Design Sustainability of Reconfigurable Machines

OLAYINKA MOHAMMED OLABANJI AND KHUMBULANI MPOFU
Department of Industrial Engineering, Tshwane University of Technology, Pretoria 0183, South Africa
Corresponding author: Olayinka Mohammed Olabanji (obayinclox@gmail.com)
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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.

Owing 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 Schöggel 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
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 1. Framework for methodology.
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
of sub-indicators, which can be referred to as indices and can be represented by counters (a, b, c, d ....... n), which varies according to the number of sub-indicators allotted to each indicator (i.e. a ≠ b ≠ c ≠ d ≠ .......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 any $a^{th}$ sub-indicator under indicator A ($A_aV$) is obtainable from (2).

$$A_aV = \sum_{B_1} B_b A_1 \cup B_1 + \sum_{C_1} C_c A_1 \cup C_1 + \sum_{D_1} D_d A_1 \cup D_1 + \cdots + \sum_{N_1} N_n A_1 \cup N_1$$  \hspace{1cm} (1)

$$A_aV = \left[ \sum_{B_1} B_b A_a \cup B_1 + \sum_{C_1} C_c A_a \cup C_1 + \sum_{D_1} D_d A_a \cup D_1 + \cdots + \sum_{N_1} N_n A_a \cup N_1 \right]$$ for $a = 1, 2, 3 \ldots \ldots a$  \hspace{1cm} (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.

| A_1 | A_2 | A_3 | A_a | \sum_{B_1} B_b A_1 \cup B_1 + \sum_{C_1} C_c A_1 \cup C_1 + \sum_{D_1} D_d A_1 \cup D_1 + \cdots + \sum_{N_1} N_n A_1 \cup N_1 |
|-----|-----|-----|-----|--------------------------------------------------|
| A_1 | A_2 | A_3 | A_a | \sum_{B_1} B_b A_1 \cup B_1 + \sum_{C_1} C_c A_1 \cup C_1 + \sum_{D_1} D_d A_1 \cup D_1 + \cdots + \sum_{N_1} N_n A_1 \cup N_1 |
| A_1 | A_2 | A_3 | A_a | \sum_{B_1} B_b A_1 \cup B_1 + \sum_{C_1} C_c A_1 \cup C_1 + \sum_{D_1} D_d A_1 \cup D_1 + \cdots + \sum_{N_1} N_n A_1 \cup N_1 |
| A_1 | A_2 | A_3 | A_a | \sum_{B_1} B_b A_1 \cup B_1 + \sum_{C_1} C_c A_1 \cup C_1 + \sum_{D_1} D_d A_1 \cup D_1 + \cdots + \sum_{N_1} N_n A_1 \cup N_1 |
| A_1 | A_2 | A_3 | A_a | \sum_{B_1} B_b A_1 \cup B_1 + \sum_{C_1} C_c A_1 \cup C_1 + \sum_{D_1} D_d A_1 \cup D_1 + \cdots + \sum_{N_1} N_n A_1 \cup N_1 |

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

$$A_{SI} = \sum_{a=1}^{n} \frac{A_{aV}}{\sum a}$$

$$B_{bV} = \frac{\sum_{b=1}^{b} \sum_{a=1}^{n} \left( A_{a} B_{b} \right) + \sum_{b=1}^{b} \sum_{a=1}^{n} \left( N_{a} N_{b} \right)}{\sum b}$$

(3)

$$B_{SI} = \frac{\sum_{b=1}^{b} \sum_{a=1}^{n} \left( A_{a} B_{b} \right) + \sum_{b=1}^{b} \sum_{a=1}^{n} \left( N_{a} N_{b} \right)}{\sum b}$$

(4)

$$N_{SI} = \left( \sum_{n=1}^{n} \sum_{n=a}^{n} \right) \prod_{n=a,b,c,...,n}$$

(5)

$$C. FUZZIFICATION OF SUSTAINABILITY INDICES$$

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 $M_1, M_2, ..., M_n$ representing one, two to $n$ number of viable relationships is determinable from (9), (10) and (11), respectively.

$$\mu_m(p) = \begin{cases} 
(p - w)/(x - w) & p \in [w, x] \\
1 & p \in [x, y] \\
(z - p)/(z - y) & p \in [y, z] \\
0 & \text{otherwise}
\end{cases}; w \leq x \leq y \leq z$$

(7)

$$M_0 = \{1, 1, 1, 1\} \equiv \{w_0, x_0, y_0, z_0\}$$

(8)

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

(9)

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

(10)

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

(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 ($L_{SI}$) and right ($R_{SI}$) 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].

$$C_1 = (w + 2x)/3$$

(12)

$$C_2 = (x + y)/2$$

(13)
deduced that the sub-aggregate for one of the RM designs ($\tilde{R}_{m_j}$) is determinable from (19).

$$\tilde{R}_{m_j} = \sum_{i=1}^{n} \left[ \frac{\tilde{n}_i}{N_{SI}} \ast \tilde{D}_{gi} \right]$$  \hspace{1cm} (18)

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

$$\cdots \left[ \tilde{R}_{m_1} \tilde{R}_{m_2} \tilde{R}_{m_3} \cdots \tilde{R}_{m_j} \right] = \begin{bmatrix} \tilde{n}_1 \\ \tilde{n}_2 \\ \tilde{n}_3 \\ \vdots \\ \tilde{n}_i \\ \vdots \\ \tilde{D}_{g_1} \\ \tilde{D}_{g_2} \\ \tilde{D}_{g_3} \\ \vdots \\ \tilde{D}_{g_i} \\ \vdots \\ \tilde{D}_{g_1} \\ \tilde{D}_{g_2} \\ \tilde{D}_{g_3} \\ \vdots \\ \tilde{D}_{g_i} \end{bmatrix}$$  \hspace{1cm} (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 $A, B, C, \ldots, N$ 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].

$$\left( R_{ij} \right)^{\Sigma} = \begin{bmatrix} \tilde{R}_{m_A}^{\Sigma} & \tilde{R}_{m_B}^{\Sigma} & \tilde{R}_{m_C}^{\Sigma} & \cdots & \tilde{R}_{m_N}^{\Sigma} \\ \tilde{R}_{m_A}^{\Sigma} & \tilde{R}_{m_B}^{\Sigma} & \tilde{R}_{m_C}^{\Sigma} & \cdots & \tilde{R}_{m_N}^{\Sigma} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{R}_{m_A}^{\Sigma} & \tilde{R}_{m_B}^{\Sigma} & \tilde{R}_{m_C}^{\Sigma} & \cdots & \tilde{R}_{m_N}^{\Sigma} \end{bmatrix}$$  \hspace{1cm} (20)

$$\left( R_{ij} \right)^{\Sigma} = \begin{bmatrix} w_{ij} - w_{ij}^{\min} & x_{ij} - x_{ij}^{\min} & y_{ij} - y_{ij}^{\min} & z_{ij} - z_{ij}^{\min} \frac{\Delta_{\max}}{\Delta_{\min}} & \frac{\Delta_{\max}}{\Delta_{\min}} & \frac{\Delta_{\max}}{\Delta_{\min}} & \frac{\Delta_{\max}}{\Delta_{\min}} \end{bmatrix}$$  \hspace{1cm} (21)
respectively. Likewise, \( \Delta_{\text{max}}^{i} = \max_{j} z_{ij}^{\text{max}} \) respectively. Since the overall sustainability index \( S_{j} \) is a function of sustainability indices of the indicators, this implies that the overall sustainability index for any of the RMs \( S_{j}^{\text{Rm}} \) can be obtained from (24) by summing the aggregates of the sustainability indicators in the normalized decision matrix [28].

\[
\begin{bmatrix}
R_{mN}^{\text{ag}_{1}} & R_{mN}^{\text{ag}_{2}} & \ldots & R_{mN}^{\text{ag}_{N}} \\
R_{mN}^{\text{ag}_{1}} & R_{mN}^{\text{ag}_{2}} & \ldots & R_{mN}^{\text{ag}_{N}} \\
R_{mN}^{\text{ag}_{1}} & R_{mN}^{\text{ag}_{2}} & \ldots & R_{mN}^{\text{ag}_{N}} \\
\vdots & \vdots & \ddots & \vdots \\
R_{mN}^{\text{ag}_{1}} & R_{mN}^{\text{ag}_{2}} & \ldots & R_{mN}^{\text{ag}_{N}}
\end{bmatrix}
\]

\[ S_{j}^{\text{Rm}} = \sum_{N=A}^{N=N} R_{mN}^{\text{ag}_{j}} \]  

(24)

In (23) and (24), \( R_{mN}^{\text{ag}_{j}} \) is the normalized value of an element in the decision matrix corresponding to the \( j^{th} \) RM with the \( N^{th} \) 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].

\[
CS \left[ R_{mN}^{\text{ag}_{ij}} N_{\ast}^{\text{N}}, R_{mN}^{\text{ag}_{ij}} N_{\ast}^{\text{N}} \right] = \left[ 1 - \left( \frac{\sum_{j=1}^{N} w_{ij}^{\ast} - w_{ij} + x_{ij}^{\ast} - x_{ij} + y_{ij}^{\ast} - y_{ij} + z_{ij}^{\ast} - z_{ij}}{4} \right) \right]_{N} \]  

(25)

In (25), \( CS \left[ R_{mN}^{\text{ag}_{ij}} N_{\ast}^{\text{N}}, R_{mN}^{\text{ag}_{ij}} N_{\ast}^{\text{N}} \right] \) is the cosine similarity measure between the ideal performance and the current performance. Also, \( R_{mN}^{\text{ag}_{ij}} N_{\ast}^{\text{N}} \) is the ideal or perfect performance which can be expressed as;

\[ R_{mN}^{\text{ag}_{ij}} N_{\ast}^{\text{N}} = [w_{ij}^{\ast}, x_{ij}^{\ast}, y_{ij}^{\ast}, z_{ij}^{\ast}] = [1, 1, 1, 1] \]  

(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 \( d (R_{mN}^{\text{ag}_{ij}}_{N}, R_{mN}^{\text{ag}_{ij}}_{N}) \) is obtainable from (27) [30, 31].

\[ d (R_{mN}^{\text{ag}_{ij}}_{N}, R_{mN}^{\text{ag}_{ij}}_{N}) = \left( 2 \left[ 1 - CS \left[ R_{mN}^{\text{ag}_{ij}}_{N}, R_{mN}^{\text{ag}_{ij}}_{N} \right] \right] \right)^{\frac{1}{2}} \]  

(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 \( S_{op}^{N} \) 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.

\[
S_{op}^{N} = \max_{N=A}^{N=N} CS \left[ R_{mN}^{\text{ag}_{ij}}_{N}, R_{mN}^{\text{ag}_{ij}}_{N} \right] = 1 \]  

(28)

\[
SSM = \sum_{N=A}^{N=N} CS \left[ R_{mN}^{\text{ag}_{ij}}_{N}, R_{mN}^{\text{ag}_{ij}}_{N} \right] \]  

(29)

\[
OS_{opt} = \sum_{N=A}^{N=N} \max_{N=A}^{N=N} CS \left[ R_{mN}^{\text{ag}_{ij}}_{N}, R_{mN}^{\text{ag}_{ij}}_{N} \right] \]  

(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
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 $\tilde{R}_{m_j}^ag$ | RM 2 $\tilde{R}_{m_j}^ag$ | RM 3 $\tilde{R}_{m_j}^ag$ | RM 4 $\tilde{R}_{m_j}^ag$ |
|------------|--------------------------|--------------------------|--------------------------|--------------------------|
| EN         | 143/9                    | 161/3                    | 24/97                    | 93/5                     |
| SO         | 38/3                     | 16/12                    | 128/5                    | 76/7                     |
| EC         | 83/6                     | 118/7                    | 53/2                     | 21/2                     |
| RE         | 13/32                    | 18/114/5                 | 59/97/8                  | 91/6                     |
| MA         | 88/5                     | 65/3                     | 180/5                    | 123/8                    |
| FU         | 18/22                    | 181/7                    | 235/7                    | 31/2                     |
| LC         | 35/2                     | 173/8                    | 235/9                    | 40/3                     |

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

| Indicators | RM1 $\tilde{R}_{m_j}^ag_N$ | RM2 $\tilde{R}_{m_j}^ag_N$ | RM3 $\tilde{R}_{m_j}^ag_N$ | RM4 $\tilde{R}_{m_j}^ag_N$ |
|------------|---------------------------|---------------------------|---------------------------|---------------------------|
| EN         | 1/3/12                    | 19/36                    | 15/16                    | 5/9/4                     |
| SO         | 1/28/31                  | 14/25                    | 1                          | 6/29/16                  |
| EC         | 0 23/59                  | 10/17                    | 10/13                    | 16/15/19                 |
| RE         | 2/9 17/42                | 37/64                    | 89/96                    | 0 13/79                  |
| MA         | 0 5/11                  | 2/3 7/8                  | 11/63 29/48              | 69/86 1                  |
| FU         | 9/70 31/91               | 35/64                    | 86/87                    | 0 13/66                  |
| LC         | 6/25 24/55               | 16/25                    | 3/71 13/61               | 11/28 5/9                |

TABLE 4. Sustainability measures for the RMs.

| Indicators | RM1 $d$ | RM2 $d$ | RM3 $d$ | RM4 $d$ |
|------------|---------|---------|---------|---------|
| EN         | 0.48    | 0.92    | 0.54    | 0.96    |
| SO         | 0.51    | 0.99    | 0.41    | 1.08    |
| EC         | 0.44    | 1.06    | 0.70    | 0.77    |
| RE         | 0.53    | 0.97    | 0.40    | 1.09    |
| MA         | 0.50    | 1.00    | 0.63    | 0.86    |
| FU         | 0.49    | 1.01    | 0.46    | 1.03    |
| LC         | 0.58    | 0.92    | 0.30    | 1.19    |

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.

$$d_{\text{best}} = \left( 2 \left( 1 - CS \left[ \tilde{R}_{mN}^{ag} N_j, \tilde{R}_{mN}^{ag} N_j \right] \right) \right)^{1/2} \approx 0$$

$$d_{\text{worst}} = \left( 2 \left( 1 - CS \left[ \tilde{R}_{mN}^{ag} N_j, \tilde{R}_{mN}^{ag} N_j \right] \right) \right)^{1/2} \approx 2^{1/2}$$

In (31) and (32), ‘$d_{\text{best}}$’ and ‘$d_{\text{worst}}$’ 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...
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...
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
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  |
|--------|--------|--------|--------|--------|--------|------|
| S01    | S01/E1 | S01/E5 | S01/E8 | S01/E4 | S01/E1 | 31/4 |
| S02    | S02/E1 | S02/E5 | S02/E8 | S02/E4 | S02/E1 | 11/2 |
| S03    | S03/E1 | S03/E5 | S03/E8 | S03/E4 | S03/E1 | 53/8 |
| S04    | S04/E1 | S04/E5 | S04/E8 | S04/E4 | S04/E1 | 13/4 |
| S05    | S05/E1 | S05/E5 | S05/E8 | S05/E4 | S05/E1 | 11/2 |
| S06    | S06/E1 | S06/E5 | S06/E8 | S06/E4 | S06/E1 | 11/2 |

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

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, 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.

\[
\text{Sim} [A, B] = \frac{\left( \sum_{i=1}^{m} A_i B_i \right)}{\left( \sum_{i=1}^{m} A_i^2 \right)^{1/2} \left( \sum_{i=1}^{m} B_i^2 \right)^{1/2}}
\]

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.
Considering the values of the similarity measures, it is evident that the closer the values of SSM or $\tilde{S}_{RM}$ 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/S01 MA1/S05 MA1/E1/C1 MA1/E1/C5 | MA1/E1 | MA1/E5 | MA1/FU1 MA1/FU5 MA1/LC1 MA1/LC5 | 17/8 | 49/8 51/8 55/8 |
| MA2 | MA2/S01 MA2/S05 MA2/E1/C2 MA2/E1/C6 | MA2/E1 | MA2/E5 | MA2/FU1 MA2/FU5 MA2/LC1 MA2/LC6 | 19/8 | 61/8 63/8 65/8 |
| MA3 | MA3/S01 MA3/S05 MA3/E1/C3 MA3/E1/C7 | MA3/E1 | MA3/E5 | MA3/FU1 MA3/FU5 MA3/LC1 MA3/LC7 | 7 29/4 15/2 8 |
| MA4 | MA4/S01 MA4/S05 MA4/E1/C4 MA4/E1/C8 | MA4/E1 | MA4/E5 | MA4/FU1 MA4/FU5 MA4/LC1 MA4/LC8 | 11/8 | 43/8 45/8 49/8 |
| MA5 | MA5/S01 MA5/S05 MA5/E1/C5 MA5/E1/C9 | MA5/E1 | MA5/E5 | MA5/FU1 MA5/FU5 MA5/LC1 MA5/LC9 | 15/8 | 37/8 39/8 43/8 |
| MA6 | MA6/S01 MA6/S05 MA6/E1/C6 MA6/E1/C10 | MA6/E1 | MA6/E5 | MA6/FU1 MA6/FU5 MA6/LC1 MA6/LC10 | 11/8 | 73/8 75/8 79/8 |
| MA7 | MA7/S01 MA7/S05 MA7/E1/C7 MA7/E1/C11 | MA7/E1 | MA7/E5 | MA7/FU1 MA7/FU5 MA7/LC1 MA7/LC11 | 17/8 | 49/8 51/8 55/8 |
| MA8 | MA8/S01 MA8/S05 MA8/E1/C8 MA8/E1/C12 | MA8/E1 | MA8/E5 | MA8/FU1 MA8/FU5 MA8/LC1 MA8/LC12 | 19/8 | 31/8 33/8 37/8 |
| MA9 | MA9/S01 MA9/S05 MA9/E1/C9 MA9/E1/C13 | MA9/E1 | MA9/E5 | MA9/FU1 MA9/FU5 MA9/LC1 MA9/LC13 | 13/8 | 55/8 57/8 61/8 |
| \( \bar{MA}_n \) = 6 | 19/3 | 46/7 | 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 \( \bar{S}_Rm \) 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...
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 Figure 11 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 ($\Sigma_F V = \frac{1}{2^1/2}$). 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 | $\sum LC_1 \cdots LC_8$ |
|----|----|----|----|----|----|------------------------|
| LC1 | SO1/1 SO1/05 | LC1/1 SO1/06 | LC1/1 SO1/07 | LC1/1 SO1/08 | LC1/1 SO1/09 | LC1/1 SO1/10 | LC1/1 SO1/11 | LC1/1 SO1/12 | 17/2 | 35/4 | 9 | 19/2 |
| LC2 | SO2/1 SO2/05 | LC2/1 SO2/06 | LC2/1 SO2/07 | LC2/1 SO2/08 | LC2/1 SO2/09 | LC2/1 SO2/10 | LC2/1 SO2/11 | LC2/1 SO2/12 | 23/8 | 5/2 | 7/2 | 31/8 |
| LC3 | SO3/1 SO3/05 | LC3/1 SO3/06 | LC3/1 SO3/07 | LC3/1 SO3/08 | LC3/1 SO3/09 | LC3/1 SO3/10 | LC3/1 SO3/11 | LC3/1 SO3/12 | 83/8 | 8/5 | 8/7 | 91/8 |
| LC4 | SO4/1 SO4/05 | LC4/1 SO4/06 | LC4/1 SO4/07 | LC4/1 SO4/08 | LC4/1 SO4/09 | LC4/1 SO4/10 | LC4/1 SO4/11 | LC4/1 SO4/12 | 11/2 | 23/4 | 6 | 13/2 |
| LC5 | SO5/1 SO5/05 | LC5/1 SO5/06 | LC5/1 SO5/07 | LC5/1 SO5/08 | LC5/1 SO5/09 | LC5/1 SO5/10 | LC5/1 SO5/11 | LC5/1 SO5/12 | 29/8 | 31/8 | 33/8 | 37/8 |
| LC6 | SO6/1 SO6/05 | LC6/1 SO6/06 | LC6/1 SO6/07 | LC6/1 SO6/08 | LC6/1 SO6/09 | LC6/1 SO6/10 | LC6/1 SO6/11 | LC6/1 SO6/12 | 4 | 17/4 | 9/2 | 5 |
| LC7 | SO7/1 SO7/05 | LC7/1 SO7/06 | LC7/1 SO7/07 | LC7/1 SO7/08 | LC7/1 SO7/09 | LC7/1 SO7/10 | LC7/1 SO7/11 | LC7/1 SO7/12 | 13/4 | 7/2 | 15/4 | 17/4 |
| LC8 | SO8/1 SO8/05 | LC8/1 SO8/06 | LC8/1 SO8/07 | LC8/1 SO8/08 | LC8/1 SO8/09 | LC8/1 SO8/10 | LC8/1 SO8/11 | LC8/1 SO8/12 | 17/2 | 35/4 | 9 | 19/2 |

Table 13. Availability of sub indicators of environmental 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 |
| EN1                     | 53/8           | 55/8 | 57/8 | 61/8 | STA | SVA | VSA | MOA | MSA | STA | MRA | MSA | VSA |
| EN2                     | 25/4           | 13/2 | 27/4 | 29/4 | MSA | STA | STA | MSA | MSA | STA | MSA | MSA | MSA |
| EN3                     | 13/4           | 7/2  | 15/4 | 17/4 | STA | VSA | MOA | MSA | MSA | STA | SVA | SVA | VSA |
| EN4                     | 31/4           | 8    | 33/4 | 35/4 | VEA | STA | SVA | MSA | MSA | STA | VSA | VSA | VSA |
| EN5                     | 13/4           | 7/2  | 15/4 | 17/4 | VSA | VEA | VSA | SVA | MSA | MSA | MSA | MSA | MSA |
| EN6                     | 29/8           | 31/8 | 33/8 | 37/8 | STA | SVA | MSA | MSA | MSA | STA | SVA | SVA | VSA |
| EN7                     | 35/8           | 37/8 | 39/8 | 41/8 | VEA | VEA | VSA | SVA | MSA | STA | VSA | VSA | VSA |
| EN8                     | 41/8           | 43/8 | 45/8 | 49/8 | STA | MSA | STA | VSA | SVA | STA | VSA | VSA | VSA |

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 (AFS) | RM2 (RVS) | RM3 (RBPM) | RM4 (RAF) |
|--------------------------|---------------|-----------|-----------|------------|-----------|
|                          |               | EO1 | EO2 | EO3 | EO1 | EO2 | EO3 | EO1 | EO2 | EO3 | EO1 | EO2 | EO3 |
| SO1 31/4 8 33/4 55/4     | MOA IMA IMA MAO STA STA SVA SVA IMA MOA SVA IMA STA STA SVA SVA | 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 |
| SO2 11/2 23/4 6 13/2     | MSA VSA STA MOA STA SVA IMA SVA IMA STA STA SVA SVA | |
| SO3 53/9 57/8 61/8       | VSA VSA VEA MOA SVA SVA IMA SVA SVA IMA STA STA SVA SVA | |
| SO4 11/2 23/4 6 13/2     | MOA SVA SVA SVA STA SVA IMA SVA SVA IMA STA STA SVA SVA | |
| SO5 13/4 7/2 15/4 17/4   | MSA SVA SVA VSA SVA STA SVA IMA SVA SVA IMA STA STA SVA SVA | |
| SO6 11/2 23/4 6 13/2     | VSA VEA STA IMA SVA SVA SVA IMA SVA SVA IMA STA STA SVA SVA | |
| SO7 7 29/4 15/2 8       | STA SVA SVA SVA SVA SVA IMA SVA SVA IMA STA STA SVA SVA | |

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

| Sustainability Indicator | Sub-indicators | RM1 (AFS) | 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 SVA STA SVA MOA SVA IMA SVA SVA | 83/6 118/7 121/6 53/2 21/2 66/5 81/5 177/810 38/3 78/5 43/2 125/9 17 81/4 80/3 |
| EC2 25/4 13/2 27/4 29/4  | MSA STA SVA IMA SVA SVA STA SVA IMA SVA SVA | |
| EC3 7/3 7/8 7/5 7/8 7/8  | STA VEA SVA SVA STA SVA IMA SVA SVA IMA SVA SVA | |
| EC4 7 29/4 15/2 8       | VSA SVA SVA STA SVA SVA SVA SVA SVA SVA | |
| EC5 3/8 5/5 5/7 61/8     | MSA SVA SVA SVA SVA SVA IMA SVA SVA IMA SVA SVA | |
| EC6 47/8 49/8 51/8 55/8  | VEA SVA SVA SVA SVA SVA SVA SVA SVA SVA | |
| EC7 7 17/4 9/2 5        | MSA SVA SVA SVA SVA SVA IMA SVA SVA IMA SVA SVA | |

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

| Sustainability Indicator | Sub-indicators | RM1 (AFS) | 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 SVA SVA STA SVA SVA SVA IMA SVA SVA | 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 |
| RE2 3/4 8 33/4 35/4      | SVA VSA SVA SVA STA SVA SVA SVA IMA SVA SVA | |
| RE3 37/4 19/2 39/4 41/4  | VEA SVA SVA SVA STA SVA SVA SVA SVA SVA | |
| RE4 47/8 37/8 73/8 79/8  | SVA VSA SVA SVA STA SVA SVA SVA SVA SVA | |
| RE5 10 41/4 21/2 11      | VEA SVA SVA SVA SVA SVA SVA SVA SVA SVA | |
| RE6 31/4 8 33/4 35/4     | MSA SVA SVA SVA SVA SVA SVA SVA SVA SVA | |

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

| Sustainability Indicator | Sub-indicators | RM1 (AFS) | 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  | VEA STA SVA SVA STA SVA SVA SVA SVA | 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 |
| MA2 59/8 61/8 63/8 65/8  | MSA SVA SVA SVA STA SVA SVA SVA SVA | |
| MA3 7 29/4 15/2 8        | MSA IMA SVA IMA SVA IMA SVA IMA SVA | |
| MA4 41/8 43/8 45/8 49/8  | VEA SVA SVA SVA SVA SVA SVA SVA SVA SVA | |
| MA5 35/8 37/8 39/8 43/8  | VEA SVA SVA SVA SVA SVA SVA SVA SVA SVA | |
| MA6 71/8 73/8 75/8 79/8  | VSA SVA SVA SVA SVA SVA SVA SVA SVA SVA | |
| MA7 47/8 49/8 51/8 55/8  | VEA SVA SVA SVA SVA SVA SVA SVA SVA SVA | |
| MA8 29/8 31/8 33/8 37/8  | MSA SVA SVA SVA SVA SVA SVA SVA SVA SVA | |
| MA9 53/8 55/8 57/8 61/8  | SVA SVA SVA SVA SVA SVA SVA SVA SVA SVA | |

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
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 in this article and creating enabling environment for this study.

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OLAYINKA MOHAMMED OLABANJI received the M.Eng. degree in mechanical engineering from the Department of Mechanical Engineering, Federal University of Technology Akure, Nigeria, in 2012, and the Ph.D. degree in industrial engineering from the Tshwane University of Technology, Pretoria West, South Africa, in 2016. He is currently a Lecturer and a Researcher with the Department of Mechanical Engineering, Federal University of Technology. He is also a Postdoctoral Research Fellow with the Department of Industrial Engineering and the Gibela Research Chair in Manufacturing and Skills Development with the Tshwane University of Technology (TUT), South Africa. He has reviewed papers for numerous Conferences including the 30th CIRP Design Conference and Journal of Engineering, design, and Technology Emerald. His research interests include mechanical engineering design, advanced manufacturing, automation, and control systems.

KHUMBULANI MPFOFU is currently a Professor of industrial engineering and the Gibela Research Chair in Manufacturing and Skills Development with the Tshwane University of Technology (TUT), South Africa. He is an NRF-rated Researcher with an unbridled passion for industrial engineering. He has reviewed papers for various conferences, including the CIRP Conference on Manufacturing Systems, the CIRP Global Conference on Sustainable Manufacturing, the Flexible Automation and Intelligent Manufacturing Conference, the Southern African Institute of Industrial Engineers Conference, the Zimbabwe Institute of Engineers, the International Conference on Appropriate Technology, the Symposium on Mechatronics and Robotics, the Botswana Institute of Engineers Conference, the Conference on Mechatronics and Machine Vision, Hybrid, and Intelligent Systems, the International Federation of Automatic Control Conference, and the CIRP Global Conference on Manufacturing. In 2008, he chaired the much-acclaimed session at the International Conference on CADCAM and Robotics and Factories of the Future. He has also participated in the CIRP General Assembly Local Organizing Committee held in Cape Town, South Africa, in 2015. He also serves the CIRP Global Conference on Sustainable Manufacturing and is the Conference Chair for the 30th CIRP Design Conference.