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Interval Analysis and DEMATEL-Based Reliability Apportionment for Energy Consumption Optimization With Energy Internet

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ABSTRACT Energy Internet represents a critical breakthrough that allows traditional energy to be transformed into intelligent energy. In this regard, the reliability apportionment technologies for modern products within Energy Internet deserve more attention because they can ensure the reliability optimization of different functional modules of systems. And because of the growingly serious energy crisis, environmental protection has become much more urgent, which requires industrial products to be more environmental friendly. However, traditional reliability apportionment methods can not do this. First, in design phase of product, most of them tend to ignore the environmental attributes, including carbon emissions and resource efficiency. Second, they fail to process the uncertainties of reliability apportionment, which is inevitable and important efficiently. Third, they pay insufficient attention to the correlations among product subsystems, which greatly influence the different product functions. To overcome these drawbacks, a reliability apportionment model based on the interval analysis and decision-making trial and evaluation laboratory is proposed. The validity of the proposed method is demonstrated by a case study.

INDEX TERMS Energy internet, energy consumption, carbon emissions, reliability apportionment, interval analysis, DEMATEL

I. INTRODUCTION

With the development of industry and society, global energy demand is rapidly increasing, which has caused the growing discrepancy between supply and demand [1]. Energy Internet is the advanced stage of combined developments in information communication and electric energy technologies. It can contribute to solve these environmental problems [2]–[4]. However, it also brings serious challenges and opportunities in the development of the world economy [5], [6]. Energy Internet is strong in achieving connections and sharing of energy utilization, the transformation of various energy types, and the combination of information as well as energy technology. The main feature of Energy Internet is the gradual integration of infrastructures in intelligent energy management (IEM), energy routers (E-router), as well as future renewable electric energy delivery and management (FREEDM), bringing a powerful ability to reduce carbon emissions and improve energy efficiency [7]–[9]. Therefore, Energy Internet is of strategic importance in energy conservation and environmental protection.

However, the development of Energy Internet is currently confronted with many challenges. For instance, it lacks social participation and renewable energy consumption. Above all, Energy Internet involves not only distributed coordinated control algorithms [10], hierarchical cluster synchronization [11], and large quantities of information, but also higher requirement for reliability of key equipment in the corresponding infrastructures. Reliability implies the capability of a system or component to perform its intended functions consistently under its definite with limited period [12], [13]. Reliability apportionment is the apportionment process for predefined requirement regarding the reliability of individual elements, whose purpose is to assign limited resources to the most important subsystems or components, as well as to ensure the designed functions of products under specific operating condition [14], [15]. Therefore, reasonable reliability apportionment in the early design stage of products is conductive to their later detailed design [16].

Energy depletion and carbon pollution have generated additional loads in the cycles within the natural ecosystem. The emissions from each link in the energy development and consumption chains have a serious impact on the safety margins of the ecosystem, and Energy Internet has emerged as the answer to these issues [17], [18]. It is obvious that the technologies supporting reliability apportionment for complex modern products within Energy Internet deserve more attention [19]. Product reliability apportionment is a multiple-criteria decision making (MCDM) task, and its typical tools include the decision-making trial and evaluation laboratory (DEMATEL), analytical hierarchical process (AHP), and integrated factors methodology (IFM), as well as analytical network processes (ANP) [20]–[25]. Product complexity and functionality also increase greatly due to the rapid progress of technology and fierce market competition; hence, traditional methodologies cannot sufficiently meet the demands for modern product reliability apportionment any longer.

Firstly, rapid development of the world industries has led to a series of environmental problems, such as climate change and global warming caused mainly by the growing amount of carbon emissions [28]. Thus, for emissions reduction and energy efficiency, products are urgently desired to be as environmentally efficient as possible [26], [27]. Most traditional reliability apportionment methodologies used in the design phase of product fail to consider a product's environmental attributes.

Nowadays, studies on carbon emissions mainly focused on one or several aspects, such as carbon emissions and climate change, emissions calculations, emission factors decomposition, as well as emissions projections [29]; few scholars attempted to combine carbon emissions with product reliability apportionment. For example, Jung *et al.* [30] performed an analysis of factors affecting carbon emissions and absorption in a university campus based in Pusan National University in Korea. Robinson *et al.* [31] conducted a study on the effects of emission control strategies on light-absorbing carbon emissions from a modern heavy-duty diesel engine. Shi and Zhao [32] analyzed China's current nonferrous metal industry (NMI) trends in the energy-saving and emission reduction efforts with the consideration of potential areas driving factors. Wang *et al.* [33] established a decomposition model with quantitative analysis for daily household energy-related carbon emissions which were related to energy consumption. These researchers paid little attention to carbon emissions with respect to product reliability apportionment. At the same time, product life cycle design is beneficial in achieving optimum product performance under conditions of the minimum environmental costs and the lowest economic cost. Product life cycle involves the product design, manufacture, use and scrap [26]. The focuses of product life cycle design are not only the products themselves but also the activities in the product life cycle related to economy, technology and environment [27]. Therefore, it has a broader design category than traditional product design. This requires that the product design activities should consider the aspects of "product", such as function, structure and material, as well as the "activities" in product life cycle, such as manufacturing, maintenance, scrap and recycling. At the same time, because of the "products" and "product life cycle" are inseparable, the best performance of the product life cycle can be achieved only when they are integrated organically. Therefore, performing product reliability apportionment from the view of the product life cycle has real significance.

Secondly, most traditional methodologies fail to efficiently address the uncertainties of the reliability apportionment process. Due to difficulties in collecting sufficient information for many engineering problems including observation distortion, resource limitations, system complexity, and so on, uncertainties are usually unavoidable when modeling real industrial products, especially at the beginning of the design process. Therefore, reasonable reliability apportionment methodologies must be good at handling such uncertainties [34]–[37].

Bayesian models and fuzzy theories were the early tools for gauging the uncertainties in traditional product reliability apportionment [38]–[41]. Wu *et al.* [42] proposed the reliability apportionment for a spacecraft solar array using fuzzy reasoning, Petri nets, and fuzzy comprehensive evaluation, but it is impracticable if the assessment information is expressed in a crisp manner by domain experts. Therefore, Sriramdas *et al.* [38] introduced the fuzzy arithmetic-based reliability apportionment during early design phase. Similarly, Cheng *et al.* [15] established a reliability apportionment model based on AHP and fuzzy mathematical calculations which put more emphasis on the fuzzy characteristics of reliability apportionment. However, Bayesian models and fuzzy theories have some shortcomings. Bayesian approaches remain such as a subjective representation of uncertainty which will reduce the accuracy of product reliability apportionment schemes. Fuzzy sets and their membership functions must be known but it is a formidable task for decision makers to specify the appropriate membership functions in advance. In order to overcome these drawbacks, the interval analysis for reliability apportionment was put forward in which many engineering parameters are specified as intervals numbers [43]–[45]. Wu and Lin [43] proposed the maximum likelihood estimator to measure the product properties in the whole life cycle. Lu *et al.* [44] put forward a programming method combined geographic information system, interval analysis and probability statistics. Wang *et al.* [45] conducted the interval analysis for product reliability redundancy optimization which has non-probabilistic uncertainties. In recent years, interval analysis has been integrated with mixed uncertainty, probability, fuzzy theory, and gray system theory for more rational reliability analysis and optimal design [46]–[48].

Thirdly, although interval analysis can handle the uncertainty issues well in product reliability apportionment, these methodologies based on interval analysis fail to pay sufficient attention to the correlations among produc subsystems. Modern products often perform different functions which are facilitated by the mutual correlations among subsystems, and these correlations should not be overlooked. Fortunately, DEMATEL is a powerful methodology that and it is good at gathering group knowledge for capturing the causal relationships between criteria, and it has been gradually used in many industrial fields, such as marketing strategies, e-learning evaluations, managers' competencies, control systems, and airline safety problems [21], [49]. Therefore, rational product reliability apportionment taken interval analysis with DEMATEL into consideration is with great research value. A practical reliability apportionment model for complex systems in the context of Energy Internet is important for guaranteeing normal functioning of Energy Internet [4]. Thus, to overcome the mentioned problems, a novel reliability apportionment methodology based on interval analysis and DEMATEL is proposed in this paper from the perspective of the product life cycle.

The remainder of this paper is organized as follows. Section II introduces the product life cycle factors and process for the proposed methodology. Section III introduces the detail operators and Section IV illustrates a case study of the reliability apportionment for a waste tire granulator using the proposed methodology. Then, Section V presents a comparison between the proposed methodology and the traditional interval analysis reliability apportionment methodology, and Section VI is the conclusion.

II. PFACTORS AND PROCESS

In order to conveniently establish the proposed models, the following factors and process are presented.

A. FACTORS

Through in-depth analysis, it can be found that one of the reasons that products have a negative impact on the environment is that most of them lacked sufficient technical consideration of environmental attributes when they were initially designed. Hence, to overcome the limitations of traditional reliability apportionment methodologies in that they tended to neglect a product's environmental attributes including carbon emissions and resource efficiency, as shown in Fig. 1, the whole product life cycle is divided into five stages: design, manufacture, service, maintenance and scrap/recycle. Then, five product life cycle factors which influence the reliability apportionment are selected to represent these stages, and they are cost sensitivity (C), carbon emission (E), failure severity (F), maintenance cost (M) and resource efficiency (T).

The relationships between these factors and the reliability apportionment are also demonstrated in Fig. 1, where R_i is the reliability apportioned to the *i*th subsystem. For cost sensitivity, subsystems with high cost sensitivity tend to be apportioned with low reliability to reduce the system cost. For carbon emissions, subsystems with high carbon emissions should be apportioned with high reliability to reduce the product's overall carbon emissions. For failure severity, subsystems with high failure severity should be apportioned with high reliability to improve the whole security of the product. For maintenance cost, subsystems with high maintenance cost should be apportioned with high reliability to reduce the whole product maintenance cost. For resource efficiency, subsystems with poor recyclability should be apportioned with high reliability to reduce the energy waste of the whole product.

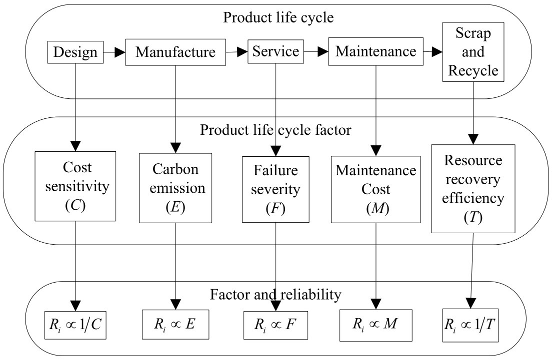


FIGURE 1. Five product life cycle factors for product reliability apportionment.

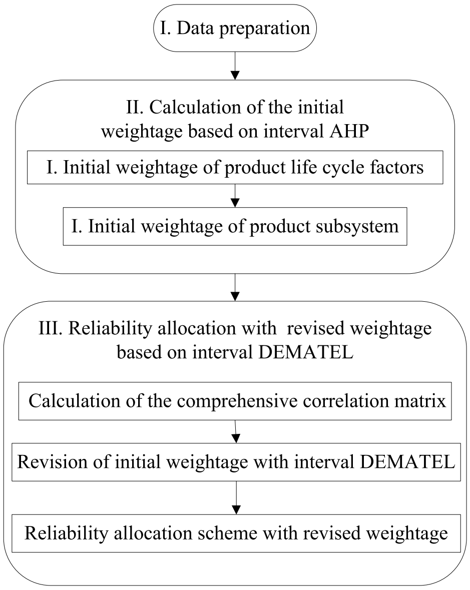


FIGURE 2. General process of the proposed reliability apportionment method.

B. PROCESS

As shown in Fig. 2, the proposed methodology contains three major phases in which the product life cycle is taken into account based on interval analysis and interval DEMATEL.

1) PHASE I

Relevant data is prepared in this phase. First, target system reliability is determined based on market demands. Then, experts on the target product are invited to assess the importance of each product life factor and subsystem based on the corresponding pairwise comparisons, as well as the degree of correlations among subsystems. Evaluation data is expressed through the internal number between [0, 9]. To avoid a distortion of the reliability apportionment results caused by high uncertainty, the width of the interval numbers must be restricted to being within 2.

2) PHASE II

Define R^* as the target system reliability, and w_i as the initial weightage of the ith subsystem ($i = 1, 2, \ldots, n$, and n is the total number of subsystems of the target product) with the traditional interval analysis reliability apportionment method, the initial apportioned reliability for the ith subsystem is calculated as shown in (1), and Section 3 describes the detail operators.

$$R_i^* = \left(R^*\right)^{w_i}, \tag{1}$$

3) PHASE III

According to the interval correlations among subsystems defuzzified and merged with the weighted sum approach, interval DEMATEL is employed to revise the initial weightage obtained in Phase II, and the final product reliability apportionment scheme is available in this phase. In addition, detailed operators are described in Section III.

III. DETAIL OPERATORS FOR THE PROPOSED METHOD

A. BASIC ARITHMETIC AND DEFUZZIFICATION

On the real number line, an interval $[a, b]$ is the set of all real numbers. In particular, an interval number is essentially a real number when $a = b$. Basic arithmetic and defuzzification of interval numbers must be introduced in order to conduct the interval analysis operators [50].

Let (m_1, n_1) and (m_2, n_2) be two interval numbers, where m_1 and m_2, n_1 and n_2 denote left-end and right-end points, respectively. Then, the basic interval arithmetic is expressed as (2)–(5). In addition, let $A^\# = [m, n]$ be an interval number, and its defuzzified value is denoted as A and it can be calculated by (6), where v is the caution indicator of the decision maker. When $v = 0$, 0.5 and 1, decision makers are in the most radical condition, the most mean condition and the most mean cautious condition, respectively.

$$[m_1, n_1] + [m_2, n_2] = [m_1 + m_2, n_1 + n_2] \tag{2}$$

$$[m_1, n_1] - [m_2, n_2] = [m_1 - n_2, n_1 - m_2] \tag{3}$$

$$\begin{aligned}[m_1, n_1][m_2, n_2] = [&\min(m_1m_2, m_1n_2, n_1m_2, n_1n_2), \\ &\max(m_1m_2, m_1n_2, n_1m_2, n_1n_2)]\end{aligned} \tag{4}$$

$$\begin{aligned}[m_1, n_1]/[m_2, n_2] &= [m_1, n_1][1/n_2, 1/m_2], \\ &\text{where } 0 \notin [m_2, n_2]\end{aligned} \tag{5}$$

$$A = [(m + n) + (2v - 1)(n - m)]/2 \tag{6}$$

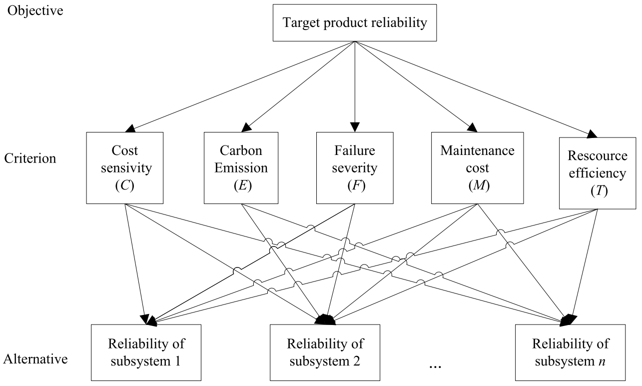


FIGURE 3. Hierarchy of reliability apportionment based on product life cycle.

B. TRADITIONAL INTERVAL ANALYSIS

A hierarchy of reliability apportionment based on product life cycle factors is shown in Fig. 3. Firstly, the weightages of the product life cycle factors should be obtained. Secondly, the initial weightage of each product subsystem is calculated.

1) WEIGHTED VECTOR FOR PRODUCT LIFE CYCLE FACTORS

As an important part of the product reliability apportionment, the weighted vector for product life cycle factors is determined mainly based on their influences. Interval numbers are selected to express the expert evaluation of the weightage of each factor due to the incomplete information included in the single value.

Step 1. The interval judgment matrix for the reliability apportionment factors $\boldsymbol{D}^\#$ is established as shown in (7).

$$\begin{aligned} D^\# &= [D^-, D^+] \\ &= \begin{bmatrix} d_{11}^\# & d_{12}^\# & \cdots & d_{1m}^\# \\ d_{21}^\# & d_{22}^\# & \cdots & d_{2m}^\# \\ \vdots & \vdots & \vdots & \vdots \\ d_{m1}^\# & d_{m2}^\# & \cdots & d_{mm}^\# \end{bmatrix} \\ &= \begin{bmatrix} [d_{11}^-, d_{11}^+] & [d_{12}^-, d_{12}^+] & \cdots & [d_{1m}^-, d_{1m}^+] \\ [d_{21}^-, d_{21}^+] & [d_{22}^-, d_{22}^+] & \cdots & [d_{2m}^-, d_{2m}^+] \\ \vdots & \vdots & \vdots & \vdots \\ [d_{m1}^-, d_{m1}^+] & [d_{m2}^-, d_{m2}^+] & \cdots & [d_{mm}^-, d_{mm}^+] \end{bmatrix} \end{aligned} \tag{7}$$

where $d_{ij}^\#$ is the relative importance between the ith and jth reliability apportionment factors ($i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, m$, and m is the total number of reliability apportionment factors).

Step 2. It is necessary to check the consistency of the interval judgment matrix by (8) and (9). If $0 < a^- < a^+ < 1$, the consistency of the interval judgment matrix is within the acceptable range, and the decision makers can go to Step 3. Otherwise, the interval judgment matrix needs to be revised and an expert evaluation should be conducted again until its consistency is allowable.

$$a^{-} = \sqrt{\sum_{j=1}^{5}\left(1/\sum_{i=1}^{5} d_{ij}^{+}\right)}, \tag{8}$$

$$a^{+} = \sqrt{\sum_{j=1}^{5}\left(1/\sum_{i=1}^{5} d_{ij}^{-}\right)}, \tag{9}$$

Step 3. The largest eigenvalues a^{-} and a^{+}, as well as the corresponding normalized eigenvectors X^{-} and X^{+} of matrices D^{-} and D^{+} can be calculated in this step, and the interval numbers of the reliability apportionment factors, $w_f^{\#}$, is available through (10).

$$w_f^{\#} = [a^{-}, a^{+}]X^{\#} = [a^{-}X^{-}, a^{+}X^{+}] \tag{10}$$

2) WEIGHTED VECTOR OF SUBSYSTEMS FOR PRODUCT

Experts are invited to assess the subsystem importance for product life cycle factors. It can be seen from Fig. 1 that the cost sensitivity and resource efficiency of a subsystem are inversely proportional to its apportioned reliability, while the carbon emissions, failure severity, and maintenance cost of a subsystem are proportional to its apportioned reliability. Thus, the evaluation rules for them are different. The higher the cost sensitivity of a subsystem, the higher the expert evaluation related to its cost sensitivity. The higher the carbon emissions for a subsystem, the lower the expert evaluation related to its carbon emissions. The higher the failure severity of a subsystem, the lower the expert evaluation related to its failure severity. The higher the maintenance cost of a subsystem, the lower the expert evaluation related to its maintenance cost. The higher the resource efficiency of a subsystem, the higher the expert evaluation related to its resource efficiency cost. As shown in Tabel I, expert evaluation information is expressed in interval numbers. The importance matrices for product life cycle factors C, E, F,M, as well as T are represented respectively as $M_1^{\#}$, $M_2^{\#}$, $M_3^{\#}$, $M_4^{\#}$, and $M_5^{\#}$, and they can be calculated by (11)–(12).

$$M_k^{\#} = \begin{bmatrix} q_{11}^{\#} & q_{12}^{\#} & \cdots & q_{1n}^{\#} \\ q_{21}^{\#} & q_{22}^{\#} & \cdots & q_{2n}^{\#} \\ \vdots & \vdots & \vdots & \vdots \\ q_{n1}^{\#} & q_{n2}^{\#} & \cdots & q_{nn}^{\#} \end{bmatrix} \tag{11}$$

$$q_{ij}^{\#k} = \frac{p_i^{\#k}}{p_i^{\#k} + p_j^{\#k}}, \quad (i \neq j) \text{ and } q_{ij}^{\#k} = [0.5, 0.5], (i = j) \tag{12}$$

The comprehensive weightage for the ith subsystem for the kth product life cycle factor is represented as $h_i^{\#k}$ The interval weighted vector of subsystems for the kth product life cycle and the comprehensive interval weighted vector of subsystems for product life cycle factors can be obtained as $N_k^{\#}$ and $CN^{\#}$ by (13)–(15). The initial interval reliability apportionment weighted vector of subsystems is defined as $w_{sub}^{\#}$ and calculated by (16).

TABLE 1. Expert evaluation table on the importance of product subsystem.

Subsystem	C	E	F	M	T
S$_1$	$p_1^{\#1}$	$p_1^{\#2}$	$p_1^{\#3}$	$p_1^{\#4}$	$p_1^{\#5}$
S$_2$	$p_2^{\#1}$	$p_2^{\#2}$	$p_2^{\#3}$	$p_2^{\#4}$	$p_2^{\#5}$
…	…	…	…	…	…
S$_n$	$p_n^{\#1}$	$p_n^{\#2}$	$p_n^{\#3}$	$p_n^{\#4}$	$p_n^{\#5}$
	C	E	F	M	T

$$h_i^{\#k} = [h_i^{k-}, h_i^{k+}] = [\frac{\sum_{i=1}^{j} q_i^{k-}}{n}, \frac{\sum_{i=1}^{j} q_i^{k+}}{n}] \tag{13}$$

$$N_k^{\#} = \begin{bmatrix} h_1^{\#k} & h_2^{\#k} & \cdots & h_n^{\#k} \end{bmatrix}_{1\times n} \tag{14}$$

$$CN^{\#} = [\,N_1^{\#} \quad N_2^{\#} \quad \cdots \quad N_2^{\#}\,]^{T} \tag{15}$$

$$w_{sub}^{\#} = w_f^{\#} \times CN^{\#} = [w_{S1}^{\#}, w_{S2}^{\#}, \cdots, w_{Sn}^{\#}] \tag{16}$$

where $w_f^{\#}$ is the interval number of the reliability apportionment factors obtained by (10), and $w_{si}^{\#} = [w_{si}^{-}, w_{si}^{+}]$ is the initial interval weightage of ith subsystem.

Finally, defuzzification of the initial interval reliability apportionment weighted vector for subsystems is necessary to get the initial defuzzified reliability apportionment weighted vector for subsystems, which is represented as $w_s = [w_{s1}, w_{s2}, \ldots, w_{sn}]$, where w_{si} is the initial defuzzified weightage of ith subsystem for reliability apportionment.

C. INTERVAL DEMATEL

Correlation information is represented by the interval number and processed to revise the initial weightage through interval DEMATEL, and then a rational reliability apportionment scheme can be established. The procedure for reliability apportionment with interval DEMATEL is as follows.

The correlations between the ith and jth subsystems are preliminarily expressed with interval numbers and the compromised interval correlation matrix $H^{\#}$ is obtained as shown in (17)

$$H^{\#} = \begin{bmatrix} [0, 0] & n_{12}^{\#} & \cdots & n_{1n}^{\#} \\ n_{21}^{\#} & [0, 0] & \cdots & n_{2n}^{\#} \\ \vdots & \vdots & \vdots & \vdots \\ n_{n1}^{\#} & n_{n2}^{\#} & \cdots & [0, 0] \end{bmatrix} \tag{17}$$

where $n_{ij}^{\#} = [n_{ij}^{-}, n_{ij}^{+}]$ is the interval correlation degree that the ith subsystem has in affecting the jth subsystem, and $n_{ij}^{\#} = [0, 0]$ when $i = j$.

The compromised matrix $H^{\#}$ is processed to be the normalized interval correlation matrix $X^{\#}$ by (18)–(20). Let

$$g_i^{\#} = \sum_{j=1}^{n} n_{ij}^{\#} = [g_i^{-}, g_i^{+}] \tag{18}$$

$$s^{\#} = \max_{1 \le i \le n} \left(\frac{g_i^- + g_i^+}{2}\right) \tag{19}$$

$$X^{\#} = H^{\#}/s^{\#} \tag{20}$$

The matrix $X^{\#}$ is defuzzified to be a numerical correlation matrix X by (6). The total correlation matrix T can be acquired using (21).

$$T = X(I - X)^{-1} \tag{21}$$

where I is denoted as the identity matrix.

Supposing $t_{ij}(i, j = 1, 2, \ldots, n)$ as the elements of total correlation matrix $\boldsymbol{T}$, the sums of the rows and the columns denoted as R_i and C_j, respectively, can be determined by (22) and (23).

$$R_i = \sum_{j=1}^{n} t_{ij} \quad (i = 1, 2, \ldots, n) \tag{22}$$

$$C_j = \sum_{i=1}^{n} t_{ij} \quad (i = 1, 2, \ldots, n) \tag{23}$$

where the $(R+C)$ value indicates the degree of relation among subsystems, and the $(R - C)$ value denotes the strength of the influence on each subsystem. To keep this value positive, the $(R - c)$ value is introduced, where c represents the average strength of influence on each subsystem, which can be computed by (24).

$$c_i = \frac{C_i}{\sum_{i=1}^{n} C_i} \quad (i = 1, 2, \ldots, n) \tag{24}$$

D. REVISION OF THE INITIAL RELIABILITY APPORTIONMENT

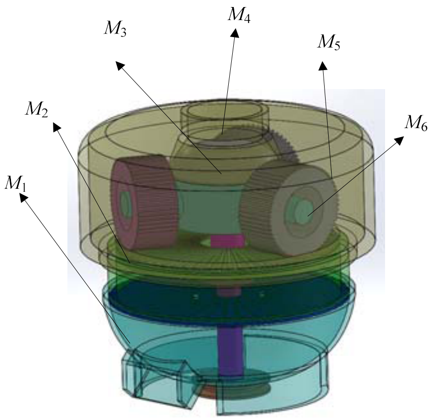
(25) is used to calculate the final apportion weightage of the ith subsystem, w_i^*, $\forall i$. Then, the final subsystem reliability for the ith subsystem, $Ri^\wedge$, is apportioned by (26), where w_{si} is the initial defuzzified weightage of the ith subsystem.

$$w_i^* = \frac{w_{si} \times (R_i - c_i)}{\sum_{i=1}^{n} [w_{si} \times (R_i - c_i)]} \tag{25}$$

$$R_i^R = (R^*)^{w_i^*} \tag{26}$$

IV. CASE STUDY

In this section, a numerical example of the reliability apportionment for a waste tire granulator is employed to demonstrate the potential application of the proposed method. Due to the growth in car ownership, the number of scrap tires is rising rapidly at an alarming rate which will fuel the crisis of resource waste and environmental pollution. These scrap tires could be beneficial for energy efficiency and carbon emission reductions with appropriate recycling. The waste tire granulator is the basic equipment in a fully mechanized crushing and recycling system which is the primary hardware system for recycling scrap tires. Hence, the waste tire granulator should be maintained at a level of high reliability over the whole service life time of the crushing and recycling system.



M_1: Mechanical support subsystem;
M_2: Electric control subsystem;
M_3: Spray cooling subsystem;
M_4: Lubricating subsystem;
M_5: Chopping and granulation subsystem;
M_6: Mechanical transmission subsystem;

FIGURE 4. **Subsystem structure of the waste tire granulator.**

However, in reality, failures in the waste tire granulator do occasionally happen. Most such failures result in potential environmental safety problems and economic loss, thus a rational reliability apportionment for the waste tire granulator would be of significant theoretical research and application value. According to market demands, the target reliability of the waste tire granulator is determined as 0.875, and as shown in Fig. 4, it is divided into six subsystems.

A. WEIGHTED VECTOR FOR PRODUCT LIFE CYCLE FACTORS

The interval judgment matrix for the reliability apportionment factors, $D^{\#}$, for the waste tire granulator is established based on the expert evaluation. By (1)–(9), the values of a^+ and a^- can be calculated as 1.1051 and 0.8901, respectively. Hence, $0 < a^- < a^+ < 1$ and the consistency of the interval judgment matrix is within the acceptable range. Then, the normalized eigenvectors X^- and X^+ of the matrixes D^- and D^+, as well as the interval number of the reliability apportionment factors, $w_f^{\#}$, can be available by (10).

$$X^- = [0.1967, 0.2951, 0.1771, 0.1151, 0.2159];$$

$$X^+ = [0.1899, 0.2925, 0.1695, 0.1014, 0.2467];$$

$$w_f^{\#} = [[0.1751, 0.2098], [0.2627, 0.3232], [0.1576, 0.1873], [0.1025, 0.1121], [0.1922, 0.2726]].$$

B. INITIAL WEIGHTED VECTOR OF SUBSYSTEMS

As shown in Table II, experts on waste tire granulators are invited to provide interval evaluation information on the importance of subsystems for the product life cycle factors

TABLE 2. Interval evaluation on the importance of subsystems for Factors.

Subsystem	C	E	F	M	T
M_1	[1.5,3.5]	[3.5, 5.2]	[7.5, 8.6]	[3.6, 4.9]	[2.1, 3.9]
M_2	[6.7,8.5]	[5.2, 7.1]	[5.5, 7.2]	[6.3, 8.1]	[5.6, 7.3]
M_3	[3.6, 5.2]	[4.6, 6.4]	[5.2, 6.9]	[2.6, 4.3]	[6.3, 7.2]
M_4	[4.5, 6.1]	[4.5, 6.2]	[5.6, 7.3]	[3.7, 4.3]	[6.2, 7.5]
M_5	[6.9, 8.9]	[5.6, 7.4]	[6.4, 8.2]	[5.7, 7.3]	[7.0, 7.8]
M_6	[4.2, 5.9]	[5.2, 6.7]	[5.7, 7.2]	[6.2, 7.5]	[5.7, 7.3]

TABLE 3. Initial defuzzified weightage of the EACH subsystem.

v	w_1	w_2	w_3	w_4	w_5
0.0	0.1921	0.1449	0.1748	0.1704	0.1515
0.2	0.1888	0.1472	0.1716	0.1770	0.1501
0.4	0.1866	0.1489	0.1693	0.1816	0.1492
0.6	0.1849	0.1502	0.1677	0.1851	0.1485
0.8	0.1836	0.1511	0.1663	0.1878	0.1479
1.0	0.1825	0.1519	0.1653	0.1899	0.1474

TABLE 4. Revised apportionment schemes with interval DEMATEL.

v	R_1*	R_2*	R_3*	R_4*	R_5*
0.0	0.9622	0.9832	0.9798	0.9704	0.9868
0.2	0.9639	0.9831	0.9801	0.9689	0.9863
0.4	0.9652	0.9829	0.9804	0.9691	0.9859
0.6	0.9662	0.9828	0.9805	0.9689	0.9856
0.8	0.9673	0.9819	0.9808	0.9691	0.9854
1.0	0.9680	0.9817	0.9809	0.9689	0.9852

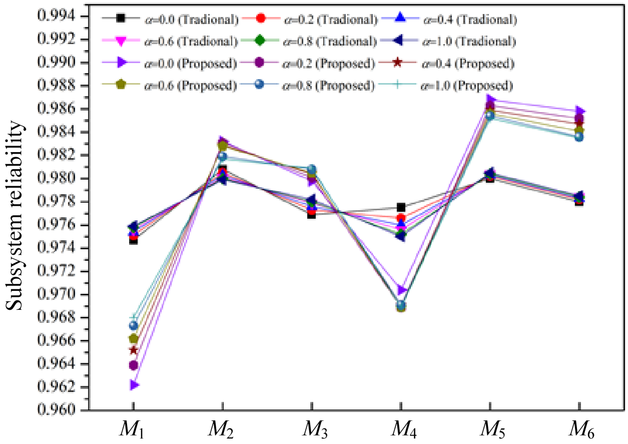


FIGURE 5. Comparison between the proposed method with the traditional interval method for the reliability apportionment of the waste tire granulator.O

selected according to the grading rules in Section II. The comprehensive interval number weighted vector of the subsystems for product life cycle factors $CN^{\#}$ and the initial interval reliability-apportionment weighted vector of subsystems $w^{\#}_{\text{sub}}$ can be obtained by (11)–(16). The initial defuzzified reliability-apportionment weightage of each subsystems included in the waste tire granulator can be available as shown in Table III using (6).

C. REVISION WITH INTERVAL DEMATEL

The interval expert evaluation on correlations among subsystems of the waste tire granulator is listed in the matrix $H^{\#}$, as shown at the top of the next page. The value of $s^{\#}$ can be obtained by (18) and (19), and $s^{\#} = [26.3, 30.3]$. The normalized interval direct-relation matrix $X^{\#}$ can be obtained by (20). Then, the numerical direct-relation matrix X and the total-relation matrix T can be acquired using (21). The revised reliability apportionment schemes with the caution indicator from the decision maker v are available through (22)–(26).The final reliability apportionment schemes for the target waste tire granulator are shown in Table IV.

V. COMPARISON

Based on Table III and Table IV, a comparison between the proposed method and the traditional interval analysis method for the reliability apportionment in a waste tire granulator is shown in Fig. 5.

From Fig. 5, conclusions can be obtained as follows.

Firstly, for the reliability apportionment of a waste tire granulator, no matter which of the methods is adopted, the proposed method or traditional interval analysis, the reliability apportioned of M_2, M_3, M_5, and M_6 is higher than that of M_1 and M_4. Compared with the reliability apportionment scheme in the traditional interval analysis method, the lower reliability apportioned of M_1 and M_4 decreases; meanwhile the higher reliability apportioned of M_2, M_3, M_5 and M_6 increases. Fig.1 shows that M_1 is the mechanical support subsystem, and M_5 and M_6 are the chopping and granulation subsystem and mechanical transmission subsystem, respectively. It is obviously that M_5 and M_6 are key subsystems for the major functions of the waste tire granulator, and the influence they have on the other subsystems is much greater than that of M_1 on the other subsystems. Thus, it is reasonable to increase the reliability of M_5 and M_6 and decrease the reliability M_1 in moderation, and the proposed method is superior to the traditional interval analysis method due to its taking the correlations among product subsystems into account.

Secondly, the reliability of M_1 becomes higher while the reliability M_5 and M_6 becomes lower when v changes from 0 to 1, indicating that the difference between the lowest subsystem reliability and the highest subsystem reliability continues to be reduced with the increase in the value of v. Hence, it can be inferred that the product service life within the proposed method is longer when the decision makers are

$$H^{\#} = \begin{bmatrix} [0, 0] & [6.2, 7.4] & [7.8, 8.6] & [5.8, 7.6] & [6.1, 7.9] & [7.2, 8.5] \\ [3.5, 5.2] & [0, 0] & [2.7, 4.3] & [2.0, 3.6] & [2.8, 3.9] & [4.1, 4.8] \\ [4.2, 5.6] & [3.6, 5.0] & [0, 0] & [3.7, 4.9] & [3.2, 3.8] & [3.5, 4.3] \\ [5.2, 6.1] & [6.8, 8.2] & [6.3, 7.5] & [0, 0] & [6.0, 7.6] & [5.9, 7.8] \\ [2.3, 3.9] & [2.9, 4.2] & [3.0, 3.9] & [3.2, 4.1] & [0, 0] & [2.5, 3.8] \\ [3.4, 4.7] & [4.1, 5.5] & [3.7, 5.1] & [4.2, 4.7] & [3.9, 5.2] & [0, 0] \end{bmatrix}$$

more cautious, because the product service life can be shortened by subsystems with extremely low reliability. Moreover, product cost with the proposed method is lower when the decision makers are more cautious, because the subsystems with extremely high reliability can boost the product economic cost drastically.

Thirdly, the apportioned reliability of M_1 and M_4 is more sensitive to the change in v than the apportioned reliability of M_2, M_3, M_5 and M_6 when the traditional interval analysis method is adopted, while the apportioned reliability of M_1, M_5, and M_6 is more sensitive to the change in v than the apportioned reliability of M_2, M_3 and M_4 when the proposed method is adopted. Thus, it can be seen that the sensitivity of the subsystem reliability varies with the product reliability apportionment methods, and it will require increased emphasis on grasping the inherent rules of this phenomenon.

VI. CONCLUSIONS

In the context of Energy Internet and based on interval analysis and interval DEMATEL, a novel reliability apportionment model is proposed which considers product life cycle factors including carbon emissions and resource efficiency. It can overcome the limitations of the traditional reliability apportionment which fails to consider the environmental attributes of products and the correlations among product subsystems, as well as the uncertainty in modern product reliability apportionment. The superiority of the proposed method to the traditional reliability apportionment methods is verified by the case study of a waste tire granulator.

The proposed method uses five factors including carbon emissions, maintenance cost, resource efficiency, cost sensitivity and failure severity to achieve reasonable reliability apportionment within Energy Internet, in which the environmental attributes, economic attributes, and security attributes of modern products are involved. Expert evaluation with respect to interval numbers facilitates the process of product reliability apportionment with uncertain, fuzzy, or insufficient information. The revision of reliability apportionments with interval DEMATEL successfully places more emphasis on the correlations among product subsystems, which plays an important role in guaranteeing the essential functions of advanced modern products. Therefore, the proposed method can be applied to the reliability apportionment of more sophisticated modern products. The proposed method is beneficial for realizing energy efficiency and emissions reductions from the perspective of the whole product life cycle, and it has great potential for expansion and in accelerating the development of Energy Internet.

It is noteworthy that the proposed reliability apportionment within Energy Internet still has certain limitations. In particular, compared with traditional methods, the proposed reliability apportionment depends on the accuracy and competency of subjective expert evaluation which may be difficult to obtain in some circumstances and may lead to inaccurate results of reliability apportionment. Hence, more attention should be paid to the quality and quantity of evaluation data. In addition, the proposed reliability apportionment entails a larger computational performance. From the perspective of calculation, how to improve its efficiency has become an important problem.

Energy Internet, a new solution for energy sustainability, is becoming a hot research topic and a mainstream technology for the reason that energy is the material basis of human development. In the development process for Energy Internet, reliability, information, and communication technology will play an important role. With the progress in technologies for reliability apportionment, power electronics, and computer communication, Energy Internet is expected to be the decisive driving force of the third industrial revolution. Hopefully, the super-sized global Energy Internet will overcome the difficulties in the energy crisis and carbon emissions as well as help drive the general development of large economies. In the near future, the global Energy Internet with high reliability, low redundancy, a wider range of services, and a more powerful configurability will be the research hotspot in the industries of energy and information as well as the development direction of future power systems. It is the necessary process for realizing the sustainable development of global energy. However, due to the highly intelligent, open, and interactive pattern of operation, as well as the various interfaces, the desired reliability for the global Energy Internet requires further scientific research and exploration.

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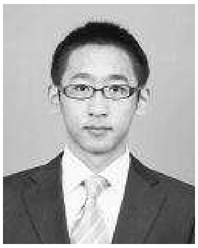

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