	0.020	8.59×10^{-8}	2	8	4	1
C49	A	0.098	0	0.005	1.57×10^{-5}	0	8	4	3
	B	0.86	0	0.0056	1.24×10^{-5}	0	8	0	
	C	0.79	0	0.0061	1.37×10^{-5}	0	8	0	
	D	0.75	0	0.0089	1.12×10^{-5}	0	8	0	
	E	0.067	0	0.0072	1.01×10^{-5}	0	8	0	
C50	A	0.19	0	0.0025	5.72×10^{-8}	2	8	4	1
C51	A	3.2	0	0.0015	6.44×10^{-7}	1	8	4	1
C52	A	50	0	0.0002	0	1	2	1	1
C53	A	5.1	0	0.035	0	0	2	1	1
	B	4.31	0	0.042	0	0	2	0	
C54	A	39.26	0	0.200	0	1	2	1	1
C55	A	33.94	0	0.280	0	1	2	1	1
C56	A	5.5	0	0.180	0	0	2	1	1
	B	4.2	0	0.195	0	0	2	0	
C57	A	2	0	0.050	1.43×10^{-7}	1	2	1	1
C58	A	3.5	0	0.100	5.29×10^{-7}	1	2	1	1
C59	A	50	0	0.140	1.43×10^{-9}	1	2	1	1
C60	A	7.455	32.2	1.980	9.16×10^{-8}	1	4	2	2
C61	A	3.725	10.54	0.530	4.00×10^{-8}	1	4	2	2
C62	A	1.49	12.9	0.500	1.66×10^{-5}	0	8	4	1
	B	1.24	12.5	0.560	1.36×10^{-5}	0	8	0	
	C	1.14	11	0.612	1.23×10^{-5}	0	8	0	
C63	A	0.24	0	0.100	1.00×10^{-6}	0	8	4	1
	B	0.31	0	0.090	1.01×10^{-6}	0	8	0	
	C	0.25	0	0.105	1.21×10^{-6}	0	8	0	
	D	0.41	0	0.086	1.58×10^{-6}	0	8	0	
	E	0.33	0	0.092	1.68×10^{-6}	0	8	0	

TABLE 30. Optional component product data:C64-C72.

Component	Model	Mass (Kg)	Power (W)	Cost (M$)	λ	Min-number	Max-number	Baseline	Ψ_i
C64	A	0.06	0	0.075	8.00×10^{-6}	0	4	2	1
	B	0.07	0	0.068	6.80×10^{-6}	0	4	0	
C65	A	0.445	0	0.060	1.00×10^{-6}	0	4	2	1
	B	0.567	0	0.051	1.31×10^{-6}	0	4	0	
C66	A	3.025	0	0.060	1.43×10^{-6}	1	2	1	1
C67	A	335.6	417	7.525	2.20×10^{-5}	1	1	1	1
C68	A	335.1	338.6	6.044	2.24×10^{-5}	1	1	1	1
C69	A	60.2	60.7	2.850	1.87×10^{-5}	0	1	1	2
	B	55.1	52.3	3.201	2.07×10^{-5}	0	1	0	
	C	51.3	49.6	3.156	1.61×10^{-5}	0	1	0	
C70	A	93.5	161	3.170	2.14×10^{-5}	0	1	1	1
	B	91.3	156	3.260	1.86×10^{-5}	0	1	0	
	C	98.6	187	3.364	1.93×10^{-5}	0	1	0	
C71	A	146.8	144	4.840	2.45×10^{-6}	1	1	1	1
C72	A	144.4	61	3.090	2.10×10^{-6}	0	1	1	1
	B	132	76	3.500	1.93×10^{-6}	0	1	0	
	C	154	68	3.264	3.01×10^{-6}	0	1	0	

TABLE 31. Optimization design schemes of C14-C31.

Component	Model	Baseline	Optimization
C14	A	1	1
C15	A	1	1
C16	A	2	1
C17	A B C D	2 0 0 1	4 4 2 4
C18	A B	1 0	2 2
C19	A	1	1
C20	A	1	2
C21	A	1	1
C22	A B C	1 0 0	0 0 1
C23	A	2	2
C24	A	2	1
C25	A	1	2
C26	A	2	2
C27	A	2	1
C28	A B	1 0	0 2
C29	A	1	1
C30	A	1	1
C31	A B C	4 0 0	0 0 3

The optimization effects are studied under different constraint conditions and the optimization effect is verified. In designing the satellite, the obtained optimization design scheme can be used as a reference for the engineers. For future research, the proposed methods will be extended to practical satellite life optimization problems with more complex BN structure and multistate conditions.

APPENDIXES

APPENDIX A

Appendix A is shown in TABLE 27. In TABLE 27, $ism(\mathbf{x}, \mathbf{y})$ is used to find the position of each element of $\mathbf{x}$ in $\mathbf{y}$, and $length(\mathbf{x})$ is the function that calculates the length of $\mathbf{x}$. -3 means that the value of the corresponding variable is non-existed.S_{i+1}^{j} is the run or phrase row start number of $c\lambda_{i+1}^{j}$. $p(C_i)$ is the marginal probability distribution of node C_i. J_{i+1}^{j} is a set and $J_{i+1}^{j}(1)$ is the first element of J_{i+1}^{j}. L_{RP} is the elements' number of RP_{i+1}^{j} and $i_{RP} = 1, 2, \cdots, L_{RP}$. $J_{i+1}^{j}(1, i_{RP})$ means the i_{RP} th element of J_{i+1}^{j}. R_{i+1}^{j} is the remainder after finishing the calculation of $c\lambda_{i+1}^{j}$, and R^{all} is the set of all R_{i+1}^{j}. $R^{all}_{J_{i+1}^{j}(1,i_{RP})}$ is the $J_{i+1}^{j}(1, i_{RP})$ th element of R^{all}. I is the position of S_{i+1}^{j} in S_{i+1}^{all}. R_{I-1}^{all} is the $(I-1)\,th$ element of R^{all}. In particular, if $c\lambda_{i+1}^{j}$ is a run and S_{i+1}^{j} is an even, $L_{r_{i+1}}^{j}$ is an even and $L_{r_{i+1}}^{j} > 2$ (or $L_{r_{i+1}}^{j}$ is an odd and $L_{r_{i+1}}^{j} > 1$), $c\lambda_{i}^{j}$and $c\lambda_{i}^{j+1}$ will be constructed at the same time. For this particular situation, RP_{i+1} and S_{i+1}^{all} are updated by the methods as shown in [30].

APPENDIX B

Appendix B includes TABLE 28, TABLE 29 and TABLE 30. In the optional component product data table, Ψ_i means the logical relationship between the selected models which

TABLE 32. Optimization design schemes of C32-C63.

Component	Model	Baseline	Optimization
C32	A B	3 0	0 1
C33	A	1	2
C34	A B C D	5 0 0 0	10 0 0 2
C35	A B C	3 0 0	2 6 1
C36	A B C	4 0 0	4 8 0
C37	A B	2 0	0 4
C38	A B C D E	5 0 0 0 0	0 0 0 1 0
C39	A	1	1
C40	A	2	2
C41	A	2	4
C42	A	2	1
C43	A B C	2 0 0	0 0 3
C44	A	2	1
C45	A	1	1
C46	A	1	1
C47	A	2	4
C48	A	4	2
C49	A B C D E	4 0 0 0 0	8 0 8 0 8
C50	A	4	3
C51	A	4	1
C52	A	1	1
C53	A B	1 0	2 0
C54	A	1	1
C55	A	1	2
C56	A B	1 0	0 2
C57	A	1	1
C58	A	1	1
C59	A	1	1
C60	A	2	1
C61	A	2	1
C62	A B C	4 0 0	1 5 0
C63	A B C D E	4 0 0 0 0	8 3 0 0 0

TABLE 33. Optimization design schemes of C64-72.

Component	Model	Baseline	Optimization
C64	A B	2 0	0 4
C65	A B	2 0	4 2
C66	A	1	1
C67	A	1	1
C68	A	1	1
C69	A B C	1 0 0	0 1 0
C70	A B C	1 0 0	0 1 0
C71	A	1	1
C72	A B C	1 0 0	1 0 0

implement the required function of the component. In the Ψ_i column of TABLE 28, TABLE 29 and TABLE 30, "1", "2" and "3" denotes the logical relationship: parallel, series and cold standby, respectively.

APPENDIX C

Appendix C is shown in TABLE 31, TABLE 32 and TABLE 33.

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