Research Article

A Comprehensive Method of Apportioning Reliability Goals for New Product of Hydraulic Excavator

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It is important to allocate a reliability goal for the hydraulic excavator in the early design stage of the new system. There are some effective methods for setting reliability target and allocating its constituent subsystems in the field of aerospace, electric, vehicles, railways, or chemical system, but until now there is no effective method for the hydraulic excavator or engineering machinery. In this paper, an approach is proposed which combines with the conventional reliability allocation methods for setting reliability goals and allocating the subsystem and parts useful in the early design stage of the hydraulic excavator newly developed. It includes Weibull analysis method, modified Aeronautical Radio Inc. (ARINC) method, and modified systematic failure mode and effect analysis (FMEA) method. After completing reliability allocation, it is necessary to organize the designers and experts to evaluate the rationality of the reliability target through FEMA analysis considering feasibility of the improvement technically for the part which was new developed or had fault in its predecessor. The proposed approach provides an easy methodology for allocate a practical reliability goal for the hydraulic excavator capturing the real life behavior of the product. It proposes a simple and unique way to capture the improvement of the subsystems or components of the hydraulic excavator. The proposed approach could be extended to consider other construction machinery equipment and have practicality value to research excellent mechanical product.

1. Introduction

Reliability goals setting and allocation are important tasks in the early design stage of the hydraulic excavator newly developed; it is essential to allocate scientific reliability target and then apportion it to the subsystems or components of the hydraulic excavator. The advantages of reliability and functions of the hydraulic excavator are key factors for enhancing core competitiveness to a manufacturing enterprise. In recent years, attention to excavator's system reliability has risen for the increase in sophistication of engineering systems used in high technology industry processes [1]. It is a difficult task to set reasonable and realizable reliability goals for excavator which has parallel system. The historical frequency of failures could be measured quantitatively but it is more difficult to quantify the cost sensitivity to the reliability level [2].

Reliability allocation is a top-down method to apportion accuracy goals in a system. Several reliability allocation methods are proposed by many researchers, including Aeronautical Radio Inc. (ARINC) method [3]; Advisory Group

of Reliability of Electronic Equipment (AGREE) method [4]; Feasibility of Objectives (FOO) method which was mentioned in MIL-HDBK-338B [5]; The Boyd method which combines equal method and ARINC method [6]; Critical Flow Method (CFM) [7]; Analytic Critical Flow Method (ACFM) [8]; Karmiol method [9]; Bracha method [10]; Integrated Factors Method (IFM) [11–14]; Analytic IFM method (A-IFM) [15, 16]; The Maximum Entropy Ordered Weighted Averaging (ME-OWA) method [17–19]; and the method using risk priority number (RPN) generated during failure modes and effect analysis (FMEA) to link reliability allocation [20–25], each with its advantages and disadvantages, but none of them is suitable for the reliability allocation of the hydraulic excavators completely. Some conventional reliability allocation methods do not consider the reliability improvement potential except the FEMA method; corrective actions are defined and implemented by identifying potential problems and calculating the risk to eliminate or reduce their occurrence possibility [26–28]. The existing methods as previously mentioned for setting achievable reliability

TABLE 1: Principal advantages and disadvantages of the allocation methods for hydraulic excavator system reliability [13, 15].

No.	Method	Advantages	Disadvantages
1	AGREE	Good detail	Only applicable to systems in series Partial subjectivity of the analyst
2	ARINC	Application simplicity Objectivity	Only applicable to systems in series Only applicable in the initial phases
3	BRACHA	Exact analytical treatment	Not easy determination of stress factors Components criticality not considered
4	KARMIOL	Very good detail Applicable to innovative systems	Subjectivity of the analyst Applicable to systems in series
5	FOO	Application simplicity	Discrete ordinal scales of measure
6	BOYD	Applicable to innovative systems Versatility	System factors are not equally weighted Only applicable to systems in series of the initial phases
7	IFM	Good detail applicable to innovative systems Applicable into different design phases in different industries and fields	Only applicable to systems in series
8	A- IFM	Accurate and realistic	Components or parts improvement not considered
9	RPN-Based	Consider reliability improvement impact on system performance	May allocate a high reliability to a subsystem having a high severity
10	ME-OWA	Accurate and flexible Applicable to systems in series-parallel	Partial subjectivity of the analyst
11	CFM	Application simplicity Applicable to systems in series-parallel	Irrespective reliability improvement
12	ACFM	Good detail Applicable to systems in series-parallel	Irrespective reliability improvement

goals to each subsystem or component are characterized by its own advantages and disadvantages. The methods were summarized and introduced in these papers [7, 13, 15] in great detail. Table 1 shows the advantages and disadvantages of the literature methods which could be applied to the hydraulic excavator.

Parallel-series systems hydraulic excavators have hundreds of components; project progress will be prolonged if each one is analyzed with the FMEA method. It is scientific to combine several methods by utilizing their advantages and remedying their disadvantages that not only conform to the actual situation, but also increase the reliability of hydraulic excavators effectively.

2. Analysis of Reliability Allocation Method

If sufficient historical failure information from previous design was available, the Aeronautical Radio Inc. (ARINC) method could be used to estimate the failure rate of subsystems easily [20].

The Aeronautical Radio Inc. (ARINC) is an apportionment technique method which is based on the failure rates of units or subsystems [29]. It can be used if database or previous experience on similar subsystem, allowing predicting failure rate of the subsystem above, is expressed as

$$\lambda_{i*}^* = w_{i*} \cdot \lambda^* \quad (1)$$

$$w_{i*} = \frac{\lambda_i}{\sum_{i=1}^k \lambda_i} \quad (2)$$

where λ_{i*}^* is the failure rate of unit i and w_{i*} is a reliability allocation weight for unit i , for $i = 1, \dots, k$.

This method seems to be the first reliability allocation methods that consider historical information for obtaining allocation weights but not consider the improvement of the subsystems and the components.

Several papers proposed reliability allocation approaches considering the field failure and failure analysis information generated during historical warranty data. The modified failure mode and effect analysis (FMEA) method which uses the risk priority number (RPN) was defined as the multiplication of the severity ranking and occurrence ranking of a failure modes in a subsystem that makes it good for verifying the feasibility of the reliability target of the subsystems or the components [20].

FMEA was developed in the 1960s by the aerospace industry. It was a systematic method for identifying different failure modes and their effects occurring in the system. A few recent papers [20–22, 26–30] use RPN information generated during the criticality analysis of FMEA considering the failure effect in reliability allocation. The RPN of failure mode j in subsystem i was given by

$$RPN_{ij} = S_{ij} \cdot O_{ij} \cdot D_{ij} \quad i = 1, 2, \dots, k, \quad j = 1, 2, \dots, N_i \quad (3)$$

Then, the reliability allocation weight is given by

$$w_i = \frac{\omega_i}{\sum_{i=1}^k \omega_i} \quad (4)$$

where $\omega_i = 1 - C_i / \sum_{i=1}^k C_i$ and $C_i = (1/N_i) \sum_{j=1}^{N_i} (S_{ij} \times O_{ij} \times D_{ij})$ where S_{ij} 's are severity ranking, an evaluation of how serious the effect would be if a given failure modes did occur, O_{ij} 's are occurrence ranking, the failure frequency, or the qualitative failure rate, and D_{ij} 's are detection ranking, an assessment of an ability of the failure being detected.

In a mission critical system, however, the detection ranking is not included in the RPN calculation because the detection of a failure mode is considered when assigning a severity ranking. Thus, the RPN for a mission critical system is given by [20]

$$\begin{aligned} \text{RPN}_{ij} &= S_{ij} \cdot O_{ij} \quad i = 1, 2, \dots, k, \quad j = 1, 2, \dots, N_i \\ w_i &= \frac{\omega_i}{\sum_{i=1}^k \omega_i} \end{aligned} \quad (5)$$

where $\omega_i = 1 - C_i / \sum_{i=1}^k C_i$
and $C_i = (1/N) \sum_{j=1}^{N_i} (S_{ij} \times O_{ij})$

Yadav proposed a reliability allocation method considering failure criticality and functional dependency [31]. The reliability allocation weight for subsystem i is given as

$$\begin{aligned} w_i &= \frac{w_D D_i + w_c C_i}{\sum_{i=1}^k (w_D D_i + w_c C_i)}, \quad i = 1, 2, \dots, k, \\ C_i &= \sum_{j=1}^{N_i} \sum_{k=1}^{K_i} (S_{ijk} O_{ijk}) \end{aligned} \quad (6)$$

where D_i and C_i denote functional dependency and criticality of subsystem i , whereas w_D and w_c represent the importance assigned to dependency and criticality, factors respectively, K_i denote the functions supported by subsystem i , and S_{ijk} , O_{ijk} indicate the severity and occurrence rankings for failure mode j of function k supported by subsystem i .

Then Kyungmee O. Kim proposed a new approach [22] that suggests exponential transformation of the original 10 point ordinal severity rating to reduce severe failure effect effectively. Therefore, the reliability weight is given as

$$\begin{aligned} w_i &= \frac{1 / (m_i \bar{S}_i F_i)}{\sum_{i=1}^k 1 / (m_i \bar{S}_i F_i)}, \quad i = 1, 2, \dots, k, \\ \bar{S}_i &= \exp(\alpha S_i) \end{aligned} \quad (7)$$

where $\bar{S}_i$ is transformed severity and F_i is failure frequency of subsystem and m_i is the number of failure modes in subsystem having maximum severity rating.

Because these ratings are follow linearity assumption in rating scale, a general understanding among design community is easy to think that improving reliability of a poor subsystem than improving reliability of a highly reliable

subsystem. And sometimes lower reliability is assigned to a subsystem already having lower failure frequency.

Yadav proposed a more realistic and effective reliability approach [1] based on nonlinear phenomena in severity rating and failure rate; the severity of subsystem i has multiple failure mode defined as

$$\bar{S}_i = \max(\bar{S}_{i1}, \bar{S}_{i2}, \dots, \bar{S}_{ij}), \quad j = 1, 2, \dots, n \quad (8)$$

$$s_i = \frac{\bar{S}_i}{\sum_{i=1}^n \bar{S}_i} \quad (9)$$

$$c_i = \frac{s_i}{e_i}, \quad i = 1, 2, \dots, n$$

where $w_i = c_i / \sum_{i=1}^n c_i$, $i = 1, 2, \dots, n$, $e_i = E_i / \sum_{i=1}^n E_i$, $E_i = -\ln \lambda_i / r$, $i = 1, 2, \dots, n$.

The reliability allocation method ensures each subsystem getting improvement target is assigned in proportion of potential for improvement and exposes technological difficulty in achieving improvement goals when negative failure rate target is assigned.

While calculating RPN, although these methods have been considering potential for subsystems or components improvement, technology difficulty and complexity of a given subsystem, to some extent, allocate reliability in accordance with degrees of difficulty in achieving reliability target; however, if the improvement effort is effective in reality, the kinds of measures that could be taken for achieving the reliability targets were not taken into account. So it is imperative to develop practical reliability allocation method for hydraulic excavators considering effective measures in accordance with degree of difficulty for improvement effort.

3. Proposed Comprehensive Methods for Reliability Allocation

In this section, based on the database of operation and maintenance of the existing hydraulic excavators, the failure rate is used for the reliability evaluation indexes; a comprehensive allocation method is proposed to perform the reliability allocation for the hydraulic excavator newly developed which considers effective measures for reliability improvement to allocate reliability. Decision-making procedure used in this study is shown in Figure 1.

3.1. Perform Reliability Goal for New System. Weibull distribution [32–34] and modifications of the Weibull distribution [35, 36] for reliability analysis were discussed by several authors. Many researchers have suggested the lifetime distribution of the hydraulic excavator follows the Weibull distribution [37–40]; they stated above use Weibull distribution as theoretical reliability model, according to the experimental data, analyzed the reliability of the subsystems for the excavator. So the reliability goal of the new systems in this study is gained based on Weibull analysis. Assume the lifetime of the hydraulic excavator follows two-parameter Weibull distribution.

FIGURE 1: Decision-making procedure used in this study.

Failure frequency function for Weibull distribution is given as follows:

$$f(t) = \left(\frac{\beta}{\eta}\right) \left(\frac{t}{\eta}\right)^{(\beta-1)} \cdot e^{-(t/\eta)^\beta} \quad t \geq 0 \quad (10)$$

Reliability function for Weibull distribution is given as follows:

$$R(t) = e^{-(t/\eta)^\beta} \quad t \geq 0 \quad (11)$$

And unreliability function or cumulative distribution function is given as

$$F(t) = 1 - R(t) = 1 - e^{-(t/\eta)^\beta} \quad t \geq 0 \quad (12)$$

And failure rate function is given as

$$\lambda = \frac{f(t)}{R(t)} = \left(\frac{\beta}{\eta}\right) \cdot \left(\frac{t}{\eta}\right)^{\beta-1} \quad (13)$$

where β is shape parameter and η is scale parameter.

3.2. Reliability Allocation. The failure data of subsystems for existing hydraulic excavators should be utilized in design of

new hydraulic excavator. The subsystem or component which has a low failure frequency is also reliable if unchanged in the new design, and it is natural to allocate a high reliability to these subsystems.

Based on the maintenance data of existing hydraulic excavators, the failure frequency factor of the subsystem or components is given as follows:

$$w_i = \frac{N_i}{N_s} = \frac{N_i}{\sum_{i=1}^n N_i} \quad (14)$$

where N_i represents the subsystem or components failure number and N_s represents the total number of failures.

We allocated the subsystems and the components which are newly designed or have recorded faults by the modified ARINC method as in (14).

3.3. Amend the Reliability Target considering the RPN of the Improvements. Commonly, the design community thought that the subsystems or components with higher failure rate must be assigned lower reliability target and with lower failure rate must be assigned higher reliability target in new corresponding subsystems, but reliability target of the subsystems or components is disproportionate to the failure rate. In the hypothesis that linear or nonlinear relationship between

failure rate and improvement effort does not usually conform to the reality, the key is that if the design community can take effective measures to reduce the failure rate or increase Mean Time Between Failure (MTBF), higher subsystems or components reliability target should be assigned; otherwise, it is adjusted to lower reliability level.

The experts are organized to evaluate the allocation reliability target in Section 3.2 term by term and provide effective measures for subsystems or components. Considering the restriction by intricacy, state of the art, maintainability, manufacturing technology, working conditions, and cost, reliability target for subsystems or components should be amended by the modified FEMA method as shown in Table 4 when an effective measures are provided; otherwise, we follow the original reliability target.

Table 2 describes the severity ranking and linguistic terms used to describe the failure effect. Table 3 presents the linguistic terms for the occurrence ranking and the corresponding quantitative failure rate; both of them are calculated through market share and failure rate of one type of particular brand hydraulic excavators and could be revised according to the actual applying.

The allocation weight of the subsystems or components that have effective measures is recalculated by

$$d_i = \frac{1}{N_i} \sum_{j=1}^{N_i} (S_{ij} \times O_{ij}) \quad j = 1, 2 \dots N_i \quad (15)$$

$$e_i = \frac{1}{N_i} \sum_{j=1}^{N_i} (S_{ij}^* \times O_{ij}^*) \quad (16)$$

So the upgrade rate of the subsystems or components is defined as

$$E_i = \left(1 - \frac{d_i}{e_i} \right) * 100\% \quad (17)$$

Replace the subsystem or component reliability target $\lambda_i^* = \lambda^* * w_i$ with

$$\lambda_{in}^* = \lambda * w_i * (1 + E_i) \quad (18)$$

3.4. Applicability of the Methodology. The proposed approach was applied to the hydraulic excavator system in the early design stage for new product development based on the ARINC method and FEMA method. It is a simple and effective approach which uses failure and maintenance data of the previous generation. The most important is that it provides a realistic reliability allocation method considering the improvement of the parts and components and can be used in different industries and filed.

3.5. Execution Steps. The proposed approach for reliability allocation applied to the hydraulic excavator is structured in the following steps.

Step 1. The following 6 units of the hydraulic excavator for facilitating subsequent improvement are pointed out:

Unit 1: hydraulic subsystem.

Unit 2: electric subsystem.

Unit 3: power subsystem.

Unit 4: working device subsystem.

Unit 5: chassis subsystem.

Unit 6: body and accessories subsystem.

Step 2. Data was collected over a period of 2 or 3 years and sorted out according to the subsystems and parts which have been pointed out in Step 1. Because the hydraulic excavators guarantee period is 2000~3000h, working hours ≤ 3000 h are chosen.

Step 3. The reliability index λ is gained based on the statistic data, as shown in Table 5.

Step 4. The reliability target (failure rate) is allocated to the subsystems in proportion to allocation weights (w_i) by the modified ARINC method.

Step 5. Reliability target for subsystems or components will be amended by the modified FEMA method, replace the subsystem or component reliability target $\lambda_i^* = \lambda w_i$ with $\lambda_{in}^* = \lambda * w_i * (1 + E_i)$ if the target allocated in Step 4 is hard to achieve.

4. Illustrative Example

In this section the proposed approach is applied to the reliability goal setting and allocation for the hydraulic excavator SC5532 in the early design stage to illustrate its feasibility and applicability. Furthermore, an analysis of the proposed methodology is subsequently performed to validate its effectiveness.

4.1. Implementation. The case study will be discussed involving a period of 2-year maintenance data of a type of SC5532 belonging to the company LISHIDE to illustrate the modeling approach proposed in Section 3. All of the failures happening time as shown in Table 6 counted 146 times for 151 excavators. Then the $f(t)$, $F(t)$, $R(t)$, and $\lambda(t)$ were calculated range from 0 to 3000 hours and the interval time was 300 hours, as shown in Table 7. The total failure rate of the current hydraulic excavator systems at 3000 hours was calculated as $\lambda = 0.01383012$. Now suppose we want to improve the failure rate by 20%, so that the system failure rate goal was given by $\lambda^* = 0.01106409$.

The failures times for failure components of the hydraulic excavator subsystems and the weights were calculated with (14), as shown in Table 8. The fault-free components with failure rate $\lambda_i^* = 0$ were excluded in Table 8.

The reliability target (λ^*) was allocated to the parts in the new system which had fault recording in existing hydraulic excavators.

After reliability allocation, the reliability targets need to be verified considering the improvement of the components

TABLE 2: Suggested ranking system for the severity of failure modes.

Rank (s_{ij})	Failure Effect	Failure Criterion	Illustration(e.g.)
10	Inconsistent with the safety legislation or the regulations	Hazardous without warning Potential safety, health, or environmental issue	failure of a braking system
9		Failure will occur with warning Potential safety, health, or environmental issue	leakage of a braking system
8	disruption or decline to facility function	The machine run malfunctioning	uncoordinated boom, arm and bucket movements
7		The machine running properly but Moderate disruption to facility function	travel slower than the speed limit
6	disruption or decline to secondary function	Some portion of secondary function is lost	failure of a position feedback of the GPS
5		Moderate disruption to secondary function Some portion of process is delayed	shock absorber of the seat damaged
4	Appearance or noise and other functions is poor	Most users(>75%) likely to complain	abnormal engine noises
3		More than half (>50%) of the users likely to complain	distortion of the hood
2		a few users(>25%) likely to complain	excessive clearances on the surfaces
1	No discernible effect on safety, environment, or mission		

TABLE 3: Suggested ranking system for the occurrence of failure modes.

Rank (O_{ij})	Comment	Failure frequency
10	Extremely high	≥ 0.2
9	Very high	≥ 0.1
8	Repeated failures	≥ 0.05
7	High	≥ 0.03
6	Moderately high	≥ 0.02
5	moderate	≥ 0.01
4	Relatively low	≥ 0.005
3	Low	≥ 0.001
2	Remote	≥ 0.0005
1	Nearly impossible	≥ 0.0001

by the designers or the experts who were responsible for sub-systems or components. In this case the hydraulic cylinders were selected to verify the rationality of the reliability target. The boom cylinders, arm cylinders, and bucket cylinders will be analyzed together for they are working on the same principle and with the same failure modes. The designers and experts were organized to do FEMA analysis and put forward the improving measures and predict S_{ij}^* , O_{ij}^* of each failure mode for cylinders as shown in Table 9.

$\lambda_{\text{cylinder}}^* = 0.001515629$ was obtained from Table 8, and $\lambda_{\text{cylinder new}}^* = 0.001016059$; then the reliability target of the cylinder $\lambda_{\text{cylinder}}^*$ was replaced with $\lambda_{\text{cylinder new}}^*$. Similar analysis as described above could be used for all the other components of the hydraulic excavators.

4.2. Comparison and Discussion. For further validation of the effectiveness of the approach proposed in this article, the comparative analysis is performed with the conventional FEMA. It must be a tedious process to do reliability goal setting and allocation to the parts or components of the hydraulic excavator which have a large, complex system by the conventional FEMA method. So the modified ARINC method here is used to extract the parts or components which can be improved as the reliability target by statistics analysis of the historical failures and maintenance data from the previous generation. As shown in Table 8, the components' preliminary reliability target was set, respectively, by the modified ARINC method. But in this step, the same reliability target is allocated to the different components with the same failure times without considering the improvement of them. That is, by using the traditional FMEA, different sets of O, S ratings can yield the same RPN value, which entails that these components should be given the same reliability target. Since the restriction by intricacy, state of the art, maintainability, manufacturing technology, working conditions, and cost, the reliability target could be higher or lower than allocated. Then the modified FEMA method could be used to amend the components' reliability target by the RPN* value considering the improvement measures of them. The proposed approach has some advantages, such as the following:

- (1) The proposed approach is effective for providing more meaningful information for risk management decision made based on the modified ARNIC method in many practical applications.
- (2) The proposed approach fuses personal judgments of FEMA team members into group assessments; it is

TABLE 4: FEMA of the parts for excavators.

Failure Part	Potential Failure Modes	Failure Cause	S_{ij}	O_{ij}	RPN	Improvement Measures	S_{ij}^*	O_{ij}^*	RPN*
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TABLE 5: Basic data of certain type of excavators.

i	Group intervals	Δn	$f(t)$	$F(t)$	$R(t)$	$\lambda(t)$
1	0-0.300					
2	0.301-0.600					
3	0.601-0.900					
	...					
10	2.700-3.000					

TABLE 6: Failures time of the predecessor's hydraulic excavator LISHIDE SC5532 in 10^3 [h].

0.098	0.256	0.427	0.729	1.035	1.436	1.994
0.177	0.221	0.413	0.788	1.126	1.489	2.023
0.183	0.237	0.441	0.790	1.066	1.460	2.019
0.189	0.245	0.430	0.771	1.182	1.493	2.071
0.196	0.280	0.587	0.795	1.130	1.530	2.109
0.199	0.223	0.565	0.833	1.069	1.554	2.193
0.128	0.259	0.557	0.818	1.181	1.512	2.225
0.167	0.221	0.532	0.869	1.233	1.562	2.348
0.159	0.282	0.548	0.822	1.274	1.573	2.386
0.184	0.248	0.566	0.894	1.215	1.587	2.217
0.189	0.281	0.573	0.731	1.223	1.665	2.371
0.195	0.236	0.578	0.983	1.286	1.697	2.424
0.267	0.222	0.581	0.921	1.299	1.733	2.470
0.296	0.358	0.785	0.929	1.272	1.789	2.493
0.207	0.373	0.792	0.936	1.338	1.731	2.513
0.212	0.396	0.806	0.945	1.337	1.829	2.516
0.216	0.325	0.611	0.960	1.359	1.880	2.635
0.225	0.324	0.650	0.974	1.304	1.896	2.768
0.248	0.419	0.674	0.983	1.311	1.903	2.844
0.267	0.402	0.727	0.997	1.353	1.971	2.972
0.284	0.417	0.710	1.031	1.357	1.989	

TABLE 7: Data of reliability of the hydraulic excavator LISHIDE SC5532 measured in 10^3 [h].

Group intervals	Δn	$f(t)$	$F(t)$	$R(t)$	$\lambda(t)$
0-0.300	34	0.00075055	0.00075055	0.999249448	0.00096866
0.301-0.600	21	0.00046358	0.00121413	0.998785872	0.00072917
0.601-0.900	19	0.00041943	0.00163355	0.998366446	0.00082251
0.901-1.200	17	0.00037528	0.00200883	0.997991170	0.00094444
1.201-1.500	18	0.00039735	0.00240618	0.997593819	0.00142857
1.501-1.800	11	0.00024283	0.00264901	0.997350993	0.00118280
1.801-2.100	10	0.00022075	0.00286976	0.997130243	0.00158730
2.101-2.400	7	0.00015453	0.00302428	0.996975717	0.00166667
2.401-2.700	6	0.00013245	0.00315673	0.996843267	0.00250000
2.700-3.000	3	0.00006623	0.00322296	0.996777042	0.00200000

TABLE 8: Weight of each component.

Units	Subsystems	Failure Parts	Failure Times	Allocation Factor (w_i)*	Failure rate (λ^*_i)
Unit1	Hydraulic	boom cylinder	10	0.06849315	0.000757814
		bucket cylinder	4	0.02739726	0.000303126
		arm cylinder	6	0.04109589	0.000454689
		pilot valve	7	0.04794521	0.000530470
		accumulator	4	0.02739726	0.000303126
		steel pipe	5	0.03424658	0.000378907
		hose	11	0.07534247	0.000833596
		main pump	7	0.04794521	0.000530470
		main valve	4	0.02739726	0.000303126
		ball valve	2	0.01369863	0.000151563
		transition joins	6	0.04109589	0.000454689
Unit2	Electric	GPS	9	0.06164384	0.000682033
		diode	3	0.02054795	0.000227344
		work lamp	1	0.00684932	0.000075781
		position switch	1	0.00684932	0.000075781
		wiring harnesses	3	0.02054795	0.000227344
		wipers	5	0.03424658	0.000378907
Unit3	Power	engine	1	0.00684932	0.000075781
		Accelerator knob	7	0.04794521	0.000530470
		auxiliary water	4	0.02739726	0.000303126
		belt	1	0.00684932	0.000075781
		starting motor	1	0.00684932	0.000075781
		gasoline pump	13	0.0890411	0.000985159
		radiator	2	0.01369863	0.000151563
		tank cap	6	0.04109589	0.000454689
Unit4	Working device	boom	5	0.03424658	0.000378907
		bucket	4	0.02739726	0.000303126
Unit5	Chassis	tension spring	3	0.02054795	0.000227344
		crawler	4	0.02739726	0.000303126
Unit6	Body and accessories	door lock	4	0.02739726	0.000303126
		sprinkling can	1	0.00684932	0.000075781
		air spring	2	0.01369863	0.000151563

able to relieve the influence of unfair opinions on the risk analysis result.

- (3) Using the proposed approach we are able to realize the reliability target allocated to the components or the parts taking into account the improvement measures, both subjective and objective weights could be considered in the reliability allocation of the hydraulic excavator systems.

5. Conclusion and Future Work

In this paper, we described an approach based on ARINC method and FEMA method for reliability target goal set and allocated the parts and components of the hydraulic excavator newly developed taking into account the reliability improvement. It is worth mentioning the following:

- (1) The reliability goal of the hydraulic excavator newly developed have been set utilizing the indicator failure

rate $\lambda^* = 0.01106409/3.0 \cdot 10^3$ [h] with analytical methods based on the failure data which obeys the Weibull (2P) distribution.

- (2) For testing the validity of the reliability target considering the improvement of the components, the designers or the experts responsible for subsystem or components were organized to do FEMA analysis of the components. The reliability target should be revised if there are effective measures for improvement.
- (3) Increasing the reliability of the hydraulic excavator is a full life-cycle activity, including the process of designing, experimental testing, technology route planning, parts purchasing, production, and maintenance. So it is important to control and prevent failures of the components and subsystems at each stage of development to achieve the reliability goal and to improve the reliability of the hydraulic excavator new products after finishing the reliability allocation.

TABLE 9: FEMA of the hydrocylinders.

Failure part	Potential Modes	Failure Cause	Failure Times	S_{ij}	O_{ij}	RPN	Improvement Measures	S_{ij}^*	O_{ij}^*	RPN*
hydro-cylinder	creeping	extra air in the cylinder excessive internal friction unfitting assembly low machining accuracy	5	7	8	56	(1) to strengthen quality inspection for hydro-cylinders;	7	4	28
	Slow speed	Excessive internal leakage Larger external load higher oil temperature	10	7	9	63	(2) make sure excellent in heat radiation of the system, (3) Adjust overflow pressure of the relief valve in hydro-cylinders	7	5	35
	Inadequate thrust	higher back pressure fault of the overflow valve unfitting assembly	5	7	7	49	(4) adjust the back pressure of the oil return	7	4	28

- (4) The proposed approach in this paper could be used not only to allocate reliability for hydraulic excavators, but also for other construction machinery equipment after a few modifications.

In the future, the research could focus on developing a software tool to make the proposed FEMA approach simple and convenient to help reliability allocation more efficient for enhancing hydraulic excavators' system reliability and safety.

Data Availability

The data used to support the findings of this study have not been made available because we have used third party data; it belongs to the LISHIDE Company which is mentioned in our manuscript; we do not own the data, and for the privacy and commercial confidentiality of the company, we cannot deposit them in a publicly available data repository. But we make sure all the data supporting the conclusions of the study is real and effective. The readers who want to obtain the source of the data could contact the company technical director: Qingxiang Huan (Email: cchc_yf001@163.com).

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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