Design Sustainability of Reconfigurable Machines

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ABSTRACT This paper presents the sustainability assessment for reconfigurable machines based on cosine similarity measures and Euclidean distances. The methodology entails the application of four peculiar sustainability indicators (Reconfigurability, Manufacturing, Functionality, and Life Cycle Analysis) that are suitable for reconfigurable machines alongside the traditional sustainability indicators (Environmental, Social, and Economic). An index relating chart approach is proposed for determining the indices of the peculiar and traditional sustainability indicators and their sub-indicators. The chart involves the identification of viable links of the sub-indicators of an indicator and the sub-indicators of other indicators. The viable links are fuzzified using the fuzzy trapezoidal set because of the multi-dimensions and units of the sustainability indicators. The cosine similarity measures of the sustainability indicators were aggregated to estimate the sustainable similarity measures of the reconfigurable machines while the Euclidean distance estimates the distances of the indicators to best and worst sustainable performance in order to identify the sustainability indicators for improvement. Experts' opinions are applied to appraise the availability of sub-indicators in the four reconfigurable machine prototypes (vibrating screen, assembly fixture, bending press machine, and flexible fixture) used as case studies. A sensitivity analysis was carried out to validate the computational process of the methodology. The sensitivity analysis shows that the application of cosine similarity measures is suitable for assessment of sustainability considering the closeness of the similarity measures for the defuzzified values of the trapezoidal fuzzy numbers and the cosine similarity values of the aggregating matrix of the indicators. Also, the findings that can be deduced from the results of the appraisal of the case studies presented in this article shows that high sustainable index and similarity measures can be achieved by creating a balance in the performance of all the sustainable indicators. The results from the assessment also support the fact that improving one sustainability indicator because of its closeness to the worst sustainable performance may cause other indicators not to perform satisfactorily.

INDEX TERMS Cosine similarity measure, design sustainability, Euclidean distance, reconfigurable machines, sustainable indicators, sustainable similarity measure.

I. INTRODUCTION

The dynamic nature of the market due to varieties in customer demand and product customization changes the manufacturing system and its environment, which has led to the emergence of the reconfigurable manufacturing paradigm [1]. The evolution of manufacturing system paradigms due to global technological advancement requires that the development of manufacturing equipment undergo a sustainability assessment from the desk of the design engineer [2]. Designing sustainable manufacturing equipment is a critical indicator in the evaluation of the life span of the entire manufacturing system [3]. The emergence

of the Reconfigurable Manufacturing System (RMS) and its counterpart assembly system (Reconfigurable Assembly System (RAS)) has given birth to the development of different Reconfigurable Machines (RMs) that can be of use in a manufacturing system [4]. Continuous effort is required to research into the sustainability of these RMs from their design stage to the implementation stage. The design of several product variants within the same part family or customized designs is a significant driver that directly affects the sustainability of the manufacturing system [5]. It is a known fact that the RMs provide a platform for the manufacturing of these product variants considering their design based on functionality.

However, an assurance of the sustainability of these RMs is necessary because achieving sustainability of the entire

manufacturing system requires a comprehensive view that goes beyond the product variants. Assessing the sustainability of manufacturing equipment goes beyond an appraisal of its functionality. It encompasses other factors that can assist in predicting whether the machine will stand the taste of time and produce profit for the manufacturer or phase out within a limited amount of time. Every manufacturer desires equipment that will enhance productivity and minimize waste of time and resources. To achieve the manufacturers' desire, assessment of design sustainability before the commencement of developing a prototype of the equipment is necessary. The assessment will further provide an insight into the details about the performance, environmental issues, and life cycle assessment of the equipment [6]. The sustainability of RMs cannot be evaluated by the mere satisfaction of the characteristics of reconfigurable manufacturing principles. Hence, a consideration of other elements of sustainability is necessary as this will provide a holistic approach to the appraisal process.

Owning to the fact that it is usually tough to directly access the sustainability of a product at the early stage of the design, several indicators are known to provide the sustainability index of a product. These indicators can be related to the conditions of the system under consideration in the design [7]. However, Harik, El Hachem [5] proposed that the general classification of these indicators can be traditional and peculiar pillars. The traditional pillars comprise of the three well-known indicators or elements, which are social, environment, and economic factors [3], [8]–[10]. Analyses on the determination of sustainability index for product design are dependent on the traditional pillars with extensive sub-features under each pillar. There may be no particular method for classifying the peculiar pillars because it changes according to the situation under consideration. Hassan, Saman [11] applied three peculiar pillars in addition to the traditional pillars in order to obtain the highest sustainability index of a new product using an integrated multicriteria decision-making model. The selection of these three peculiar pillars (remanufacturing, functionality, and manufacturing) is dependent on the design elements of a personal digital assistant, which is the product under consideration.

II. LITERATURE REVIEW

Several approaches on the appraisal of sustainability of designs are carried out using suitable peculiar pillars. De Silva *et al.* [12] Jayal *et al.* [13] did make use of the same peculiar pillars of Hassan *et al.* [14] in order to determine the sustainability of product design. Hence, there is an assertion that functionality and manufacturability are part of the peculiar performance indicators that have a link to the sustainability of design. The remanufacturing pillar attempts to encompass the 6Rs of sustainability (Redesign, Recover, Remanufacture, Recycle, Reuse, and Reduce) as described by Schöggl *et al.* [6] and Maginnis *et al.* [15]. The 6Rs tend to address the sustainability of design from the

performance perspective of the product up until after usage. However, the life cycle analysis of the design in terms of satisfactory performance during its useful life is a relevant factor that needs attention for inclusion in the sustainability assessment. An excellent way to achieve practical assessment of the design life cycle is to analyze the design into four stages which are: pre-manufacturing, manufacturing, use, and post-use phases [16]. Also, the sustainability of product design depends on life cycle supporters. Zhang *et al.* [17] extensively address the classification of these supporters (raw materials, manufacture, transport, sales, use, maintenance, and recovery). Another approach to the identification of sustainability indicators for product design is identifiable as Quality Function Deployment (QFD) and the technical requirements of the design [18]. With the help of QFD, there is a consideration of end-users needs in the product design process, thus allowing the design to be more customer-friendly with high quality. The essence of employing the QFD analysis in the design process is to ensure that there is an assessment of the design life cycle at the early stage [19]. An assessment of the technicality of design in order to appraise its sustainability is traceable to the required function or performance of the design, which is obtainable from the structural, process, and dynamic parameters of the design [20].

A holistic approach to the determination of sustainability of product design considering several indicators is no doubt the right method. However, the challenge of handling these indicators usually leads the design engineer into the problem of decision-making, particularly when it is required to assign a weight to the indicators. Weight apportioning is necessary since the overall sustainability index of the design is a function of the sustainability index of each indicator. Several methods exist to address the issue of weight apportioning to sustainability indicators and solving the decision-making process in order to obtain the overall sustainability index of the design [21]. The normalization method by Shuaib *et al.* [22] uses benchmark regulations, best and worst-case scenarios, and expert assessment to determine the weights of the sustainability indicators and the overall product sustainability index. An analysis of the indicators into sub-indicators provides a convincing overall sustainability index of the design through normalizing and averaging the sustainability indices of the sub-indicators [11]. Applying the weights of the Original Equipment Manufacturer (OEM) [12] and opinion of stakeholders (investor, employee, suppliers, and customers) [23] are also methods for obtaining the weights of these indicators. The consumer and manufacturer-based survey of De Silva *et al.* [12] was useful in the determination of indices for the sub-indicators of Jayal *et al.* [13] using the imaginary numbers of Jawahir *et al.* [24], and the sustainability index of the indicators were obtained from the average weights of the sub-indicators. However, there is a shortcoming on the consideration of the multidimensional nature of these indicators in the computational process. Also, the economic
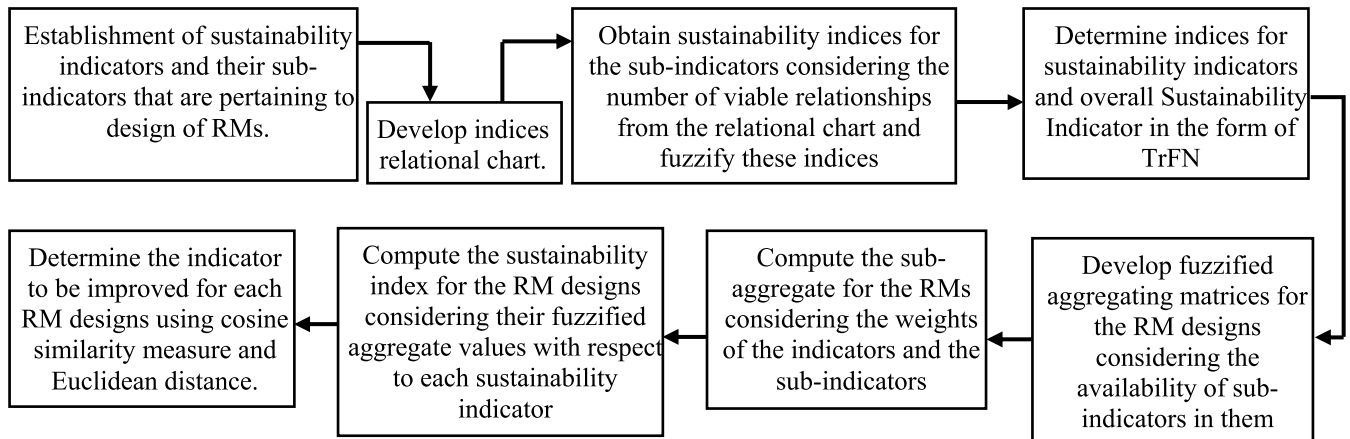
FIGURE 1. Framework for methodology.

index appears to be a keen interest in concern in the view of all the stakeholders, thereby undermining other sustainability indicators.

In order to consider the type and influence of the sustainability indicators in the determination of the overall sustainability index, a scoring method is necessary. The scoring method by Harik *et al.* [5] uses a qualitative and quantitative approach to address the type (nature) of the sub-indicators allotted to each sustainability indicator. The use of positive and negative signs in the scoring concept helped determine the contributions of these sub-indicators to the weight of indicators and the overall sustainability index. Although a thorough analysis of the extent of contributions of the sub-indicator is not certain by the mere apportioning of positive and negative signs to the sub-indicators, there is a certainty on which indictor should be minimized or maximized in the decision-making process. A further effort by Younesi and Roghanian [18] is the determination of design sustainability via a hybridized multicriteria decision-making model. The hybrid model combines fuzzy DEMATEL, fuzzy Quality Function Deployment for Environment (QFDE), and fuzzy Analytic Network Process (FANP). Customer Attributes (CA) and Technical Requirement (TR) of the design were the basis for obtaining the product design sustainability criteria. The fuzzy DEMATEL model provides correlations among the CAs, and the integration of the FANP and QFDE also provides a solution to the determination of weights for the technical requirements of the design. An exciting aspect of the solution is the introduction of fuzzy sets using linguistic expressions to cater for the various units and dimensions of the design attributes. Still, a thorough analysis of the extent of the sub-indicators is necessary for consideration.

To this end, it can be observed from the literature review that, there is a perception that the sustainability of product design can be appraised by considering peculiar indicators such as remanufacturing, functionality, life cycle analysis and manufacturing alongside the traditional indicators. However, there is no certainty that this perception is sufficient

in assessing the sustainability of RMs, considering the peculiarities of these machines in the RMS. In essence, the peculiar indicators that will be applied in the assessment of sustainability of RMs should consider the features of RMS and the conventional peculiar indicators identified from the literature. Also, the application of several indicators having sub-indicators in the assessment of the sustainability of design requires a multi-attribute decision-making model that will provide a thorough analysis of the contributions of the indicators and their sub-indicators to the overall sustainability index of the design. However, it will be better if the analysis can identify which of the indicators can be improved in order to improve the sustainability of the design. Hence, this article is proposing that the weights of the sub-indicators of a sustainability indicator should be dependent on their relationships with the sub-indicators of other sustainability indicators. Further, the article proposes a methodology for the identification of the sustainability indicator that needs improvement, considering four case studies of RM prototypes. The multidimensional nature of the sustainability indicators and their sub-indicators will be considered as fuzzy sets, which will be implemented using linguistic terms and Trapezoidal Fuzzy Number (TrFN). The reason for using TrFN is the detailed shape of the building blocks which comprises of four membership function. It is expected that the comprehensive shape of the TrFN membership function will best characterize the linguistic term compared to the triangular fuzzy number whose building block comprises of three membership function. Also, the membership function of the TrFN is piecewise linear and can completely capture the vagueness of the linguistic assessment. The TrFN will eliminate the apportioning of crisp value and assist the design engineer in reducing vague and subjective perception.

III. METHODOLOGY
For ease of analysis, a framework of the methodology is presented in Figure 1. Sustainability indices are obtained from the indices relating charts that are developed by comparing the sub-indicators of one sustainability indicator
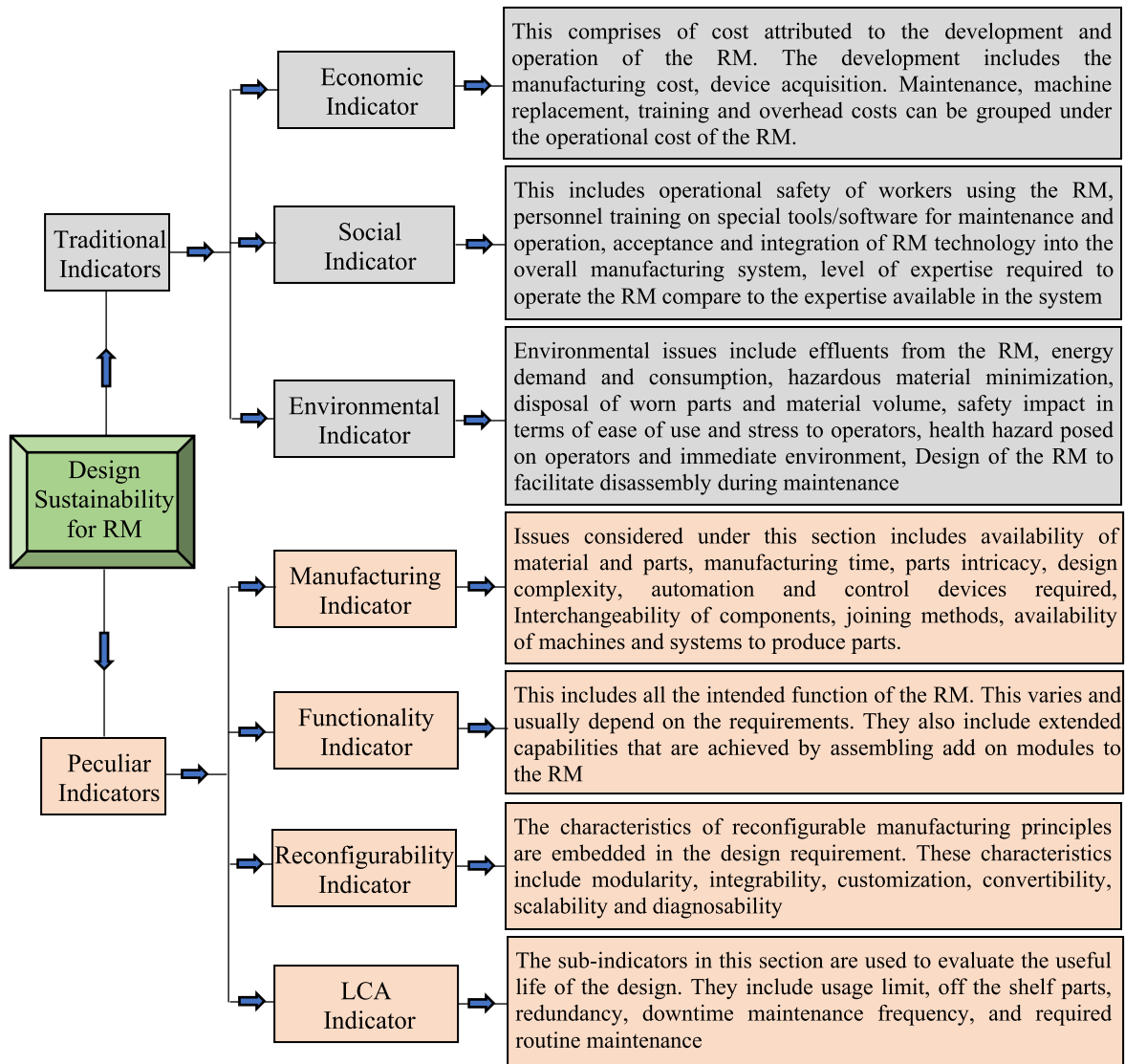
FIGURE 2. Sustainability indicators and sub-indicators for RMs.

with the sub-indicators of other sustainability indicators. The indices are fuzzified in order to consider the imprecise information in the comparison process of the relational chart and the fuzzified viable relationships are used to determine aggregates for the RMs considering the availability of sub-indicators. The aggregates play a vital role in the computation of sustainability indices for the RMs. The sustainability indices to be improved are identified from the cosine similarity measures and Euclidean distance.

A. INDICATORS FOR SUSTAINABLE RMs

The indicators considered for the sustainable design of the RM encompasses issues that have a role to play in its development and usage in the entire manufacturing system. In order to consider all the design requirements needed, the peculiar indicators proposed in this article will comprise of the indicators used for assessing product design as identified from the literature review alongside the reconfigurability indicator. In essence, these indicators

are functionality, reconfigurability, manufacturing, and Life Cycle Analysis (LCA). The traditional indicators and these peculiar indicators are useful tools that can provide a holistic approach to the design of a RM considering their development, performance, and reliability in the manufacturing system. Figure 2 presents a descriptive framework showing the perspective for the selection of sub-indicators for a RM. Considerations under each indicator are identified and classified in order to identify the sub-indicators that will be applied in the appraisal process. The sub-indicators are design features, manufacturing or prototyping constraints and factors or characteristic performance that can be attributed to the sustainability indicators. Figure 2 considers all the design requirements, constraints, and standardizations that need to be incorporated in the design of RMs.

B. INDICES RELATING CHART

Consider N number of sustainability indicators represented as $(A, B, C, D......N)$. Let each indicator has different sets

	$B_1 \ldots B_b$	$C_1 \ldots C_c$	$D_1 \ldots D_d$	$N_1 \ldots N_n$	$\sum \bar{\cup}$
A_1	$A_1\bar{\cup}B_1, A_1\cup B_2,$ $A_1\cup B_3, A_1\bar{\cup}B_4$ $\ldots A_1\bar{\cup}B_b$	$A_1\bar{\cup}C_1, A_1\cup C_2,$ $A_1\cup C_3, A_1\bar{\cup}C_4$ $\ldots A_1\bar{\cup}C_c$	$A_1\bar{\cup}D_1, A_1\cup D_2,$ $A_1\cup D_3, A_1\bar{\cup}D_4$ $\ldots A_1\bar{\cup}D_d$	$A_1\bar{\cup}N_1, A_1\cup N_2,$ $A_1\cup N_3, A_1\bar{\cup}N_4$ $\ldots A_1\bar{\cup}N_n$	$\sum_{B_1}^{B_b}A_1\big|_{\bar{\cup}} \ldots \sum_{N_1}^{N_n}A_1\big|_{\bar{\cup}}$
A_2	$A_2\bar{\cup}B_1, A_2\cup B_2,$ $A_2\cup B_3, A_2\bar{\cup}B_4$ $\ldots A_2\bar{\cup}B_b$	$A_2\bar{\cup}C_1, A_2\cup C_2,$ $A_2\cup C_3, A_2\bar{\cup}C_4$ $\ldots A_2\bar{\cup}C_c$	$A_2\bar{\cup}D_1, A_2\cup D_2,$ $A_2\cup D_3, A_2\bar{\cup}D_4$ $\ldots A_2\bar{\cup}D_d$	$A_2\bar{\cup}N_1, A_2\cup N_2,$ $A_2\cup N_3, A_2\bar{\cup}N_4$ $\ldots A_2\bar{\cup}N_n$	$\sum_{B_1}^{B_b}A_2\big|_{\bar{\cup}} \ldots \sum_{N_1}^{N_n}A_2\big|_{\bar{\cup}}$
A_3	$A_3\bar{\cup}B_1, A_3\cup B_2,$ $A_3\cup B_3, A_3\bar{\cup}B_4$ $\ldots A_3\bar{\cup}B_b$	$A_3\bar{\cup}C_1, A_3\cup C_2,$ $A_3\cup C_3, A_3\bar{\cup}C_4$ $\ldots A_3\bar{\cup}C_c$	$A_3\bar{\cup}D_1, A_3\cup D_2,$ $A_3\cup D_3, A_3\bar{\cup}D_4$ $\ldots A_3\bar{\cup}D_d$	$A_3\bar{\cup}N_1, A_3\cup N_2,$ $A_3\cup N_3, A_3\bar{\cup}N_4$ $\ldots A_3\bar{\cup}N_n$	$\sum_{B_1}^{B_b}A_3\big|_{\bar{\cup}} \ldots \sum_{N_1}^{N_n}A_3\big|_{\bar{\cup}}$
A_a	$A_a\bar{\cup}B_1, A_a\cup B_2,$ $A_a\cup B_3, A_a\bar{\cup}B_4$ $\ldots A_a\bar{\cup}B_b$	$A_a\bar{\cup}C_1, A_a\cup C_2,$ $A_a\cup C_3, A_a\bar{\cup}C_4$ $\ldots A_a\bar{\cup}C_c$	$A_a\bar{\cup}D_1, A_a\cup D_2,$ $A_a\cup D_3, A_a\bar{\cup}D_4$ $\ldots A_a\bar{\cup}D_d$	$A_a\bar{\cup}N_1, A_a\cup N_2,$ $A_a\cup N_3, A_a\bar{\cup}N_4$ $\ldots A_a\bar{\cup}N_n$	$\sum_{B_1}^{B_b}A_a\big|_{\bar{\cup}} \ldots \sum_{N_1}^{N_n}A_a\big|_{\bar{\cup}}$
$\sum \bar{\cup}$	$\sum_{B_1}^{B_b}A_1\big|_{\bar{\cup}}\ldots\sum_{B_1}^{B_b}A_a\big|_{\bar{\cup}}$	$\sum_{C_1}^{C_c}A_1\big|_{\bar{\cup}}\ldots\sum_{C_1}^{C_c}A_a\big|_{\bar{\cup}}$	$\sum_{D_1}^{D_d}A_1\big|_{\bar{\cup}}\ldots\sum_{D_1}^{D_d}A_a\big|_{\bar{\cup}}$	$\sum_{N_1}^{N_n}A_1\big|_{\bar{\cup}}\ldots\sum_{N_1}^{N_n}A_a\big|_{\bar{\cup}}$	

FIGURE 3. Comparison chart for relating indices of the sustainability indicators.

of sub-indicators, which can be referred to as indices and can be represented by counters ($a, b, c, d \ldots\ldots n$), which varies according to the number of sub-indicators allotted to each indicator (i.e. $a \neq b \neq c \neq d \neq \ldots\ldots n$). It is possible to develop an index relating chart such that the indices of an indicator are related to the indices of other indicators. A search for a viable relationship is possible after connecting all the sub-indicators, and the total number of VRs can be identified and fuzzified in order to determine the sustainability indices of the indicators and sub-indicators. The term viable relationship here means that there is a link between the two sub-indicators. A simple way to express this phenomenon is to develop a chart showing the sub-indicators of one indicator relating to other indicators, as presented in Figure 3. If viable and non-viable relationships are represented with $\bar{\cup}$ and $\cup$ respectively, then the total number of viable relationships for a sub-indicator is determinable.

Considering Figure 3, the term $A_a\bar{\cup}N_n$ represents a viable relationship due to the interaction between a^{th} index of indicator A and n^{th} index of indicator N. This implies that the interaction can be counted for both indices under comparison. The total number of VRs for the first sub-indicator (A_{1V}) under indicator A is obtainable from (1). This implies that the

total number of viable relationships for any a^{th} sub-indicator under indicator A (A_{aV}) is obtainable from (2).

$$A_{1V} = \sum_{B_1}^{B_b} A_1\big|_{\bar{\cup}} + \sum_{C_1}^{C_c} A_1\big|_{\bar{\cup}} + \sum_{D_1}^{D_d} A_1\big|_{\bar{\cup}} + \ldots\ldots \sum_{N_1}^{N_n} A_1\big|_{\bar{\cup}} \quad (1)$$

$$A_{aV} = \left[\sum_{B_1}^{B_b} A_a\big|_{\bar{\cup}} + \sum_{C_1}^{C_c} A_a\big|_{\bar{\cup}} + \sum_{D_1}^{D_d} A_a\big|_{\bar{\cup}} + \ldots\ldots \sum_{N_1}^{N_n} A_a\big|_{\bar{\cup}} \right]\Bigg|$$
$$\text{for } a = 1, 2, 3 \ldots\ldots a \quad (2)$$

Hence, the sustainability index for indicator A is obtainable by summing all the viable relationships of sub-indicators in A as a result of relating it to other indicators. Equation (3) presents the sustainability index for indicator A (A_{SI}).

The second stage is to develop the index relating chart for the indices of indicator B. The interactions obtained from the comparison of the indices of indicator A with indices of indicator B will be used vice versa. The same scenario implies for the third stage comparison between indicators A and C and likewise, B and C. Hence, this is an indication that the comparison reduces at every stage.

Also, the total number of viable relationships for any b^{th} sub-indicator under indicator B (B_{bV}) is determinable. Obtaining an expression for the sustainability index for indicator B (B_{SI}) is possible by summing all the viable relationships of sub-indicators in B. In essence, (4) and (5) present expressions for determining B_{bV} and B_{SI} respectively.

$$A_{SI} = \sum_{a=1}^{a=a} A_{aV} \bigg/ \sum a$$

$$= \frac{\sum_{a=1}^{a=a}\left[\sum_{B_1}^{B_b} A_a|_{\cup} + \sum_{C_1}^{C_c} A_a|_{\cup} + \sum_{D_1}^{D_d} A_a|_{\cup} + \ldots \sum_{N_1}^{N_n} A_a|_{\cup}\right]}{\sum a}$$

(3)

$$B_{bV}$$

$$= \left[\left[\sum_{A_1}^{A_a} B_b|_{\cup} + \sum_{C_1}^{C_c} B_b|_{\cup} + \sum_{D_1}^{D_d} B_b|_{\cup} + \ldots \sum_{N_1}^{N_n} B_b|_{\cup}\right]\right]$$

$$for\ b = 1, 2, 3 \ldots b \quad (4)$$

In essence, the sustainability index for an indicator can be obtained from each comparison chart by summing the sustainability indices of all the sub-indicators and dividing it by the total number of sub-indicators. In a general term, the sustainability index of any N^{th} indicator having n number of sub-indicators is obtainable from (6).

$$B_{SI} = \sum_{b=1}^{b=b} B_{bV} \bigg/ \sum b$$

$$= \frac{\sum_{b=1}^{b=b}\left[\sum_{A_1}^{A_a} B_b|_{\cup} + \sum_{C_1}^{C_c} B_b|_{\cup} + \sum_{D_1}^{D_d} B_b|_{\cup} + \ldots \sum_{N_1}^{N_n} B_b|_{\cup}\right]}{\sum b}$$

(5)

$$N_{SI} = \left.\left(\sum_{n=a}^{n=n} N_{nV} \bigg/ \sum n\right)\right|_{n=a,b,c\ldots n}^{\forall N=A,B,C,D\ldots\ldots N}$$

(6)

C. FUZZIFICATION OF SUSTAINABILITY INDICES

The indices obtained for the sub-indicators need to be fuzzified because the decisions of the design engineers may not be accurate. For instance, allocating a value of one to any viable relationship between the sub-indicators does not depict the extent of the viability. Hence, there is a need to avoid the ambiguous nature of the sustainability indicators and their sub-indicators by using a trapezoidal fuzzy membership function. An illustration of this scenario is like random numbers that are used in simulations. Also, since these indices will be applicable in the determination of the aggregates of the RM designs from a fuzzified aggregating matrix, it is necessary to consider fuzzifying these viable relationships in order to obtain a Fuzzified

Viable Relationship. The reason for adopting the trapezoidal fuzzy membership function is its simple process of arithmetic operation and ease of interpretation. It is necessary to establish how the trapezoidal fuzzy membership function will be generated to represent the number of VRs obtained from the comparison charts. To achieve this, consider a TrFN $M = \{w, x, y, z\}$ whose membership function $[\mu_m(p)]$ can be expressed in (7). In order to generate a random TrFN for the number of viable relationships of the sustainability, sub-indicators let there be an assumption that if there is no viable relationship, then the TrFN can be represented as a unity because the two sub-indicators under consideration belongs to two different indicators and as such, they have an equal preference as presented in (8). If this assumption holds, then other TrFNs such as $M_1, M_2 \ldots \ldots M_n$ representing one, two to n number of viable relationships is determinable from (9), (10) and (11), respectively.

A logical and simple approach to rank these TrFNs is proposed by determining the centroids of the TrFNs and estimating the left and right scores from these centroids.

$$\mu_m(p) = \left.\begin{cases} (p-w)/(x-w) & p \in [w,x] \\ 1 & p \in [x,y] \\ (z-p)/(z-y) & p \in [y,z] \\ 0 & otherwise \end{cases}\right|; w \le x \le y \le z$$

(7)

$$M_0 = \{1, 1, 1, 1\} \equiv \{w_0, x_0, y_0, z_0\} \quad (8)$$

$$M_1 = \{w_1, x_1, y_1, z_1\}$$
$$= \left\{\frac{x_0+y_0}{2}, \frac{x_0+y_0}{2} + \frac{1}{4}, \frac{x_0+y_0}{2}\right.$$
$$\left. + \frac{1}{2}, \frac{x_0+y_0}{2} + 1\right\}$$

(9)

$$M_2 = \{w_2, x_2, y_2, z_2\}$$
$$= \left\{\frac{x_1+y_1}{2}, \frac{x_1+y_1}{2} + \frac{1}{4}, \frac{x_1+y_1}{2} + \frac{1}{2},\right.$$
$$\left. \frac{x_1+y_1}{2} + 1\right\}$$

(10)

$$M_n = \{w_n, x_n, y_n, z_n\}$$
$$= \left\{\frac{x_{n-1}+y_{n-1}}{2}, \frac{x_{n-1}+y_{n-1}}{2} + \frac{1}{4}, \frac{x_{n-1}+y_{n-1}}{2}\right.$$
$$\left. + \frac{1}{2}, \frac{x_{n-1}+y_{n-1}}{2} + 1\right\}$$

(11)

The centroids of the orthocentres (C_1, C_2, C_3) of the membership function are obtainable from (12), (13) and (14), as presented in Figure 4 [25]. The left (L_S) and right (R_S) scores of these centroids is determinable from the centroids. Combining (12), (13) and (14), the left and right scores can be expressed in the form of the membership function of the TrFNs as presented in (15) and (16) respectively. The TrFNs can then be ranked by obtaining the average of these left and right scores as obtainable from (17) [26].

$$C_1 = (w + 2x)/3 \quad (12)$$
$$C_2 = (x + y)/2 \quad (13)$$

TABLE 1. Membership function of linguistic scale.

| Linguistic Terms	Crisp Value	Trapezoidal Fuzzy Membership Function				Membership Function Reciprocal			
Indeterminate Availability (IDA)	1	1	1	1	1	1	1	1	1
Indeterminate -Moderate Availability (IMA)	2	1	5/4	3/2	2	1/2	2/3	4/5	1
Moderate Availability (MOA)	3	11/8	13/8	15/8	19/8	8/19	8/15	8/13	8/11
Moderate-Strong Availability (MSA)	4	7/4	2	9/4	11/4	4/11	4/9	1/2	4/7
Strong Availability (STA)	5	17/8	19/8	21/8	25/8	8/25	8/21	8/19	8/17
Strong-Very Strong Availability (SVA)	6	5/2	11/4	3	7/2	2/7	1/3	4/11	2/5
Very Strong Availability (VSA)	7	23/8	25/8	27/8	31/8	8/31	8/27	8/25	8/23
Very Strong-Extreme Availability (VEA)	8	13/4	7/2	15/4	17/4	4/17	4/15	2/7	4/13
Extreme Availability (EXA)	9	29/8	31/8	33/8	37/8	8/37	8/33	8/31	8/29
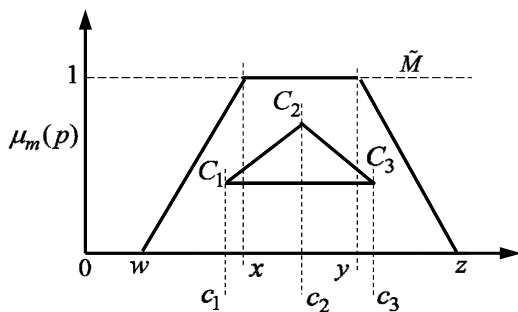
FIGURE 4. Orthocentres of the TrFNs.

$$C_3 = (2y + z)/3 \tag{14}$$

$$L_S = C_2/(1 + C_2 - C_1) = 3(x + y)/(6 + 3y - 2w - x) \tag{15}$$

$$R_S = C_3/(1 + C_3 - C_2) = 2(2y + z)/(6 + y + 2z - 3x) \tag{16}$$

$$M^* = (L_S + R_S)/2 \tag{17}$$

D. FUZZIFIED AGGREGATING MATRIX

It is necessary to analyze the availability of the sub-indicators in the RM designs in order to aggregate their sub-indicator indices relative to the sustainability indicators. This analysis will obtain a sub-aggregate for the RM designs considering each of the sustainability indicators. To achieve this, aggregating matrices of the form '$\tilde{D}_{gi}^{j}$' can be developed such that the availability of the sub-indicator is aggregated for the RMs in a matrix. It is necessary to establish a scale of relative availability that will be useful as a linguistic scale with the TrFNs. Table 1 presents the linguistic terms for the fuzzified aggregating matrices by using (9), (10) and (11) to generate their corresponding TrFNs. The membership functions of the TrFNs are expressed in fractions in order to avoid rounding up decimals during computation which may provide inconsistency in the final values. Equation (18) describes the form of the fuzzified aggregating matrix in which i and j represent the rows and columns, respectively. It is worthwhile to know that i and j are the number sub-indicators under the sustainability indicator in consideration and number of RM designs, respectively. This implies that (18) will be developed for all the sustainability indicator. Considering (18), it can be

deduced that the sub-aggregate for one of the RM designs (R_{mj}^{ag}) is determinable from (19).

$$\tilde{R}_{mj}^{ag} = \sum_{i=1}^{i=i} \left[\left(\tilde{n}_i / \tilde{N}_{SI} \right)^* \tilde{D}_{gi}^{j} \right] \tag{18}$$

In (18), $\tilde{N}_{SI}$ is the TrFN representing the weight of the Nth sustainability indicator and $\tilde{n}_i$ is the TrFN representing the weight of the nth sub-indicator under the Nth sustainability indicator in consideration.

$$\therefore \begin{bmatrix} \tilde{R}_{m1}^{ag} & \tilde{R}_{m2}^{ag} & \tilde{R}_{m3}^{ag} & \cdots & \tilde{R}_{mj}^{ag} \end{bmatrix}$$
$$= \begin{bmatrix} \frac{1}{\tilde{N}_{SI}} \end{bmatrix} \begin{bmatrix} \tilde{n}_1 \\ \tilde{n}_2 \\ \tilde{n}_3 \\ \vdots \\ \tilde{n}_i \end{bmatrix} \begin{bmatrix} \tilde{D}_{g1}^{1} & \tilde{D}_{g1}^{2} & \tilde{D}_{g1}^{3} & \cdots & \tilde{D}_{g1}^{j} \\ \tilde{D}_{g2}^{1} & \tilde{D}_{g2}^{2} & \tilde{D}_{g2}^{3} & & \tilde{D}_{g2}^{j} \\ \tilde{D}_{g3}^{1} & \tilde{D}_{g3}^{2} & \tilde{D}_{g3}^{3} & & \tilde{D}_{g3}^{j} \\ \vdots & \vdots & \vdots & & \vdots \\ \tilde{D}_{gi}^{1} & \tilde{D}_{gi}^{2} & \tilde{D}_{gi}^{3} & \cdots & \tilde{D}_{gi}^{j} \end{bmatrix} \tag{19}$$

The sub aggregates of the RMs for each sustainability indices are used to form a decision matrix, as presented in (20). In essence, for A, B, C, …….N number of sustainability indicators the decision matrix can be written as presented in (20). The elements of the decision matrix in (20) can be normalized by applying (21) and (22) for beneficial and cost indicators respectively using the membership function defined in (7) in order to obtain a normalized decision matrix as presented in (23) [27].

$$\begin{bmatrix} \tilde{R}_{mA}^{ag}\big|_1 & \tilde{R}_{mA}^{ag}\big|_2 & \tilde{R}_{mA}^{ag}\big|_3 & \cdots & \tilde{R}_{mA}^{ag}\big|_j \\ \tilde{R}_{mB}^{ag}\big|_1 & \tilde{R}_{mB}^{ag}\big|_2 & \tilde{R}_{mB}^{ag}\big|_3 & \cdots & \tilde{R}_{mB}^{ag}\big|_j \\ \tilde{R}_{mC}^{ag}\big|_1 & \tilde{R}_{mC}^{ag}\big|_2 & \tilde{R}_{mC}^{ag}\big|_3 & \cdots & \tilde{R}_{mC}^{ag}\big|_j \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{R}_{mN}^{ag}\big|_1 & \tilde{R}_{mN}^{ag}\big|_2 & \tilde{R}_{mN}^{ag}\big|_3 & \cdots & \tilde{R}_{mN}^{ag}\big|_j \end{bmatrix} \tag{20}$$

$$\left(R_{ij} \right)^{\overline{N}}$$

$$= \left[\frac{w_{ij} - w_j^{\min}}{\Delta_{\min}^{\max}}, \frac{x_{ij} - w_j^{\min}}{\Delta_{\min}^{\max}}, \frac{y_{ij} - w_j^{\min}}{\Delta_{\min}^{\max}}, \frac{z_{ij} - w_j^{\min}}{\Delta_{\min}^{\max}} \right];$$
$$i = 1, \ldots\ldots n; \quad j \in \Omega_b \tag{21}$$

$(R_{ij})^{\overline{N}}$

$$= \left[\frac{z_j^{\max} - z_{ij}}{\Delta_{\min}^{\max}}, \frac{z_j^{\max} - y_{ij}}{\Delta_{\min}^{\max}}, \frac{z_j^{\max} - x_{ij}}{\Delta_{\min}^{\max}}, \frac{z_j^{\max} - w_{ij}}{\Delta_{\min}^{\max}} \right];$$

$$i = 1, \ldots n; \quad j \in \Omega_c \qquad (22)$$

In (21) and (22), $w_j^{\min} = \text{Min} w_{ij}$ and $z_j^{\max} = \text{Max} z_{ij}$ respectively. Likewise, $\Delta_{\min}^{\max} = z_j^{\max} - w_j^{\min}$. Also, Ω_b and Ω_c are sets of benefit and cost indicators, respectively. Since the overall sustainability index (S_I) is a function of sustainability indices of the indicators, this implies that the overall sustainability index for any of the RMs ($\tilde{S}_I^{\text{Rm}}$) can be obtained from (24) by summing the aggregates of the sustainability indicators in the normalized decision matrix [28].

$$\begin{bmatrix} \tilde{R}_{mA}^{ag}\Big|_1^{\overline{N}} & \tilde{R}_{mA}^{ag}\Big|_2^{\overline{N}} & \tilde{R}_{mA}^{ag}\Big|_3^{\overline{N}} & \cdots & \tilde{R}_{mA}^{ag}\Big|_j^{\overline{N}} \\ \tilde{R}_{mB}^{ag}\Big|_1^{\overline{N}} & \tilde{R}_{mB}^{ag}\Big|_2^{\overline{N}} & \tilde{R}_{mB}^{ag}\Big|_3^{\overline{N}} & \cdots & \tilde{R}_{mB}^{ag}\Big|_j^{\overline{N}} \\ \tilde{R}_{mC}^{ag}\Big|_1^{\overline{N}} & \tilde{R}_{mC}^{ag}\Big|_2^{\overline{N}} & \tilde{R}_{mC}^{ag}\Big|_3^{\overline{N}} & \cdots & \tilde{R}_{mC}^{ag}\Big|_j^{\overline{N}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{R}_{mN}^{ag}\Big|_1^{\overline{N}} & \tilde{R}_{mN}^{ag}\Big|_2^{\overline{N}} & \tilde{R}_{mN}^{ag}\Big|_3^{\overline{N}} & \cdots & \tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}} \end{bmatrix} \qquad (23)$$

$$\tilde{S}_I^{\text{Rm}}\Big|_j = \sum_{N=A}^{N=N} \tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}} \qquad (24)$$

In (23) and (24), $\tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}}$ is the normalized value of an element in the decision matrix corresponding to the jth RM with the Nth sustainability index.

E. SUSTAINABLE SIMILARITY MEASURE

The elements of the normalized decision matrix in (23) represents the performance of the RMs considering their sustainability indicators. Further, suppose it is desired to measure the extent of the performances. In that case, an ideal situation needs to be created that will be used to compare the current performance of the elements in the normalized decision matrix. Practically, there is no unlimited possibility that a RM will perform perfectly in all the sustainability indicators. However, it is expected that the machine should have a satisfactory performance in all the indicators. Hence there is a need for continuous improvements in the design in order to have a satisfactory performance in all the sustainability indicators. Considering the TrFNs of the current performance of the RMs in (23), if we define an ideal TrFN that can be used to compare the current performance, then it is possible to obtain the level of improvement required in the sustainability indicators as presented by the cosine similarity measure in (25) [29].

$$CS\left[\tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}*}, \tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}} \right]$$

$$= \left[1 - \left(\frac{\left|w_j^* - w_j\right| + \left|x_j^* - x_j\right| + \left|y_j^* - y_j\right| + \left|z_j^* - z_j\right|}{4} \right) \right]\Bigg|_N \qquad (25)$$

In (25), $CS\left[\tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}*}, \tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}} \right]$ is the cosine similarity measure between the ideal performance and the current performance. Also, $\tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}*}$ is the ideal or perfect performance which can be expressed as;

$$\tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}*} = \left[w_j^*, x_j^*, y_j^*, z_j^* \right] = [1, 1, 1, 1] \qquad (26)$$

Further, it is expected that the higher the similarity measure, the better the performance of the RM relative to sustainability indicator under consideration, but the Euclidean distance is required to provide how close or far is the performance of the indicator to perfection. The Euclidean distance $d\left(R_m^{N*}, R_m^N\right)$ is obtainable from (27) [30, 31].

$$d\left(R_m^{N*}, R_m^N\right) = \left(2\left(1 - CS\left[\tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}*}, \tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}} \right]\right)\right)^{\frac{1}{2}} \qquad (27)$$

Considering (25), a higher value of the similarity measure is preferable for the sustainability indicators because it depicts the closeness of the RM to the optimum sustainability measure $\left(S_{opt}^N\right)$ with respect to the indicator under consideration. The optimum sustainability measure for any indicator is obtained as the similarity measure equals unity. However, it is sometimes practically impossible to achieve optimum sustainability measures for all the indicators because some trade-offs will be encountered in the design process in order to ensure that all the indicators have satisfactory sustainable performance. This implies that the optimum sustainability for any of the indicators can be obtained from (28). Hence, the Sustainable Similarity Measure (SSM) of the RMs can be obtained by summing all the similarity measures for all the indicators, as presented in (29). This implies that the overall Optimum Sustainability (OS$_{opt}$) is expected to be equal to the number of indicators, as presented in (30). Also, it is practically difficult for the sustainable similarity measure for a RM to be equal to the overall optimum sustainability measure, but a significant performance is expected from the RMs. The SSM provides a clearer picture of the performance of the RMs compare to the sustainability index obtained from (24) because it shows their sustainability measure relative to the overall optimum sustainability.

$$S_{opt}^N = \text{Max}\left[CS\left[\tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}*}, \tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}} \right] \right] = 1 \qquad (28)$$

$$\text{SSM} = \sum_{N=A}^{N=N} CS\left[\tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}*}, \tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}} \right] \qquad (29)$$

$$\text{OS}_{opt} = \sum_{N=A}^{N=N} \text{Max}\left[CS\left[\tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}*}, \tilde{R}_{mN}^{ag}\Big|_j^{\overline{N}} \right] \right] \qquad (30)$$

In order to identify the indicators to improve, it is necessary to develop an analysis of the Euclidean distances of the indicators relative to the highest Euclidean distance that the indicators must not approach. For ease of analysis, as the sustainable similarity measure of the indicator tends
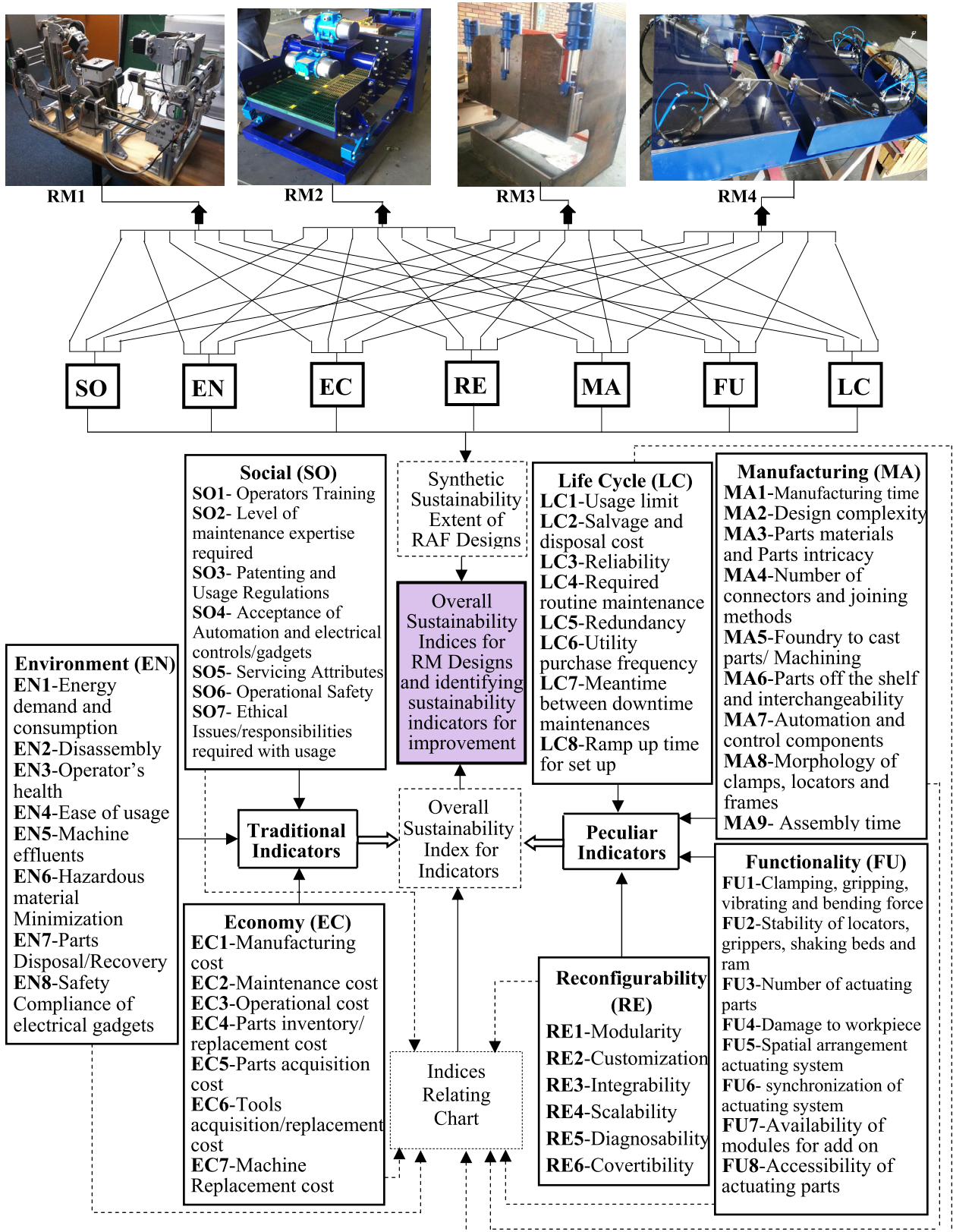
FIGURE 5. Framework for sustainable design of RMs.

to zero in (27), the Euclidean distance tends to a maximum value, which depicts the worst sustainable performance for

the indicator. On the contrary, as the sustainable similarity measure increases, the Euclidean distance tends to a

TABLE 2. Fuzzified aggregating matrix.

Indicators	RM 1 $\left[\tilde{R}^{ag}_{m\,j}\right]$	RM 2 $\left[\tilde{R}^{ag}_{m\,j}\right]$	RM 3 $\left[\tilde{R}^{ag}_{m\,j}\right]$	RM 4 $\left[\tilde{R}^{ag}_{m\,j}\right]$
EN	143/9 161/3 24 97/3	115/8 92/5 133/6 121/4	40/3 86/5 125/6 86/3	101/6 127/6 176/7 168/5
SO	38/3 16 172/9 128/5	76/7 14 17 162/7	23/2 117/8 53/3 24	113/9 79/5 19 76/3
EC	83/6 118/7 121/6 53/2	21/2 66/5 81/5 177/8	10 38/3 78/5 43/2	125/9 17 81/4 80/3
RE	13 31/2 18 114/5	59/6 97/8 115/8 19	79/7 96/7 16 104/5	96/7 49/3 113/6 143/6
MA	88/5 65/3 180/7 235/7	91/6 19 137/6 218/7	123/8 96/5 23 94/3	53/3 196/9 155/6 69/2
FU	18 22 181/7 235/7	31/2 173/9 23 121/4	35/2 43/2 177/7 263/8	93/5 68/3 80/3 241/7
LC	35/2 173/8 233/9 67/2	40/3 17 145/7 83/3	25/2 16 138/7 80/3	17 21 126/5 98/3

TABLE 3. Normalised aggregating matrix and left and right scores.

	RMs			
	RM1	RM2	RM3	RM4
Indicators	$\tilde{R}^{ag}_{mN}\big|^{\overline{N}}_{j}$	$\tilde{R}^{ag}_{mN}\big|^{\overline{N}}_{j}$	$\tilde{R}^{ag}_{mN}\big|^{\overline{N}}_{j}$	$\tilde{R}^{ag}_{mN}\big|^{\overline{N}}_{j}$
EN	1/8 1/3 19/36 15/16	5/99 1/4 17/39 5/6	0 4/21 27/73 28/37	11/64 29/75 7/12 1
SO	1/8 28/31 14/25 1	0 6/29 16/39 5/6	1/23 11/43 31/67 74/83	3/26 1/3 52/95 62/63
EC	0 23/59 10/17 10/13	16/59 49/78 21/26 32/33	14/15 2/3 37/44 1	0 5/13 38/65 23/30
RE	2/9 17/42 37/64 89/96	0 13/79 25/77 15/23	8/77 5/18 4/9 40/51	23/83 7/15 38/59 1
MA	0 5/11 2/3 7/8	11/63 29/48 69/86 1	8/49 29/49 34/43 93/94	0 31/69 27/41 67/77
FU	9/70 31/91 35/64 86/87	0 13/66 9/23 39/50	4/37 6/19 44/85 11/12	13/79 27/71 43/73 1
LC	6/25 24/55 16/25 1	3/71 13/61 11/28 55/76	0 1/6 19/55 52/77	16/75 13/32 37/61 26/27
Centroid	2 17/5 44/9	5/3 3 13/3	17/9 25/8 9/2	11/5 7/2 5
[Ls Rs]	97/66 185/94	4/3 9/5	7/5 15/8	3/2 2

TABLE 4. Sustainability measures for the RMs.

	RMs							
	RM1		RM2		RM3		RM4	
Indicators	CS	d	CS	d	CS	d	CS	d
EN	0.48	1.02	0.39	1.10	0.33	1.16	0.54	0.96
SO	0.51	0.99	0.36	1.13	0.41	1.08	0.50	1.00
EC	0.44	1.06	0.67	0.81	0.70	0.77	0.43	1.06
RE	0.53	0.97	0.29	1.20	0.40	1.09	0.60	0.90
MA	0.50	1.00	0.65	0.84	0.63	0.86	0.49	1.01
FU	0.49	1.01	0.34	1.15	0.46	1.03	0.53	0.97
LC	0.58	0.92	0.34	1.15	0.30	1.19	0.55	0.95
$\tilde{S}^{Rm}_{I}$	1.72		1.55		1.64		1.76	
SSM	3.53		3.04		3.24		3.64	

minimum value of zero, which depicts the best sustainable performance for the indicator. Again, the zero value of the Euclidean distance is not practically achievable, but it is usually best desired to keep this value as close to zero as possible. Hence, from (31) and (32), a value of zero and the square root of two indicates the best and worst sustainable performance, respectively.

$$d_{best} = \left(2\left(1 - CS\left[\tilde{R}^{ag}_{mN}\big|^{\overline{N}*}_{j}, \tilde{R}^{ag}_{mN}\big|^{\overline{N}}_{j}\right]\Big|_{MAX}\right)\right)^{\frac{1}{2}} \approx 0 \quad (31)$$

$$d_{worst} = \left(2\left(1 - CS\left[\tilde{R}^{ag}_{mN}\big|^{\overline{N}*}_{j}, \tilde{R}^{ag}_{mN}\big|^{\overline{N}}_{j}\right]\Big|_{MIN}\right)\right)^{\frac{1}{2}} \approx 2^{\frac{1}{2}} \quad (32)$$

In (31) and (32), 'd_{best}' and 'd_{worst}' represents the best and worst values of the Euclidean distance, respectively.

IV. APPLICATION TO RMs

This section presents the implementation of the developed methodology for the sustainable design of different RMs. Four RM prototypes considered are Reconfigurable Bending Press Machine (RBPM), Reconfigurable Vibrating Screen (RVS), Reconfigurable Assembly Fixture (RAF), and an Automated Flexible Fixture System (AFFS). It is essential to know that the essence of using four RMs is not to compare their performance or to prove that a design is better than the other. These RMs are chosen as examples of how to apply the developed model on the assessment of their sustainability. This implies that one RM would have been used, but in order to create a sufficient application of the developed model, four RMs were considered. The AFFS is a reconfigurable type of flexible fixture that can be reconfigured to accommodate different part geometries and rapidly provide automatic set-up and changeovers during operation [32]. The RAF is
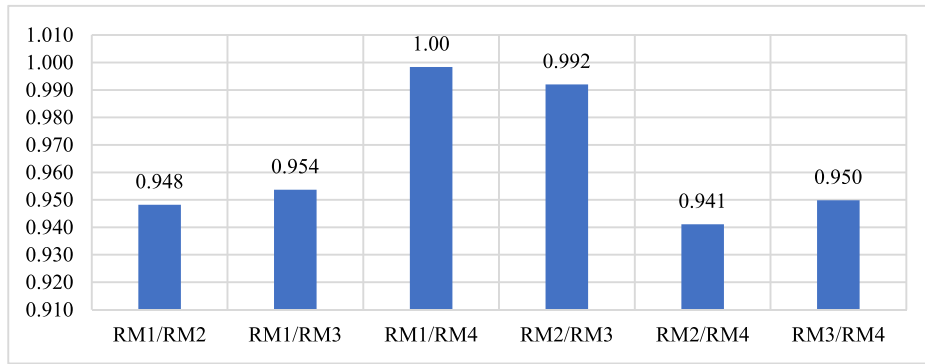
FIGURE 6. Similarity measures of paired RMs based on defuzzified TrFNs.
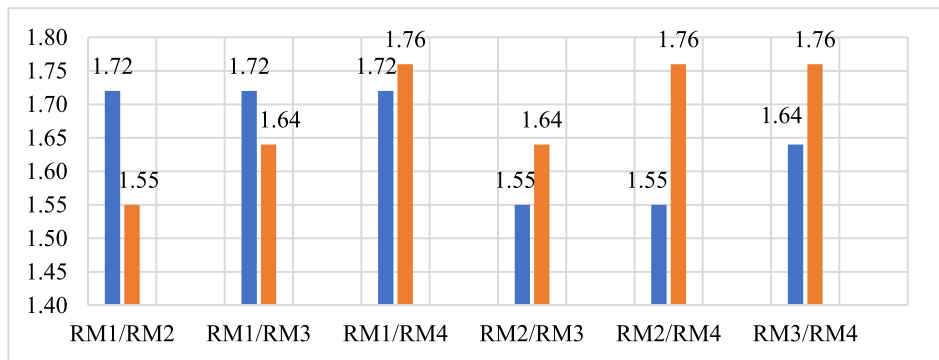
FIGURE 7. Values of sustainability indices for RMs.
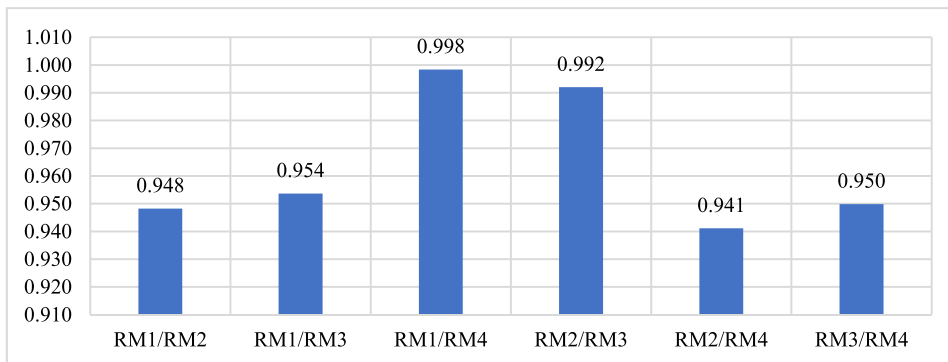
FIGURE 8. Similarity measures of paired RMs based on CS values.
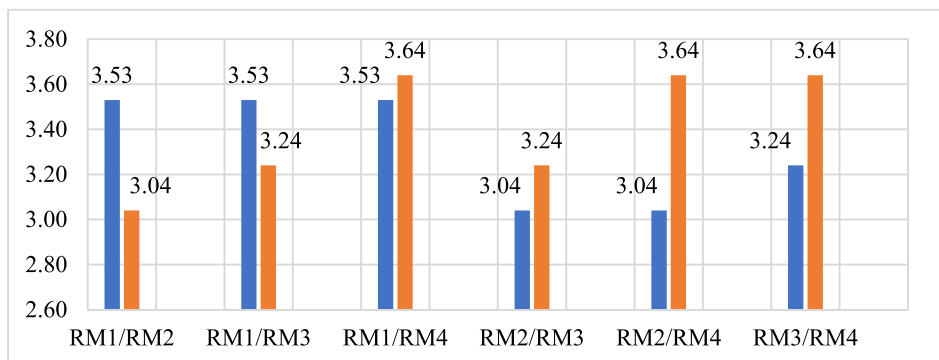
FIGURE 9. Values of CS for RMs.

designed as major enabling equipment in a RAS to rapidly position the frames of a workpiece while other components are assembled to it. The demand for a variety of press brake sizes and models necessitate the design of the RAF in order to have a sustainable RAS for assembly of these press brakes models [33], [34]. The RAF achieves reconfiguration

TABLE 5. Sensitivity analysis.

Sustainability Indicators		RM Designs				Design Pairings (similarity Measures)					
		RM1	RM2	RM3	RM4	RM1/RM2	RM1/RM3	RM1/RM4	RM2/RM3	RM2/RM4	RM3/RM4
Defuzzified TrFN Values	EN	0.454	0.380	0.326	0.499						
	SO	0.473	0.354	0.396	0.464						
	EC	0.479	0.674	0.704	0.475						
	RE	0.503	0.290	0.392	0.557	0.948	0.954	1.000	0.992	0.941	0.950
	MA	0.535	0.656	0.646	0.531						
	FU	0.464	0.339	0.442	0.498						
	LC	0.541	0.342	0.302	0.515						
$\tilde{S}_I^{Rm}$		1.72	1.55	1.64	1.76	1.72/1.55	1.72/1.64	1.72/1.76	1.55/1.64	1.55/1.76	1.64/1.76
CS Values	EN	0.482	0.393	0.329	0.535						
	SO	0.507	0.363	0.413	0.495						
	EC	0.439	0.669	0.704	0.434						
	RE	0.533	0.285	0.403	0.597	0.930	0.938	0.998	0.989	0.921	0.933
	MA	0.500	0.645	0.634	0.494						
	FU	0.493	0.342	0.465	0.533						
	LC	0.579	0.343	0.297	0.547						
SSM		3.53	3.04	3.24	3.64	3.53/3.04	3.53/3.24	3.53/3.64	3.04/3.24	3.04/3.64	3.24/3.64
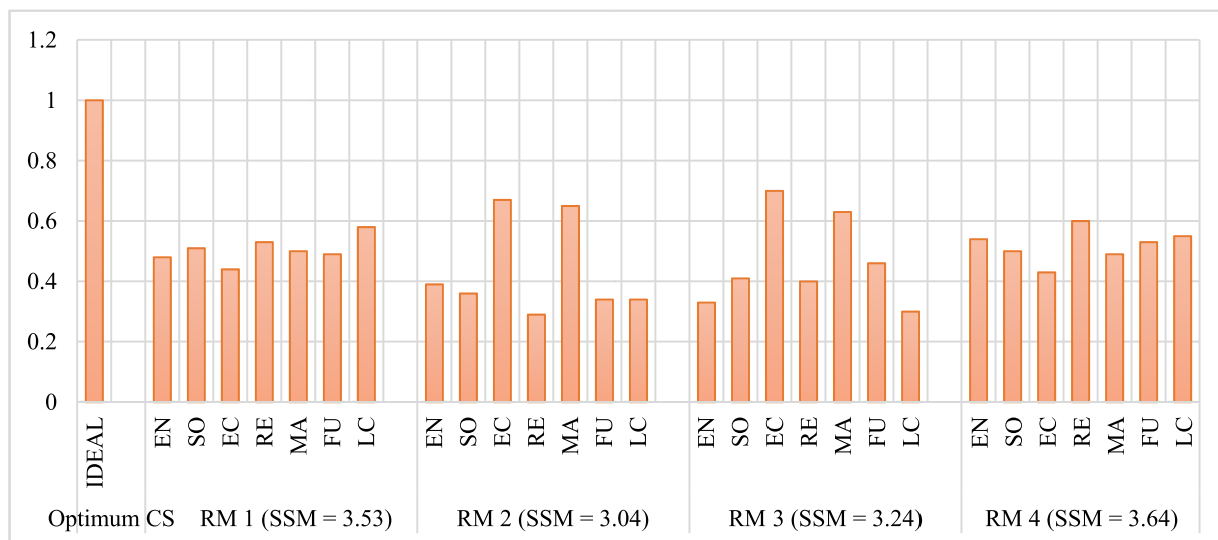
FIGURE 10. Cosine similarity measures for the sustainability indicators of the RMs.

using a reconfiguration model that coordinates the positions of hydraulic actuators. These actuators are synchronized to ensure uniform gripping of the frames in operation [35], [36]. The RVS is a type of vibrating screen with variable screen capacity to accommodate the variations in demand for mineral materials. The machine provides changeability to the screen size and capacity through a reconfiguration model and an agent-based maintenance system. The reconfiguration model also computes the throughput capacity required for operating the new screen capacity [37]. Also, the RBPM is a type of press brake that has variations in bed length and stroke height. This machine achieves its reconfiguration by addition of add-on modules. These modules comprise of several parts that are selected based on the required configuration [38]. Figure 5 presents the framework showing

all the sub-indicators considered in the design sustainability of the RMs.

In order to simplify the application of the developed model, Table 6, in APPENDIX, A present the index relating chart for sub-indicators of the environmental indicator when related to sub-indicators of other indicators in consideration. The index relating chart of other sub-indicators is presented in Tables 7 to 12 of APPENDIX A. The text with font colour green in the charts represents the Fuzzified Viable Relationships (FVR) that are represented with TrFN in the FVR column following (2). The last rows of the charts present the fuzzified sustainability index for the indicators following (3). Further, fuzzified sub-aggregating matrices are developed from three expert's opinions using the linguistic scale presented in Table 1. The indices obtained from the

FIGURE 11. Euclidean distance of the sustainability indicators relative to the worst performance.

TABLE 6. Index relating chart for environmental indicator.

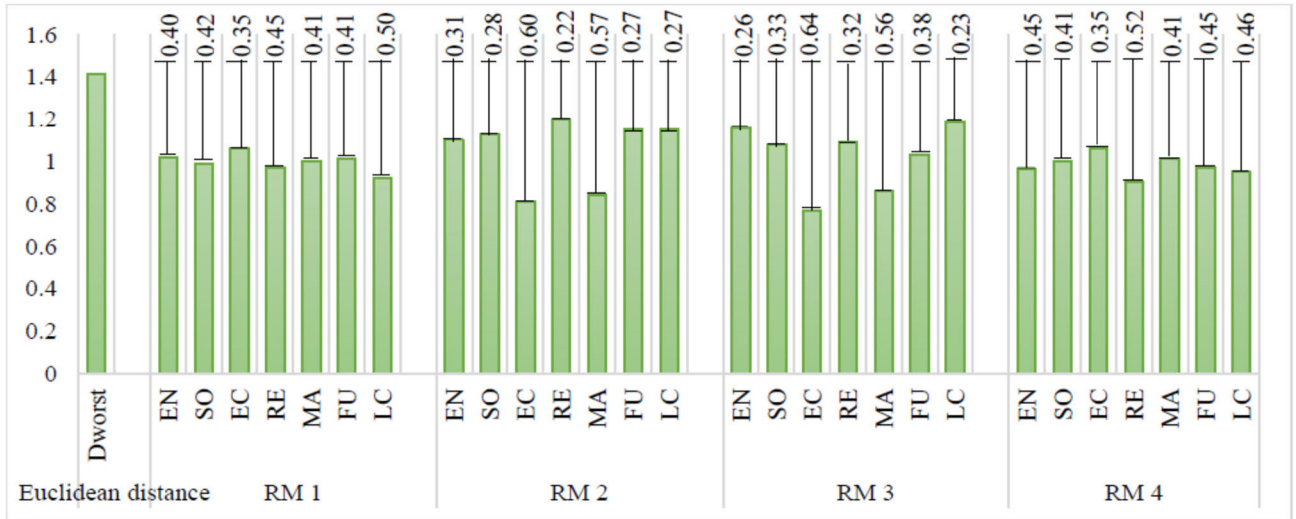|	SO	EC	RE	MA	FU	LC	FVR $\sum EN_1 \cdots EN_8$
EN1	EN1/SO1 EN1/SO5 EN1/SO2 EN1/SO6 EN1/SO3 EN1/SO7 EN1/SO4	EN1/EC1 EN1/EC5 EN1/EC2 EN1/EC6 EN1/EC3 EN1/EC7 EN1/EC4	EN1/RE1 EN1/RE4 EN1/RE2 EN1/RE5 EN1/RE3 EN1/RE6	EN1/MA1 EN1/MA5 EN1/MA2 EN1/MA6 EN1/MA3 EN1/MA7 EN1/MA4 EN1/MA8 EN1/MA9	EN1/FU1 EN1/FU5 EN1/FU2 EN1/FU6 EN1/FU3 EN1/FU7 EN1/FU4 EN1/FU8	EN1/LC1 EN1/LC5 EN1/LC2 EN1/LC6 EN1/LC3 EN1/LC7 EN1/LC4 EN1/LC8	53/8 55/8 57/8 61/8
EN2	EN2/SO1 EN2/SO5 EN2/SO2 EN2/SO6 EN2/SO3 EN2/SO7 EN2/SO4	EN2/EC1 EN2/EC5 EN2/EC2 EN2/EC6 EN2/EC3 EN2/EC7 EN2/EC4	EN2/RE1 EN2/RE4 EN2/RE2 EN2/RE5 EN2/RE3 EN2/RE6	EN2/MA1 EN2/MA5 EN2/MA2 EN2/MA6 EN2/MA3 EN2/MA7 EN2/MA4 EN2/MA8 EN2/MA9	EN2/FU1 EN2/FU5 EN2/FU2 EN2/FU6 EN2/FU3 EN2/FU7 EN2/FU4 EN2/FU8	EN2/LC1 EN2/LC5 EN2/LC2 EN2/LC6 EN2/LC3 EN2/LC7 EN2/LC4 EN2/LC8	25/4 13/2 27/4 29/4
EN3	EN3/SO1 EN3/SO5 EN3/SO2 EN3/SO6 EN3/SO3 EN3/SO7 EN3/SO4	EN3/EC1 EN3/EC5 EN3/EC2 EN3/EC6 EN3/EC3 EN3/EC7 EN3/EC4	EN3/RE1 EN1/RE4 EN3/RE2 EN1/RE5 EN3/RE3 EN1/RE6	EN3/MA1 EN3/MA5 EN3/MA2 EN3/MA6 EN3/MA3 EN3/MA7 EN3/MA4 EN3/MA8 EN3/MA9	EN3/FU1 EN3/FU5 EN3/FU2 EN3/FU6 EN3/FU3 EN3/FU7 EN3/FU4 EN3/FU8	EN3/LC1 EN3/LC5 EN3/LC2 EN3/LC6 EN3/LC3 EN3/LC7 EN3/LC4 EN3/LC8	13/4 7/2 15/4 17/4
EN4	EN4/SO1 EN4/SO5 EN4/SO2 EN4/SO6 EN4/SO3 EN4/SO7 EN4/SO4	EN4/EC1 EN4/EC5 EN4/EC2 EN4/EC6 EN4/EC3 EN4/EC7 EN4/EC4	EN4/RE1 EN4/RE4 EN4/RE2 EN4/RE5 EN4/RE3 EN4/RE6	EN4/MA1 EN4/MA5 EN4/MA2 EN4/MA6 EN4/MA3 EN4/MA7 EN4/MA4 EN4/MA8 EN4/MA9	EN4/FU1 EN4/FU5 EN4/FU2 EN4/FU6 EN4/FU3 EN4/FU7 EN4/FU4 EN4/FU8	EN4/LC1 EN4/LC5 EN4/LC2 EN4/LC6 EN4/LC3 EN4/LC7 EN4/LC4 EN4/LC8	31/4 8 33/4 35/4
EN5	EN5/SO1 EN5/SO5 EN5/SO2 EN5/SO6 EN5/SO3 EN5/SO7 EN5/SO4	EN5/EC1 EN5/EC5 EN5/EC2 EN5/EC6 EN5/EC3 EN5/EC7 EN5/EC4	EN5/RE1 EN5/RE4 EN5/RE2 EN5/RE5 EN5/RE3 EN5/RE6	EN5/MA1 EN5/MA5 EN5/MA2 EN5/MA6 EN5/MA3 EN5/MA7 EN5/MA4 EN5/MA8 EN5/MA9	EN5/FU1 EN5/FU5 EN5/FU2 EN5/FU6 EN5/FU3 EN5/FU7 EN5/FU4 EN5/FU8	EN5/LC1 EN5/LC5 EN5/LC2 EN5/LC6 EN5/LC3 EN5/LC7 EN5/LC4 EN5/LC8	13/4 7/2 15/4 17/4
EN6	EN6/SO1 EN6/SO5 EN6/SO2 EN6/SO6 EN6/SO3 EN6/SO7 EN6/SO4	EN6/EC1 EN6/EC5 EN6/EC2 EN6/EC6 EN6/EC3 EN6/EC7 EN6/EC4	EN6/RE1 EN6/RE4 EN6/RE2 EN6/RE5 EN6/RE3 EN6/RE6	EN6/MA1 EN6/MA5 EN6/MA2 EN6/MA6 EN6/MA3 EN6/MA7 EN6/MA4 EN6/MA8 EN6/MA9	EN6/FU1 EN6/FU5 EN6/FU2 EN6/FU6 EN6/FU3 EN6/FU7 EN6/FU4 EN6/FU8	EN6/LC1 EN6/LC5 EN6/LC2 EN6/LC6 EN6/LC3 EN6/LC7 EN6/LC4 EN6/LC8	29/8 31/8 33/8 37/8
EN7	EN7/SO1 EN7/SO5 EN7/SO2 EN7/SO6 EN7/SO3 EN7/SO7 EN7/SO4	EN7/EC1 EN7/EC5 EN7/EC2 EN7/EC6 EN7/EC3 EN7/EC7 EN7/EC4	EN7/RE1 EN7/RE4 EN7/RE2 EN7/RE5 EN7/RE3 EN7/RE6	EN7/MA1 EN7/MA5 EN7/MA2 EN7/MA6 EN7/MA3 EN7/MA7 EN7/MA4 EN7/MA8 EN7/MA9	EN7/FU1 EN7/FU5 EN7/FU2 EN7/FU6 EN7/FU3 EN7/FU7 EN7/FU4 EN7/FU8	EN7/LC1 EN7/LC5 EN7/LC2 EN7/LC6 EN7/LC3 EN7/LC7 EN7/LC4 EN7/LC8	35/8 37/8 39/8 41/8
EN8	EN8/SO1 EN8/SO5 EN8/SO2 EN8/SO6 EN8/SO3 EN8/SO7 EN8/SO4	EN8/EC1 EN8/EC5 EN8/EC2 EN8/EC6 EN8/EC3 EN8/EC7 EN8/EC4	EN8/RE1 EN8/RE4 EN8/RE2 EN8/RE5 EN8/RE3 EN8/RE6	EN8/MA1 EN8/MA5 EN8/MA2 EN8/MA6 EN8/MA3 EN8/MA7 EN8/MA4 EN8/MA8 EN8/MA9	EN8/FU1 EN8/FU5 EN8/FU2 EN8/FU6 EN8/FU3 EN8/FU7 EN8/FU4 EN8/FU8	EN8/LC1 EN8/LC5 EN8/LC2 EN8/LC6 EN8/LC3 EN8/LC7 EN8/LC4 EN8/LC8	41/8 43/8 45/8 49/8

$$\widetilde{EN}_{VR} = 5 \quad 37/7 \quad 11/2 \quad 6$$

index relating charts for the indicators and sub-indicators are used to obtain sub-aggregates for the RMs by applying (18) and (19). Tables 13 to 19 of APPENDIX B shows the aggregating matrices for all the indicators, considering

TABLE 7. Index relating chart for social indicator.

	EN	EC	RE	MA	FU	LC	FVR $\sum SO_1 \cdots SO_7$
SO1	SO1/EN1 SO1/EN5 SO1/EN2 SO1/EN6 SO1/EN3 SO1/EN7 SO1/EN4 SO1/EN8	SO1/EC1 SO1/EC5 SO1/EC2 SO1/EC6 SO1/EC3 SO1/EC7 SO1/EC4	SO1/RE1 SO1/RE4 SO1/RE2 SO1/RE5 SO1/RE3 SO1/RE6	SO1/MA1 SO1/MA5 SO1/MA2 SO1/MA6 SO1/MA3 SO1/MA7 SO1/MA4 SO1/MA8 SO1/MA9	SO1/FU1 SO1/FU5 SO1/FU2 SO1/FU6 SO1/FU3 SO1/FU7 SO1/FU4 SO1/FU8	SO1/LC1 SO1/LC5 SO1/LC2 SO1/LC6 SO1/LC3 SO1/LC7 SO1/LC4 SO1/LC8	31/4 8 33/4 35/4
SO2	SO2/EN1 SO2/EN5 SO2/EN2 SO2/EN6 SO2/EN3 SO2/EN7 SO2/EN4 SO2/EN8	SO2/EC1 SO2/EC5 SO2/EC2 SO2/EC6 SO2/EC3 SO2/EC7 SO2/EC4	SO2/RE1 SO2/RE4 SO2/RE2 SO2/RE5 SO2/RE3 SO2/RE6	SO2/MA1 SO2/MA5 SO2/MA2 SO2/MA6 SO2/MA3 SO2/MA7 SO2/MA4 SO2/MA8 SO2/MA9	SO2/FU1 SO2/FU5 SO2/FU2 SO2/FU6 SO2/FU3 SO2/FU7 SO2/FU4 SO2/FU8	SO2/LC1 SO2/LC5 SO2/LC2 SO2/LC6 SO2/LC3 SO2/LC7 SO2/LC4 SO2/LC8	11/2 23/4 6 13/2
SO3	SO3/EN1 SO3/EN5 SO3/EN2 SO3/EN6 SO3/EN3 SO3/EN7 SO3/EN4 SO3/EN8	SO3/EC1 SO3/EC5 SO3/EC2 SO3/EC6 SO3/EC3 SO3/EC7 SO3/EC4	SO3/RE1 SO3/RE4 SO3/RE2 SO3/RE5 SO3/RE3 SO3/RE6	SO3/MA1 SO3/MA5 SO3/MA2 SO3/MA6 SO3/MA3 SO3/MA7 SO3/MA4 SO3/MA8 SO3/MA9	SO3/FU1 SO3/FU5 SO3/FU2 SO3/FU6 SO3/FU3 SO3/FU7 SO3/FU4 SO3/FU8	SO3/LC1 SO3/LC5 SO3/LC2 SO3/LC6 SO3/LC3 SO3/LC7 SO3/LC4 SO3/LC8	53/8 55/8 57/8 61/8
SO4	SO4/EN1 SO4/EN5 SO4/EN2 SO4/EN6 SO4/EN3 SO4/EN7 SO4/EN4 SO4/EN8	SO4/EC1 SO4/EC5 SO4/EC2 SO4/EC6 SO4/EC3 SO4/EC7 SO4/EC4	SO4/RE1 SO4/RE4 SO4/RE2 SO4/RE5 SO4/RE3 SO4/RE6	SO4/MA1 SO4/MA5 SO4/MA2 SO4/MA6 SO4/MA3 SO4/MA7 SO4/MA4 SO4/MA8 SO4/MA9	SO4/FU1 SO4/FU5 SO4/FU2 SO4/FU6 SO4/FU3 SO4/FU7 SO4/FU4 SO4/FU8	SO4/LC1 SO4/LC5 SO4/LC2 SO4/LC6 SO4/LC3 SO4/LC7 SO4/LC4 SO4/LC8	11/2 23/4 6 13/2
SO5	SO5/EN1 SO5/EN5 SO5/EN2 SO5/EN6 SO5/EN3 SO5/EN7 SO5/EN4 SO5/EN8	SO5/EC1 SO5/EC5 SO5/EC2 SO5/EC6 SO5/EC3 SO5/EC7 SO5/EC4	SO5/RE1 SO5/RE4 SO5/RE2 SO5/RE5 SO5/RE3 SO5/RE6	SO5/MA1 SO5/MA5 SO5/MA2 SO5/MA6 SO5/MA3 SO5/MA7 SO5/MA4 SO5/MA8 SO5/MA9	SO5/FU1 SO5/FU5 SO5/FU2 SO5/FU6 SO5/FU3 SO5/FU7 SO5/FU4 SO5/FU8	SO5/LC1 SO5/LC5 SO5/LC2 SO5/LC6 SO5/LC3 SO5/LC7 SO5/LC4 SO5/LC8	13/4 7/2 15/4 17/4
SO6	SO6/EN1 SO6/EN5 SO6/EN2 SO6/EN6 SO6/EN3 SO6/EN7 SO6/EN4 SO6/EN8	SO6/EC1 SO6/EC5 SO6/EC2 SO6/EC6 SO6/EC3 SO6/EC7 SO6/EC4	SO6/RE1 SO6/RE4 SO6/RE2 SO6/RE5 SO6/RE3 SO6/RE6	SO6/MA1 SO6/MA5 SO6/MA2 SO6/MA6 SO6/MA3 SO6/MA7 SO6/MA4 SO6/MA8 SO6/MA9	SO6/FU1 SO6/FU5 SO6/FU2 SO6/FU6 SO6/FU3 SO6/FU7 SO6/FU4 SO6/FU8	SO6/LC1 SO6/LC5 SO6/LC2 SO6/LC6 SO6/LC3 SO6/LC7 SO6/LC4 SO6/LC8	11/2 23/4 6 13/2
SO7	SO7/EN1 SO7/EN5 SO7/EN2 SO7/EN6 SO7/EN3 SO7/EN7 SO7/EN4 SO7/EN8	SO7/EC1 SO7/EC5 SO7/EC2 SO7/EC6 SO7/EC3 SO7/EC7 SO7/EC4	SO7/RE1 SO7/RE4 SO7/RE2 SO7/RE5 SO7/RE3 SO7/RE6	SO7/MA1 SO7/MA5 SO7/MA2 SO7/MA6 SO7/MA3 SO7/MA7 SO7/MA4 SO7/MA8 SO7/MA9	SO7/FU1 SO7/FU5 SO7/FU2 SO7/FU6 SO7/FU3 SO7/FU7 SO7/FU4 SO7/FU8	SO7/LC1 SO7/LC5 SO7/LC2 SO7/LC6 SO7/LC3 SO7/LC7 SO7/LC4 SO7/LC8	7 29/4 15/2 8

$$\tilde{SO}_{VR} = 47/8 \quad 49/8 \quad 51/8 \quad 55/8$$

the four RMs used as case studies in this article. The fuzzified sub-aggregates from these matrices are harnessed as the decision matrices, as presented in Table 2. The elements of the fuzzified aggregation matrix in Table 2 are normalized by applying (21) and (22). The economic and manufacturing indicators are considered as cost sustainability indicators because it is usually desired to reduce these two indicators during development. Also, the environmental, social, reconfigurability, functionality, and life cycle analysis are treated as beneficial sustainability indicators because they are attributes required for the sustainable performance of the RMs. Table 3 present the normalized aggregating matrix, the centroid and left and right scores, while Table 4 present the overall sustainability index, the cosine similarity measure, sustainable similarity measures, and Euclidean distances of the indicators considering all the RMs. The overall sustainability index and cosine similarity measures are obtained from (24) and (25) respectively, while the Euclidean distances and sustainable similarity measures are obtained from (27) and (29) respectively.

A. SENSITIVITY ANALYSIS
In order to validate the results of the assessment, a sensitivity analysis was done by similarity measure of the values of the normalized TrFN in Table 3 and the cosine similarity

measures of the RMs in Table 4 considering all the indicators. Firstly, all the normalized TrFN were defuzzified using (12) to (17) and harnessed to form a decision matrix together with the values of the cosine similarity measures for all the RMs. Similarity measures were done by pairing all the RM designs. In essence, since there are four RMs, then six pairs were done as presented in Table 5. The similarity measurement applied in this article is achieved using the cosine similarity. The cosine similarity accomplishes similarity measurement by the cosine of the angle between two vectors and determines whether two vectors are pointing in roughly the same direction as presented in (33). In essence, the elements for the RMs in Table 5 are compared to validate their similarity to the results of the sustainable index and cosine similarity measures.

$$\text{Sim}[A, B] = \left(\sum_{i=1}^{i=i} [A_i^* B_i] \right) \Big/ \left(\sqrt{\sum_{i=1}^{i=i} A_i^2} \right) \left(\sqrt{\sum_{i=1}^{i=i} B_i^2} \right) \tag{33}$$

In (33), A and B represent 'i' set of values to be checked for similarity. These are the values of the pairing for the RMs in this case. Considering Table 5, an example of pairing RM1 and RM2 using the defuzzified TrFN data from (33) can be expressed as [39]; Sim[RM1, RM2], as shown at the bottom of the 16th page.

TABLE 8. Index relating chart for economic indicator.

	SO	EN	RE	MA	FU	LC	FVR ∑$EC_1 \cdots EC_7$
EC1	EC1/SO1 EC1/SO5 EC1/SO2 EC1/SO6 EC1/SO3 EC1/SO7 EC1/SO4	EC1/EN1 EC1/EN5 EC1/EN2 EC1/EN6 EC1/EN3 EC1/EN7 EC1/EN4 EC1/EN8	EC1/RE1 EC1/RE4 EC1/RE2 EC1/RE5 EC1/RE3 EC1/RE6	EC1/MA1 EC1/MA5 EC1/MA2 EC1/MA6 EC1/MA3 EC1/MA7 EC1/MA4 EC1/MA8 EC1/MA9	EC1/FU1 EC1/FU5 EC1/FU2 EC1/FU6 EC1/FU3 EC1/FU7 EC1/FU4 EC1/FU8	EC1/LC1 EC1/LC5 EC1/LC2 EC1/LC6 EC1/LC3 EC1/LC7 EC1/LC4 EC1/LC8	25/4 13/2 27/4 29/4
EC2	EC2/SO1 EC2/SO5 EC2/SO2 EC2/SO6 EC2/SO3 EC2/SO7 EC2/SO4	EC2/EN1 EC2/EN5 EC2/EN2 EC2/EN6 EC2/EN3 EC2/EN7 EC2/EN4 EC2/EN8	EC2/RE1 EC2/RE4 EC2/RE2 EC2/RE5 EC2/RE3 EC2/RE6	EC2/MA1 EC2/MA5 EC2/MA2 EC2/MA6 EC2/MA3 EC2/MA7 EC2/MA4 EC2/MA8 EC2/MA9	EC2/FU1 EC2/FU5 EC2/FU2 EC2/FU6 EC2/FU3 EC2/FU7 EC2/FU4 EC2/FU8	EC2/LC1 EC2/LC5 EC2/LC2 EC2/LC6 EC2/LC3 EC2/LC7 EC2/LC4 EC2/LC8	25/4 13/2 27/4 29/4
EC3	EC3/SO1 EC3/SO5 EC3/SO2 EC3/SO6 EC3/SO3 EC3/SO7 EC3/SO4	EC3/EN1 EC3/EN5 EC3/EN2 EC3/EN6 EC3/EN3 EC3/EN7 EC3/EN4 EC3/EN8	EC3/RE1 EC3/RE4 EC3/RE2 EC3/RE5 EC3/RE3 EC3/RE6	EC3/MA1 EC3/MA5 EC3/MA2 EC3/MA6 EC3/MA3 EC3/MA7 EC3/MA4 EC3/MA8 EC3/MA9	EC3/FU1 EC3/FU5 EC3/FU2 EC3/FU6 EC3/FU3 EC3/FU7 EC3/FU4 EC3/FU8	EC3/LC1 EC3/LC5 EC3/LC2 EC3/LC6 EC3/LC3 EC3/LC7 EC3/LC4 EC3/LC8	71/8 73/8 75/8 79/8
EC4	EC4/SO1 EC4/SO5 EC4/SO2 EC4/SO6 EC4/SO3 EC4/SO7 EC4/SO4	EC4/EN1 EC4/EN5 EC4/EN2 EC4/EN6 EC4/EN3 EC4/EN7 EC4/EN4 EC4/EN8	EC4/RE1 EC4/RE4 EC4/RE2 EC4/RE5 EC4/RE3 EC4/RE6	EC4/MA1 EC4/MA5 EC4/MA2 EC4/MA6 EC4/MA3 EC4/MA7 EC4/MA4 EC4/MA8 EC4/MA9	EC4/FU1 EC4/FU5 EC4/FU2 EC4/FU6 EC4/FU3 EC4/FU7 EC4/FU4 EC4/FU8	EC4/LC1 EC4/LC5 EC4/LC2 EC4/LC6 EC4/LC3 EC4/LC7 EC4/LC4 EC4/LC8	7 29/4 15/2 8
EC5	EC5/SO1 EC5/SO5 EC5/SO2 EC5/SO6 EC5/SO3 EC5/SO7 EC5/SO4	EC5/EN1 EC5/EN5 EC5/EN2 EC5/EN6 EC5/EN3 EC5/EN7 EC5/EN4 EC5/EN8	EC5/RE1 EC5/RE4 EC5/RE2 EC5/RE5 EC5/RE3 EC5/RE6	EC5/MA1 EC5/MA5 EC5/MA2 EC5/MA6 EC5/MA3 EC5/MA7 EC5/MA4 EC5/MA8 EC5/MA9	EC5/FU1 EC5/FU5 EC5/FU2 EC5/FU6 EC5/FU3 EC5/FU7 EC5/FU4 EC5/FU8	EC5/LC1 EC5/LC5 EC5/LC2 EC5/LC6 EC5/LC3 EC5/LC7 EC5/LC4 EC5/LC8	47/8 49/8 51/8 55/8
EC6	EC6/SO1 EC6/SO5 EC6/SO2 EC6/SO6 EC6/SO3 EC6/SO7 EC6/SO4	EC6/EN1 EC6/EN5 EC6/EN2 EC6/EN6 EC6/EN3 EC6/EN7 EC6/EN4 EC6/EN8	EC6/RE1 EC6/RE4 EC6/RE2 EC6/RE5 EC6/RE3 EC6/RE6	EC6/MA1 EC6/MA5 EC6/MA2 EC6/MA6 EC6/MA3 EC6/MA7 EC6/MA4 EC6/MA8 EC6/MA9	EC6/FU1 EC6/FU5 EC6/FU2 EC6/FU6 EC6/FU3 EC6/FU7 EC6/FU4 EC6/FU8	EC6/LC1 EC6/LC5 EC6/LC2 EC6/LC6 EC6/LC3 EC6/LC7 EC6/LC4 EC6/LC8	47/8 49/8 51/8 55/8
EC7	EC7/SO1 EC7/SO5 EC7/SO2 EC7/SO6 EC7/SO3 EC7/SO7 EC7/SO4	EC7/EN1 EC7/EN5 EC7/EN2 EC7/EN6 EC7/EN3 EC7/EN7 EC7/EN4 EC7/EN8	EC7/RE1 EC7/RE4 EC7/RE2 EC7/RE5 EC7/RE3 EC7/RE6	EC7/MA1 EC7/MA5 EC7/MA2 EC7/MA6 EC7/MA3 EC7/MA7 EC7/MA4 EC7/MA8 EC7/MA9	EC7/FU1 EC7/FU5 EC7/FU2 EC7/FU6 EC7/FU3 EC7/FU7 EC7/FU4 EC7/FU8	EC7/LC1 EC7/LC5 EC7/LC2 EC7/LC6 EC7/LC3 EC7/LC7 EC7/LC4 EC7/LC8	4 17/4 9/2 5

$$\tilde{EC}_{VR} = 32/5 \quad 20/3 \quad 7 \quad 37/5$$

TABLE 9. Index relating chart for reconfigurability indicator.

	SO	EC	EN	MA	FU	LC	FVR ∑$RE_1 \cdots RE_6$
RE1	RE1/SO1 RE1/SO5 RE1/SO2 RE1/SO6 RE1/SO3 RE1/SO7 RE1/SO4	RE1/EC1 RE1/EC5 RE1/EC2 RE1/EC6 RE1/EC3 RE1/EC7 RE1/EC4	RE1/EN1 RE1/EN4 RE1/EN2 RE1/EN5 RE1/EN3 RE1/EN6 RE1/EN7 RE1/EN8	RE1/MA1 RE1/MA5 RE1/MA2 RE1/MA6 RE1/MA3 RE1/MA7 RE1/MA4 RE1/MA8 RE1/MA9	RE1/FU1 RE1/FU5 RE1/FU2 RE1/FU6 RE1/FU3 RE1/FU7 RE1/FU4 RE1/FU8	RE1/LC1 RE1/LC5 RE1/LC2 RE1/LC6 RE1/LC3 RE1/LC7 RE1/LC4 RE1/LC8	59/8 61/8 63/8 67/8
RE2	RE2/SO1 RE2/SO5 RE2/SO2 RE2/SO6 RE2/SO3 RE2/SO7 RE2/SO4	RE2/EC1 RE2/EC5 RE2/EC2 RE2/EC6 RE2/EC3 RE2/EC7 RE2/EC4	RE2/EN1 RE2/EN4 RE2/EN2 RE2/EN5 RE2/EN3 RE2/EN6 RE2/EN7 RE2/EN8	RE2/MA1 RE2/MA5 RE2/MA2 RE2/MA6 RE2/MA3 RE2/MA7 RE2/MA4 RE2/MA8 RE2/MA9	RE2/FU1 RE2/FU5 RE2/FU2 RE2/FU6 RE2/FU3 RE2/FU7 RE2/FU4 RE2/FU8	RE2/LC1 RE2/LC5 RE2/LC2 RE2/LC6 RE2/LC3 RE2/LC7 RE2/LC4 RE2/LC8	31/4 8 33/4 35/4
RE3	RE3/SO1 RE3/SO5 RE3/SO2 RE3/SO6 RE3/SO3 RE3/SO7 RE3/SO4	RE3/EC1 RE3/EC5 RE3/EC2 RE3/EC6 RE3/EC3 RE3/EC7 RE3/EC4	RE3/EN1 RE3/EN4 RE3/EN2 RE3/EN5 RE3/EN3 RE3/EN6 RE3/EN7 RE3/EN8	RE3/MA1 RE3/MA5 RE3/MA2 RE3/MA6 RE3/MA3 RE3/MA7 RE3/MA4 RE3/MA8 RE3/MA9	RE3/FU1 RE3/FU5 RE3/FU2 RE3/FU6 RE3/FU3 RE3/FU7 RE3/FU4 RE3/FU8	RE3/LC1 RE3/LC5 RE3/LC2 RE3/LC6 RE3/LC3 RE3/LC7 RE3/LC4 RE3/LC8	37/4 19/2 39/4 41/4
RE4	RE4/SO1 RE4/SO5 RE4/SO2 RE4/SO6 RE4/SO3 RE4/SO7 RE4/SO4	RE4/EC1 RE4/EC5 RE4/EC2 RE4/EC6 RE4/EC3 RE4/EC7 RE4/EC4	RE4/EN1 RE4/EN4 RE4/EN2 RE4/EN5 RE4/EN3 RE4/EN6 RE4/EN7 RE4/EN8	RE4/MA1 RE4/MA5 RE4/MA2 RE4/MA6 RE4/MA3 RE4/MA7 RE4/MA4 RE4/MA8 RE4/MA9	RE4/FU1 RE4/FU5 RE4/FU2 RE4/FU6 RE4/FU3 RE4/FU7 RE4/FU4 RE4/FU8	RE4/LC1 RE4/LC5 RE4/LC2 RE4/LC6 RE4/LC3 RE4/LC7 RE4/LC4 RE4/LC8	71/8 73/8 75/8 79/8
RE5	RE5/SO1 RE5/SO5 RE5/SO2 RE5/SO6 RE5/SO3 RE5/SO7 RE5/SO4	RE5/EC1 RE5/EC5 RE5/EC2 RE5/EC6 RE5/EC3 RE5/EC7 RE5/EC4	RE5/EN1 RE5/EN4 RE5/EN2 RE5/EN5 RE5/EN3 RE5/EN6 RE5/EN7 RE5/EN8	RE5/MA1 RE5/MA5 RE5/MA2 RE5/MA6 RE5/MA3 RE5/MA7 RE5/MA4 RE5/MA8 RE5/MA9	RE5/FU1 RE5/FU5 RE5/FU2 RE5/FU6 RE5/FU3 RE5/FU7 RE5/FU4 RE5/FU8	RE5/LC1 RE5/LC5 RE5/LC2 RE5/LC6 RE5/LC3 RE5/LC7 RE5/LC4 RE5/LC8	10 41/4 21/2 11
RE6	RE6/SO1 RE6/SO5 RE6/SO2 RE6/SO6 RE6/SO3 RE6/SO7 RE6/SO4	RE6/EC1 RE6/EC5 RE6/EC2 RE6/EC6 RE6/EC3 RE6/EC7 RE6/EC4	RE6/EN1 RE6/EN4 RE6/EN2 RE6/EN5 RE6/EN3 RE6/EN6 RE6/EN7 RE6/EN8	RE6/MA1 RE6/MA5 RE6/MA2 RE6/MA6 RE6/MA3 RE6/MA7 RE6/MA4 RE6/MA8 RE6/MA9	RE6/FU1 RE6/FU5 RE6/FU2 RE6/FU6 RE6/FU3 RE6/FU7 RE6/FU4 RE6/FU8	RE6/LC1 RE6/LC5 RE6/LC2 RE6/LC6 RE6/LC3 RE6/LC7 RE6/LC4 RE6/LC8	31/4 8 33/4 35/4

$$\tilde{RE}_{VR} = 17/2 \quad 35/4 \quad 9 \quad 19/2$$

Considering the values of the similarity measures, it is evident that the closer the values of SSM or $\tilde{S}_I^{Rm}$ for any RM design under pairing the higher the value of the similarity measures which signifies that the two values are almost

TABLE 10. Index relating chart for manufacturing indicator.

	SO	EC	RE	EN	FU	LC	FVR $\sum MA_1 \cdots MA_9$			
MA1	MA1/SO1 MA1/SO5 MA1/SO2 MA1/SO6 MA1/SO3 MA1/SO7 MA1/SO4	MA1/EC1 MA1/EC5 MA1/EC2 MA1/EC6 MA1/EC3 MA1/EC7 MA1/EC4	MA1/RE1 MA1/RE4 MA1/RE2 MA1/RE5 MA1/RE3 MA1/RE6	MA1/EN1 MA1/EN5 MA1/EN2 MA1/EN6 MA1/EN3 MA1/EN7 MA1/EN4 MA1/EN8	MA1/FU1 MA1/FU5 MA1/FU2 MA1/FU6 MA1/FU3 MA1/FU7 MA1/FU4 MA1/FU8	MA1/LC1 MA1/LC5 MA1/LC2 MA1/LC6 MA1/LC3 MA1/LC7 MA1/LC4 MA1/LC8	47/8	49/8	51/8	55/8
MA2	MA2/SO1 MA2/SO5 MA2/SO2 MA2/SO6 MA2/SO3 MA2/SO7 MA2/SO4	MA2/EC1 MA2/EC5 MA2/EC2 MA2/EC6 MA2/EC3 MA2/EC7 MA2/EC4	MA2/RE1 MA2/RE4 MA2/RE2 MA2/RE5 MA2/RE3 MA2/RE6	MA2/EN1 MA2/EN5 MA2/EN2 MA2/EN6 MA2/EN3 MA2/EN7 MA2/EN4 MA2/EN8	MA2/FU1 MA2/FU5 MA2/FU2 MA2/FU6 MA2/FU3 MA2/FU7 MA2/FU4 MA2/FU8	MA2/LC1 MA2/LC5 MA2/LC2 MA2/LC6 MA2/LC3 MA2/LC7 MA2/LC4 MA2/LC8	59/8	61/8	63/8	65/8
MA3	MA3/SO1 MA3/SO5 MA3/SO2 MA3/SO6 MA3/SO3 MA3/SO7 MA3/SO4	MA3/EC1 MA3/EC5 MA3/EC2 MA3/EC6 MA3/EC3 MA3/EC7 MA3/EC4	MA3/RE1 MA1/RE4 MA3/RE2 MA1/RE5 MA3/RE3 MA1/RE6	MA3/EN1 MA3/EN5 MA3/EN2 MA3/EN6 MA3/EN3 MA3/EN7 MA3/EN4 MA3/EN8	MA3/FU1 MA3/FU5 MA3/FU2 MA3/FU6 MA3/FU3 MA3/FU7 MA3/FU4 MA3/FU8	MA3/LC1 MA3/LC5 MA3/LC2 MA3/LC6 MA3/LC3 MA3/LC7 MA3/LC4 MA3/LC8	7	29/4	15/2	8
MA4	MA4/SO1 MA4/SO5 MA4/SO2 MA4/SO6 MA4/SO3 MA4/SO7 MA4/SO4	MA4/EC1 MA4/EC5 MA4/EC2 MA4/EC6 MA4/EC3 MA4/EC7 MA4/EC4	MA4/RE1 MA4/RE4 MA4/RE2 MA4/RE5 MA4/RE3 MA4/RE6	MA4/EN1 MA4/EN5 MA4/EN2 MA4/EN6 MA4/EN3 MA4/EN7 MA4/EN4 MA4/EN8	MA4/FU1 MA4/FU5 MA4/FU2 MA4/FU6 MA4/FU3 MA4/FU7 MA4/FU4 MA4/FU8	MA4/LC1 MA4/LC5 MA4/LC2 MA4/LC6 MA4/LC3 MA4/LC7 MA4/LC4 MA4/LC8	41/8	43/8	45/8	49/8
MA5	MA5/SO1 MA5/SO5 MA5/SO2 MA5/SO6 MA5/SO3 MA5/SO7 MA5/SO4	MA5/EC1 MA5/EC5 MA5/EC2 MA5/EC6 MA5/EC3 MA5/EC7 MA5/EC4	MA5/RE1 MA5/RE4 MA5/RE2 MA5/RE5 MA5/RE3 MA5/RE6	MA5/EN1 MA5/EN5 MA5/EN2 MA5/EN6 MA5/EN3 MA5/EN7 MA5/EN4 MA5/EN8	MA5/FU1 MA5/FU5 MA5/FU2 MA5/FU6 MA5/FU3 MA5/FU7 MA5/FU4 MA5/FU8	MA5/LC1 MA5/LC5 MA5/LC2 MA5/LC6 MA5/LC3 MA5/LC7 MA5/LC4 MA5/LC8	35/8	37/8	39/8	43/8
MA6	MA6/SO1 MA6/SO5 MA6/SO2 MA6/SO6 MA6/SO3 MA6/SO7 MA6/SO4	MA6/EC1 MA6/EC5 MA6/EC2 MA6/EC6 MA6/EC3 MA6/EC7 MA6/EC4	MA3/RE1 MA1/RE4 MA3/RE2 MA1/RE5 MA3/RE3 MA1/RE6	MA6/EN1 MA6/EN5 MA6/EN2 MA6/EN6 MA6/EN3 MA6/EN7 MA6/EN4 MA6/EN8	MA6/FU1 MA6/FU5 MA6/FU2 MA6/FU6 MA6/FU3 MA6/FU7 MA6/FU4 MA6/FU8	MA6/LC1 MA6/LC5 MA6/LC2 MA6/LC6 MA6/LC3 MA6/LC7 MA6/LC4 MA6/LC8	71/8	73/8	75/8	79/8
MA7	MA7/SO1 MA7/SO5 MA7/SO2 MA7/SO6 MA7/SO3 MA7/SO7 MA7/SO4	MA7/EC1 MA7/EC5 MA7/EC2 MA7/EC6 MA7/EC3 MA7/EC7 MA7/EC4	MA7/RE1 MA7/RE4 MA7/RE2 MA7/RE5 MA7/RE3 MA7/RE6	MA7/EN1 MA7/EN5 MA7/EN2 MA7/EN6 MA7/EN3 MA7/EN7 MA7/EN4 MA7/EN8	MA7/FU1 MA7/FU5 MA7/FU2 MA7/FU6 MA7/FU3 MA7/FU7 MA7/FU4 MA7/FU8	MA7/LC1 MA7/LC5 MA7/LC2 MA7/LC6 MA7/LC3 MA7/LC7 MA7/LC4 MA7/LC8	47/8	49/8	51/8	55/8
MA8	MA8/SO1 MA8/SO5 MA8/SO2 MA8/SO6 MA8/SO3 MA8/SO7 MA8/SO4	MA8/EC1 MA8/EC5 MA8/EC2 MA8/EC6 MA8/EC3 MA8/EC7 MA8/EC4	MA8/RE1 MA8/RE4 MA8/RE2 MA8/RE5 MA8/RE3 MA8/RE6	MA8/EN1 MA8/EN5 MA8/EN2 MA8/EN6 MA8/EN3 MA8/EN7 MA8/EN4 MA8/EN8	MA8/FU1 MA8/FU5 MA8/FU2 MA8/FU6 MA8/FU3 MA8/FU7 MA8/FU4 MA8/FU8	MA8/LC1 MA8/LC5 MA8/LC2 MA8/LC6 MA8/LC3 MA8/LC7 MA8/LC4 MA8/LC8	29/8	31/8	33/8	37/8
MA9	MA9/SO1 MA9/SO5 MA9/SO2 MA9/SO6 MA9/SO3 MA9/SO7 MA9/SO4	MA9/EC1 MA9/EC5 MA9/EC2 MA9/EC6 MA9/EC3 MA9/EC7 MA9/EC4	MA3/RE1 MA1/RE4 MA3/RE2 MA1/RE5 MA3/RE3 MA1/RE6	MA9/EN1 MA9/EN5 MA9/EN2 MA9/EN6 MA9/EN3 MA9/EN7 MA9/EN4 MA9/EN8	MA9/FU1 MA9/FU5 MA9/FU2 MA9/FU6 MA9/FU3 MA9/FU7 MA9/FU4 MA9/FU8	MA9/LC1 MA9/LC5 MA9/LC2 MA9/LC6 MA9/LC3 MA9/LC7 MA9/LC4 MA9/LC8	53/8	55/8	57/8	61/8

$$\tilde{MA}_{VR} = 6 \quad 19/3 \quad 46/7 \quad 7$$

the same as shown in Figures 6 to 9. This observation can be supported by the similarity measure between RM1 and RM4 having highest similarity measure of 1 in the defuzzified TrFN values and 0.998 in the CS values.

Conversely, the farther the values of SSM or $\tilde{S}_I^{Rm}$ for any RM design pair the smaller the value of the similarity measures which signifies that the two values are different from each other as displayed by the similarity measure between RM2 and RM4. It is worthwhile to know that the values obtained from all the similarity measures are because the values of the RMs are close. However, the analysis was able to detect minute difference irrespective of how close the values are. This implies that the larger the differences in the final values, the lower the similarity measures. In essence, it can be hypothetically stated that the methodology applied in the assessment is viable and can be adopted for the evaluation of the sustainability of RMs.

V. DISCUSSIONS

The results obtained from the application of the developed methodology to the four case studies of RMs shows that it is possible to determine indices for the sustainability indicators. Also, considering the availability of sub-indicators in the RMs, sub-aggregating matrices have been created from which the sustainability index of the RMs is obtainable. Considering the cosine similarity measures of the sustainability indicators for the RMs shown in Figure 10, it is evident that the performance of the RMs is somewhat satisfactory because there is no sign of any sustainability indicator having a value of zero similarity measure or a value close to zero. Hence, it can be hypothetically stated that the case studies of RMs are sustainable. However, improvements can still be made to increase the indices of the indicators further. Also, the difference in values of the *SSM* for the RMs can be accrued different values of similarity measures. Likewise, it can be noticed that the variations in the similarity measures of the indicators for RM1 and RM4 are small, which is a satisfactory performance because it is an indication that the design process of both machines considered all the sustainability indicators. The effect of the small variation can be observed in the final values of their sustainable similarity measures. However, there is still a need for

$$\text{Sim}[RM1, RM2] = \frac{(0.454*0.380) + (0.473 + 0.354) + \ldots(0.541 + 0.342)}{\left[\sqrt{(0.454^2 + 0.473^2 + \ldots 0.541^2)}\right]\left[\sqrt{(0.380^2 + 0.354^2 + \ldots 0.342^2)}\right]}$$
$$= 0.948$$

TABLE 11. Index relating chart for functionality indicator.

	SO	EC	RE	MA	EN	LC	FVR $\sum FU_1 \cdots FU_8$			
FU1	FU1/SO1 FU1/SO5 FU1/SO2 FU1/SO6 FU1/SO3 FU1/SO7 FU1/SO4	FU1/EC1 FU1/EC5 FU1/EC2 FU1/EC6 FU1/EC3 FU1/EC7 FU1/EC4	FU1/RE1 FU1/RE4 FU1/RE2 FU1/RE5 FU1/RE3 FU1/RE6	FU1/MA1 FU1/MA5 FU1/MA2 FU1/MA6 FU1/MA3 FU1/MA7 FU1/MA4 FU1/MA8 FU1/MA9	FU1/EN1 FU1/EN5 FU1/EN2 FU1/EN6 FU1/EN3 FU1/EN7 FU1/EN4 FU1/EN8	FU1/LC1 FU1/LC5 FU1/LC2 FU1/LC6 FU1/LC3 FU1/LC7 FU1/LC4 FU1/LC8	47/8	49/8	51/8	55/8
FU2	FU2/SO1 FU2/SO5 FU2/SO2 FU2/SO6 FU2/SO3 FU2/SO7 FU2/SO4	FU2/EC1 FU2/EC5 FU2/EC2 FU2/EC6 FU2/EC3 FU2/EC7 FU2/EC4	FU2/RE1 FU2/RE4 FU2/RE2 FU2/RE5 FU2/RE3 FU2/RE6	FU2/MA1 FU2/MA5 FU2/MA2 FU2/MA6 FU2/MA3 FU2/MA7 FU2/MA4 FU2/MA8 FU2/MA9	FU2/EN1 FU2/EN5 FU2/EN2 FU2/EN6 FU2/EN3 FU2/EN7 FU2/EN4 FU2/EN8	FU2/LC1 FU2/LC5 FU2/LC2 FU2/LC6 FU2/LC3 FU2/LC7 FU2/LC4 FU2/LC8	47/8	49/8	51/8	55/8
FU3	FU3/SO1 FU3/SO5 FU3/SO2 FU3/SO6 FU3/SO3 FU3/SO7 FU3/SO4	FU3/EC1 FU3/EC5 FU3/EC2 FU3/EC6 FU3/EC3 FU3/EC7 FU3/EC4	FU3/RE1 FU3/RE4 FU3/RE2 FU3/RE5 FU3/RE3 FU3/RE6	FU3/MA1 FU3/MA5 FU3/MA2 FU3/MA6 FU3/MA3 FU3/MA7 FU3/MA4 FU3/MA8 FU3/MA9	FU3/EN1 FU3/EN5 FU3/EN2 FU3/EN6 FU3/EN3 FU3/EN7 FU3/EN4 FU3/EN8	FU3/LC1 FU3/LC5 FU3/LC2 FU3/LC6 FU3/LC3 FU3/LC7 FU3/LC4 FU3/LC8	31/4	8	33/4	35/4
FU4	FU4/SO1 FU4/SO5 FU4/SO2 FU4/SO6 FU4/SO3 FU4/SO7 FU4/SO4	FU4/EC1 FU4/EC5 FU4/EC2 FU4/EC6 FU4/EC3 FU4/EC7 FU4/EC4	FU4/RE1 FU4/RE4 FU4/RE2 FU4/RE5 FU4/RE3 FU4/RE6	FU4/MA1 FU4/MA5 FU4/MA2 FU4/MA6 FU4/MA3 FU4/MA7 FU4/MA4 FU4/MA8 FU4/MA9	FU4/EN1 FU4/EN5 FU4/EN2 FU4/EN6 FU4/EN3 FU4/EN7 FU4/EN4 FU4/EN8	FU4/LC1 FU4/LC5 FU4/LC2 FU4/LC6 FU4/LC3 FU4/LC7 FU4/LC4 FU4/LC8	41/8	43/8	45/8	49/8
FU5	FU5/SO1 FU5/SO5 FU5/SO2 FU5/SO6 FU5/SO3 FU5/SO7 FU5/SO4	FU5/EC1 FU5/EC5 FU5/EC2 FU5/EC6 FU5/EC3 FU5/EC7 FU5/EC4	FU5/RE1 FU5/RE4 FU5/RE2 FU5/RE5 FU5/RE3 FU5/RE6	FU5/MA1 FU5/MA5 FU5/MA2 FU5/MA6 FU5/MA3 FU5/MA7 FU5/MA4 FU5/MA8 FU5/MA9	FU5/EN1 FU5/EN5 FU5/EN2 FU5/EN6 FU5/EN3 FU5/EN7 FU5/EN4 FU5/EN8	FU5/LC1 FU5/LC5 FU5/LC2 FU5/LC6 FU5/LC3 FU5/LC7 FU5/LC4 FU5/LC8	19/4	5	21/4	23/4
FU6	FU6/SO1 FU6/SO5 FU6/SO2 FU6/SO6 FU6/SO3 FU6/SO7 FU6/SO4	FU6/EC1 FU6/EC5 FU6/EC2 FU6/EC6 FU6/EC3 FU6/EC7 FU6/EC4	FU6/RE1 FU6/RE4 FU6/RE2 FU6/RE5 FU6/RE3 FU6/RE6	FU6/MA1 FU6/MA5 FU6/MA2 FU6/MA6 FU6/MA3 FU6/MA7 FU6/MA4 FU6/MA8 FU6/MA9	FU6/EN1 FU6/EN5 FU6/EN2 FU6/EN6 FU6/EN3 FU6/EN7 FU6/EN4 FU6/EN8	FU6/LC1 FU6/LC5 FU6/LC2 FU6/LC6 FU6/LC3 FU6/LC7 FU6/LC4 FU6/LC8	35/8	37/8	39/8	43/8
FU7	FU7/SO1 FU7/SO5 FU7/SO2 FU7/SO6 FU7/SO3 FU7/SO7 FU7/SO4	FU7/EC1 FU7/EC5 FU7/EC2 FU7/EC6 FU7/EC3 FU7/EC7 FU7/EC4	FU7/RE1 FU7/RE4 FU7/RE2 FU7/RE5 FU7/RE3 FU7/RE6	FU7/MA1 FU7/MA5 FU7/MA2 FU7/MA6 FU7/MA3 FU7/MA7 FU7/MA4 FU7/MA8 FU7/MA9	FU7/EN1 FU7/EN5 FU7/EN2 FU7/EN6 FU7/EN3 FU7/EN7 FU7/EN4 FU7/EN8	FU7/LC1 FU7/LC5 FU7/LC2 FU7/LC6 FU7/LC3 FU7/LC7 FU7/LC4 FU7/LC8	83/8	85/8	87/8	91/8
FU8	FU8/SO1 FU8/SO5 FU8/SO2 FU8/SO6 FU8/SO3 FU8/SO7 FU8/SO4	FU8/EC1 FU8/EC5 FU8/EC2 FU8/EC6 FU8/EC3 FU8/EC7 FU8/EC4	FU8/RE1 FU8/RE4 FU8/RE2 FU8/RE5 FU8/RE3 FU8/RE6	FU8/MA1 FU8/MA5 FU8/MA2 FU8/MA6 FU8/MA3 FU8/MA7 FU8/MA4 FU8/MA8 FU8/MA9	FU8/EN1 FU8/EN5 FU8/EN2 FU8/EN6 FU8/EN3 FU8/EN7 FU8/EN4 FU8/EN8	FU8/LC1 FU8/LC5 FU8/LC2 FU8/LC6 FU8/LC3 FU8/LC7 FU8/LC4 FU8/LC8	11/2	23/4	6	13/2

$$\tilde{FU}_{VR} = 31/5 \quad 58/9 \quad 47/7 \quad 36/5$$

improving these indicators in order to improve the values of sustainable similarity measures. On the contrary, there is a slightly significant variation in the similarity measure of the indicators for RM2 and RM3 as a result of the improved performance of the machines in terms of economic and manufacturing indicators. However, there is no assertion that this slightly significant variation contributed to the reduced value of the sustainable similarity measure. However, there may be proof to support the fact that an improvement in other sustainability indicators will reduce the indices of the economic and manufacturing indicators. Hence, it can be supposedly stated that an increase in the index of one or two sustainability indicators of the RM may not depict an excellent performance in the sustainable similarity measures of RM. Also, considering the values of the overall sustainability indices for RM2 and RM3, it can be agreed that the increase in the index of one or two of their sustainability indicators does contribute to the overall sustainability index of the machine.

Further analysis of the performance of the sustainability indicators in terms of their Euclidean distances in Figure11 provides a view on which indicator to improve

in order to improve the overall sustainability of the RM. Figure 11 presents the distances of the indicators to the worst sustainable performance index ($2^{1/2}$). A close distance to this value for an indicator depicts that such an indicator should be improved. An observation from Figure 11 shows that the sustainability indicators of RM1 and RM4 maintain relatively the same distance to the worst sustainable index. This will make it easy to improve all the indicators at the same time in order to improve the performance of the machines. This implies that the essence of creating a balance in the similarity measures of the indicators is not only to improve the sustainable similarity measure but also to depict how to improve the performance of all the sustainability indicators. This is valid because the effect of arbitrarily improving an indicator because it is close to the worst sustainable performance index will reduce the performance of another indicator. This fact can be supported by the performances of some indicators in RM2 and RM3, which shows an increase towards the worst sustainable performance index. For instance, if the reconfigurable sustainability of RM2 is improved because it is close to the worst sustainable performance index, this might cause an increase in the

TABLE 12. Index relating chart for life cycle indicator.

	SO	EC	RE	MA	FU	EN	FVR $\sum LC_1 \cdots LC_8$
LC1	LC1/SO1 LC1/SO5 LC1/SO2 LC1/SO6 LC1/SO3 LC1/SO7 LC1/SO4	LC1/EC1 LC1/EC5 LC1/EC2 LC1/EC6 LC1/EC3 LC1/EC7 LC1/EC4	LC1/RE1 LC1/RE4 LC1/RE2 LC1/RE5 LC1/RE3 LC1/RE6	LC1/MA1 LC1/MA5 LC1/MA2 LC1/MA6 LC1/MA3 LC1/MA7 LC1/MA4 LC1/MA8 LC1/MA9	LC1/FU1 LC1/FU5 LC1/FU2 LC1/FU6 LC1/FU3 LC1/FU7 LC1/FU4 LC1/FU8	LC1/EN1 LC1/EN5 LC1/EN2 LC1/EN6 LC1/EN3 LC1/EN7 LC1/EN4 LC1/EN8	17/2 35/4 9 19/2
LC2	LC2/SO1 LC2/SO5 LC2/SO2 LC2/SO6 LC2/SO3 LC2/SO7 LC2/SO4	LC2/EC1 LC2/EC5 LC2/EC2 LC2/EC6 LC2/EC3 LC2/EC7 LC2/EC4	LC2/RE1 LC2/RE4 LC2/RE2 LC2/RE5 LC2/RE3 LC2/RE6	LC2/MA1 LC2/MA5 LC2/MA2 LC2/MA6 LC2/MA3 LC2/MA7 LC2/MA4 LC2/MA8 LC2/MA9	LC2/FU1 LC2/FU5 LC2/FU2 LC2/FU6 LC2/FU3 LC2/FU7 LC2/FU4 LC2/FU8	LC2/EN1 LC2/EN5 LC2/EN2 LC2/EN6 LC2/EN3 LC2/EN7 LC2/EN4 LC2/EN8	23/8 25/8 27/8 31/8
LC3	LC3/SO1 LC3/SO5 LC3/SO2 LC3/SO6 LC3/SO3 LC3/SO7 LC3/SO4	LC3/EC1 LC3/EC5 LC3/EC2 LC3/EC6 LC3/EC3 LC3/EC7 LC3/EC4	LC3/RE1 LC1/RE4 LC3/RE2 LC1/RE5 LC3/RE3 LC1/RE6	LC3/MA1 LC3/MA5 LC3/MA2 LC3/MA6 LC3/MA3 LC3/MA7 LC3/MA4 LC3/MA8 LC3/MA9	LC3/FU1 LC3/FU5 LC3/FU2 LC3/FU6 LC3/FU3 LC3/FU7 LC3/FU4 LC3/FU8	LC3/EN1 LC3/EN5 LC3/EN2 LC3/EN6 LC3/EN3 LC3/EN7 LC3/EN4 LC3/EN8	83/8 85/8 87/8 91/8
LC4	LC4/SO1 LC4/SO5 LC4/SO2 LC4/SO6 LC4/SO3 LC4/SO7 LC4/SO4	LC4/EC1 LC4/EC5 LC4/EC2 LC4/EC6 LC4/EC3 LC4/EC7 LC4/EC4	LC4/RE1 LC4/RE4 LC4/RE2 LC4/RE5 LC4/RE3 LC4/RE6	LC4/MA1 LC4/MA5 LC4/MA2 LC4/MA6 LC4/MA3 LC4/MA7 LC4/MA4 LC4/MA8 LC4/MA9	LC4/FU1 LC4/FU5 LC4/FU2 LC4/FU6 LC4/FU3 LC4/FU7 LC4/FU4 LC4/FU8	LC4/EN1 LC4/EN5 LC4/EN2 LC4/EN6 LC4/EN3 LC4/EN7 LC4/EN4 LC4/EN8	11/2 23/4 6 13/2
LC5	LC5/SO1 LC5/SO5 LC5/SO2 LC5/SO6 LC5/SO3 LC5/SO7 LC5/SO4	LC5/EC1 LC5/EC5 LC5/EC2 LC5/EC6 LC5/EC3 LC5/EC7 LC5/EC4	LC5/RE1 LC5/RE4 LC5/RE2 LC5/RE5 LC5/RE3 LC5/RE6	LC5/MA1 LC5/MA5 LC5/MA2 LC5/MA6 LC5/MA3 LC5/MA7 LC5/MA4 LC5/MA8 LC5/MA9	LC5/FU1 LC5/FU5 LC5/FU2 LC5/FU6 LC5/FU3 LC5/FU7 LC5/FU4 LC5/FU8	LC5/EN1 LC5/EN5 LC5/EN2 LC5/EN6 LC5/EN3 LC5/EN7 LC5/EN4 LC5/EN8	29/8 31/8 33/8 37/8
LC6	LC6/SO1 LC6/SO5 LC6/SO2 LC6/SO6 LC6/SO3 LC6/SO7 LC6/SO4	LC6/EC1 LC6/EC5 LC6/EC2 LC6/EC6 LC6/EC3 LC6/EC7 LC6/EC4	LC6/RE1 LC6/RE4 LC6/RE2 LC6/RE5 LC6/RE3 LC6/RE6	LC6/MA1 LC6/MA5 LC6/MA2 LC6/MA6 LC6/MA3 LC6/MA7 LC6/MA4 LC6/MA8 LC6/MA9	LC6/FU1 LC6/FU5 LC6/FU2 LC6/FU6 LC6/FU3 LC6/FU7 LC6/FU4 LC6/FU8	LC6/EN1 LC6/EN5 LC6/EN2 LC6/EN6 LC6/EN3 LC6/EN7 LC6/EN4 LC6/EN8	4 17/4 9/2 5
LC7	LC7/SO1 LC7/SO5 LC7/SO2 LC7/SO6 LC7/SO3 LC7/SO7 LC7/SO4	LC7/EC1 LC7/EC5 LC7/EC2 LC7/EC6 LC7/EC3 LC7/EC7 LC7/EC4	LC7/RE1 LC7/RE4 LC7/RE2 LC7/RE5 LC7/RE3 LC7/RE6	LC7/MA1 LC7/MA5 LC7/MA2 LC7/MA6 LC7/MA3 LC7/MA7 LC7/MA4 LC7/MA8 LC7/MA9	LC7/FU1 LC7/FU5 LC7/FU2 LC7/FU6 LC7/FU3 LC7/FU7 LC7/FU4 LC7/FU8	LC7/EN1 LC7/EN5 LC7/EN2 LC7/EN6 LC7/EN3 LC7/EN7 LC7/EN4 LC7/EN8	13/4 7/2 15/4 17/4
LC8	LC8/SO1 LC8/SO5 LC8/SO2 LC8/SO6 LC8/SO3 LC8/SO7 LC8/SO4	LC8/EC1 LC8/EC5 LC8/EC2 LC8/EC6 LC8/EC3 LC8/EC7 LC8/EC4	LC8/RE1 LC8/RE4 LC8/RE2 LC8/RE5 LC8/RE3 LC8/RE6	LC8/MA1 LC8/MA5 LC8/MA2 LC8/MA6 LC8/MA3 LC8/MA7 LC8/MA4 LC8/MA8 LC8/MA9	LC8/FU1 LC8/FU5 LC8/FU2 LC8/FU6 LC8/FU3 LC8/FU7 LC8/FU4 LC8/FU8	LC8/EN1 LC8/EN5 LC8/EN2 LC8/EN6 LC8/EN3 LC8/EN7 LC8/EN4 LC8/EN8	17/2 35/4 9 19/2

$$\tilde{LC}_{VR} = 35/6 \quad 6 \quad 19/3 \quad 41/6$$

TABLE 13. Availability of sub indicators of environmental sustainability in the RM designs.

Sustainability Indicator	Sub-indicators	RM1 (AFFS) EO1	EO2	EO3	RM2 (RVS) EO1	EO2	EO3	RM3 (RBPM) EO1	EO2	EO3	RM4 (RAF) EO1	EO2	EO3
EN1	53/8 55/8 57/8 61/8	STA	SVA	VSA	MOA	MSA	STA	IMA	MOA	MOA	VSA	STA	VSA
EN2	25/4 13/2 27/4 29/4	MSA	STA	STA	MSA	STA	MOA	MSA	STA	MOA	STA	SVA	MSA
EN3	13/4 7/2 15/4 17/4	STA	VSA	MOA	MSA	MOA	SVA	MOA	STA	SVA	SVA	VSA	STA
EN4	31/4 8 33/4 35/4	VEA	STA	MSA	STA	MSA	MOA	MSA	VSA	STA	VSA	SVA	VSA
EN5	13/4 7/2 15/4 17/4	VSA	VEA	SVA	SVA	VSA	SVA	MOA	MSA	MOA	MOA	MSA	MSA
EN6	29/8 31/8 33/8 37/8	STA	SVA	MSA	STA	MSA	VSA	MSA	MOA	SVA	VSA	STA	VSA
EN7	35/8 37/8 39/8 41/8	VEA	VEA	VSA	SVA	VSA	VEA	MSA	STA	VSA	VSA	SVA	VEA
EN8	41/8 43/8 45/8 49/8	STA	MSA	STA	VSA	SVA	VEA	VSA	VEA	VSA	STA	VSA	VSA
$\tilde{R}_{mj}^{ag}$	101/6 127/6 176/7 168/5	143/9	161/8	24	97/3	115/8	92/5	133/6	121/4	40/3	86/5	125/6	86/3

Left of Table 13: $1/\tilde{EN}_{VR} = $ 1/6 2/11 7/37 1/5

distances of other indicators, which will affect the overall performance of the RM. This same scenario applies to other indicators like the life cycle analysis for RM3. In essence, the desire of the design engineer or manufacturer is not only to increase the distances of these indicators to the worst sustainable performance index but also to maintain a balance in all the index such that none of the indicators have a poor performance.

VI. CONCLUSION

The significance of appraising the sustainability of RMs cannot be overemphasized considering their importance in the RMS. Aside from the traditional indicators of sustainability, it is necessary to consider peculiar indicators such as the reconfigurability indicator because of its essential contribution to the performance evaluation of RMs. This article has been able to show that the sustainability indices

TABLE 14. Availability of sub indicators of social sustainability in the RM designs.

Sustainability Indicator	Sub-indicators	RM1 (AFFS)			RM2 (RVS)			RM3 (RBPM)			RM4 (RAF)		
		EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3
	SO1 31/4 8 33/4 35/4	MOA	IMA	MSA	IMA	MOA	STA	MSA	STA	STA	SVA	MSA	MSA
	SO2 11/2 23/4 6 13/2	MSA	VSA	STA	MOA	STA	MSA	IMA	STA	SVA	MOA	SVA	MSA
	SO3 53/8 55/8 57/8 61/8	SVA	VSA	VEA	MOA	MSA	MSA	SVA	VSA	MOA	MOA	MOA	VSA
$1/\tilde{SO}_{VR} =$	SO4 11/2 23/4 6 13/2	MOA	MSA	MOA	SVA	STA	VSA	MOA	STA	IMA	VSA	STA	MOA
8/55 8/51 8/49 8/47	SO5 13/4 7/2 15/4 17/4	MSA	MSA	VSA	MSA	VEA	STA	VSA	STA	VEA	MOA	SVA	MOA
	SO6 11/2 23/4 6 13/2	VSA	VEA	STA	IMA	STA	MSA	MSA	IMA	STA	STA	VSA	MSA
	SO7 7 29/4 15/2 8	STA	SVA	MSA	MOA	SVA	MOA	MSA	STA	MOA	VSA	STA	VSA

$\tilde{R}^{ag}_{mj}$: 38/3 16 172/9 128/5 76/7 14 17 162/7 23/2 117/8 53/3 24 113/9 79/5 19 76/3

TABLE 15. Availability of sub indicators of economic sustainability in the RM designs.

Sustainability Indicator	Sub-indicators	RM1 (AFFS)			RM2 (RVS)			RM3 (RBPM)			RM4 (RAF)		
		EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3
	EC1 25/4 13/2 27/4 29/4	VSA	VEA	VEA	MSA	STA	VSA	MOA	MSA	IMA	SVA	VSA	VEA
	EC2 25/4 13/2 27/4 29/4	MSA	STA	VSA	IMA	MSA	MOA	STA	MOA	MSA	MSA	SVA	VSA
	EC3 71/8 73/8 75/8 79/8	STA	VEA	SVA	MOA	STA	IMA	MOA	IMA	MSA	STA	SVA	MSA
$1/\tilde{EC}_{VR} =$	EC4 7 29/4 15/2 8	VSA	SVA	VSA	STA	MSA	SVA	MSA	MSA	SVA	VSA	STA	VSA
5/37 1/7 3/20 5/32	EC5 53/8 55/8 57/8 61/8	MOA	MSA	MOA	SVA	STA	MSA	MOA	STA	SVA	MOA	STA	SVA
	EC6 47/8 49/8 51/8 55/8	IMA	STA	MOA	MOA	MOA	IMA	MSA	MOA	MSA	MSA	STA	SVA
	EC7 4 17/4 9/2 5	MSA	MOA	SVA	IMA	MOA	MSA	MSA	MOA	IMA	MSA	STA	MOA

$\tilde{R}^{ag}_{mj}$: 83/6 118/7 121/6 53/2 21/2 66/5 81/5 177/8 10 38/3 78/5 43/2 125/9 17 81/4 80/3

TABLE 16. Availability of sub indicators of reconfigurable sustainability in the RM designs.

Sustainability Indicator	Sub-indicators	RM1 (AFFS)			RM2 (RVS)			RM3 (RBPM)			RM4 (RAF)		
		EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3
	RE1 59/8 61/8 63/8 67/8	MSA	MOA	MSA	MSA	MOA	MSA	VEA	SVA	VSA	VSA	VEA	STA
	RE2 31/4 8 33/4 35/4	SVA	VSA	STA	MOA	SVA	STA	MOA	STA	VSA	STA	MSA	VEA
$1/\tilde{RE}_{VR} =$	RE3 37/4 19/2 39/4 41/4	VEA	VSA	SVA	STA	SVA	MOA	STA	MSA	MOA	VEA	VSA	SVA
2/19 1/9 4/35 2/17	RE4 71/8 73/8 75/8 79/8	MSA	SVA	VEA	MOA	VSA	STA	MSA	VSA	STA	VSA	STA	MOA
	RE5 10 41/4 21/2 11	VSA	VEA	VSA	MSA	STA	MSA	MOA	SVA	MSA	MSA	SVA	VSA
	RE6 31/4 8 33/4 35/4	MOA	MSA	MSA	MOA	IMA	MOA	STA	STA	MOA	VSA	SVA	VEA

$\tilde{R}^{ag}_{mj}$: 13 31/2 18 114/5 59/6 97/8 115/8 19 79/7 96/7 16 104/5 96/7 49/3 113/6 143/6

TABLE 17. Availability of sub indicators of manufacturing sustainability in the RM designs.

Sustainability Indicator	Sub-indicators	RM1 (AFFS)			RM2 (RVS)			RM3 (RBPM)			RM4 (RAF)		
		EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3
	MA1 47/8 49/8 51/8 55/8	VSA	STA	SVA	MSA	STA	MOA	MSA	MSA	MOA	STA	VSA	SVA
	MA2 59/8 61/8 63/8 65/8	MOA	MSA	MOA	STA	MOA	MSA	VSA	VSA	STA	MOA	MSA	VSA
	MA3 7 29/4 15/2 8	MSA	IMA	MSA	MOA	IMA	MSA	MSA	MSA	IMA	MSA	STA	MOA
	MA4 41/8 43/8 45/8 49/8	SVA	MSA	MOA	IMA	MOA	IMA	VSA	MSA	VSA	SVA	STA	MSA
$1/\tilde{MA}_{VR} =$	MA5 35/8 37/8 39/8 43/8	VEA	VSA	VSA	SVA	VSA	STA	MOA	STA	MSA	MOA	MSA	MOA
1/7 7/46 3/19 1/6	MA6 71/8 73/8 75/8 79/8	VSA	VSA	STA	SVA	MSA	VSA	STA	MSA	STA	VSA	STA	SVA
	MA7 47/8 49/8 51/8 55/8	VEA	VEA	VSA	MOA	STA	MSA	STA	STA	MOA	VSA	VSA	STA
	MA8 29/8 31/8 33/8 37/8	MSA	MOA	MSA	VSA	SVA	SVA	MSA	STA	VSA	VEA	VSA	SVA
	MA9 53/8 55/8 57/8 61/8	SVA	STA	VSA	SVA	MSA	VSA	MOA	MSA	MSA	VSA	STA	SVA

$\tilde{R}^{ag}_{mj}$: 88/5 65/3 180/7 172/5 91/6 19 137/6 218/7 123/8 96/5 23 94/3 53/3 196/9 155/6 69/2

of sustainability indicators and their sub-indicators can be obtained from index relating charts, which entails the identification of viable relationships among sub-indicators of different sustainability indicators. This article further shows that the determination of sustainable similarity measures for the RMs is achievable by the evaluation of the sustainability indices and cosine similarity measures of their indicators. This approach will enable the identification of sustainability indicators that will be improved in order to increase the index and sustainable similarity measure of the RM. The determination of the Euclidean distance of the indicators considering the four case studies supports the fact that the excellent performance of a RM in some sustainability indicators does not imply that the overall performance of the RM may be satisfactory. Also, the improvement of one sustainability indicator because of its closeness to the worst sustainable performance may increase the Euclidean distance of other indicators, which in turn will make them close to the worst sustainable performance. In essence, it is practically advisable to improve all the indicators at the same rate in

TABLE 18. Availability of sub indicators of functional sustainability in the RM designs.

Sustainability Indicator	Sub-indicators	RM1 (AFFS)			RM2 (RVS)			RM3 (RBPM)			RM4 (RAF)		
		EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3
$1/\tilde{FU}_{VR} =$ 5/36 7/47 9/58 5/31	FU1 47/8 49/8 51/8 55/8	VSA	SVA	MSA	VSA	VSA	STA	VSA	VEA	SVA	VEA	VSA	STA
	FU2 47/8 49/8 51/8 55/8	VEA	VSA	VSA	VSA	STA	STA	MSA	STA	SVA	VSA	SVA	VEA
	FU3 31/4 8 33/4 35/4	VSA	VEA	VSA	VSA	STA	SVA	SVA	MSA	VSA	SVA	VEA	VEA
	FU4 41/8 43/8 45/8 49/8	VSA	VSA	VEA	VEA	VEA	VSA	VSA	VEA	SVA	VEA	VEA	VSA
	FU5 19/4 5 21/4 23/4	SVA	VSA	VEA	MSA	SVA	STA	MSA	MSA	STA	SVA	STA	VSA
	FU6 35/8 37/8 39/8 43/8	VEA	VSA	STA	MSA	MSA	SVA	MSA	SVA	STA	VEA	SVA	SVA
	FU7 83/8 85/8 87/8 91/8	MSA	MSA	STA	MOA	MSA	MOA	VEA	VSA	VSA	MSA	VEA	MSA
	FU8 11/2 23/4 6 13/2	VSA	VSA	MSA	VSA	MSA	STA	STA	SVA	VEA	VSA	MSA	VEA
	$\tilde{R}^{ag}_{mj}$	18 22 181/7 235/7			31/2 173/9 23 121/4			35/2 43/2 177/7 263/8			93/5 68/3 80/3 241/7		

TABLE 19. Availability of sub indicators of life cycle sustainability in the RM designs.

Sustainability Indicator	Sub-indicators	RM1 (AFFS)			RM2 (RVS)			RM3 (RBPM)			RM4 (RAF)		
		EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3	EO1	EO2	EO3
$1/\tilde{LC}_{VR} =$ 6/41 3/19 1/6 6/35	LC1 17/2 35/4 9 19/2	STA	STA	MSA	MSA	MOA	MSA	MSA	MSA	MOA	MSA	STA	VSA
	LC2 23/8 25/8 27/8 31/8	VEA	VSA	VSA	IMA	MOA	MOA	STA	MSA	MOA	STA	SVA	SVA
	LC3 83/8 85/8 87/8 91/8	VSA	VSA	VEA	SVA	STA	VSA	SVA	MSA	MOA	SVA	VSA	SVA
	LC4 11/2 23/4 6 13/2	MSA	VSA	MSA	MOA	MOA	MSA	MSA	STA	MSA	VSA	MSA	STA
	LC5 29/8 31/8 33/8 37/8	VEA	VSA	VSA	VEA	SVA	VSA	SVA	STA	STA	VEA	VSA	VEA
	LC6 4 17/4 9/2 5	VSA	SVA	VEA	SVA	VEA	STA	MSA	STA	STA	VSA	SVA	VEA
	LC7 13/4 7/2 15/4 17/4	SVA	SVA	VSA	MSA	MOA	MOA	VEA	VSA	VSA	MSA	VSA	SVA
	LC8 17/2 35/4 9 19/2	VSA	STA	STA	MOA	MSA	MSA	MOA	IMA	MOA	MSA	STA	VSA
	$\tilde{R}^{ag}_{mj}$	35/2 173/8 233/9 67/2			40/3 17 145/7 83/3			25/2 16 138/7 80/3			17 21 126/5 98/3		

order to create a balance in their performance and also to improve the final value of the sustainable similarity measure of the RM. Enhancing the performance of a RM in terms of the sustainability indicators is achievable by improving the design features that are attributed to the sub-indicators without compromising other sustainability indicators. Hence, a balance will be created in the design process of the RM. The sustainability indices obtained for the RMs depends on the availability of sub-indicators in them which is subjective to three expert's opinion. Hence it can be theoretically stated that the approach presented in this article is better compared to existing approaches in the aspect of determining the indices of sustainability indicators from fuzzified viable relational links and the identification of indicators to be improved by considering their Euclidean distances to the best and worst sustainable performance. The use of several expert's opinions in the fields of application of the RMs used as case studies has really helped in the determination of sub-aggregates in the application of the methodology. However, a better way to harness the availability of the sub-indicators in the RMs would have been to collect data related to the sub indicators from the machines during operation. Also, this will ensure that the information about their sustainability is time based and continuous over the period of data collection.

APPENDIX A
See Tables 6–12.

APPENDIX B
See Tables 12–19.

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