An Approach to Solution Variants Screening in Morphological Matrix based Conceptual Design

Shuaibu Alani Balogun
School of Mechanical Engineering, University Teknologi Malaysia (UTM)

Mohamad Kasim Abdul Jalil
School of Mechanical Engineering, University Teknologi Malaysia (UTM)

Jamaluddin Mohd Taib
School of Mechanical Engineering, University Teknologi Malaysia (UTM)

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An Approach to Solution Variants Screening in Morpholo gical Matrix based Conceptual Design

Shuaibu Alani Balogun[1*], Mohamad Kasim Abdul Jalil[1], Jamaluddin Mohd Taib[1]
[1]School of Mechanical Engineering, University Teknologi Malaysia (UTM), Johor Bahru, Malaysia

*Author to whom correspondence should be addressed:
E-mail: sabalogun@graduate.utm.my

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Abstract: To make morphological matrix based conceptual design more efficient, a systematic procedure which enables complete extraction of the feasible solution variants (concepts) is developed. The approach entails: functional decomposition, generation of alternative solution principles for each subfunction, formation of combinatorial solution variants chains, and 3D space matrix and multi-objective concept optimisation-based concept screening. The approach was tested using the conceptual design of river cleaning machine. 625 theoretical concepts are obtained from the morphological matrix. The concepts are screened to 114 feasible concepts and optimised to obtain a preliminary design concept. Consequently, the concept selected for the river cleaning machine is outstanding based on efficiency, manufacturability, repairability and cost.

Keywords: Feasible concept, solution principle, solution variant, physical parameter, river cleaning machine

1. Introduction

Conceptual design has been accorded the most significant stage in the design process [1]. In fact, 70% of the life cycle cost of products, is influenced by the conceptual design stage [2]. For these reasons, sixty to seventy percent of the design cost, is often expended at the conceptual design stage [3]. Conceptual design process, can be considered as the transformation of design specification [4] -which is given as requirements list- [5] into one or more concepts, that can satisfy these requirements for further development [6]. During the conceptual design phase, design problems are formulated [7], possible solutions to the problems are generated [8], then the seemingly best solution is selected after evaluating the various solutions variants (SVs) [9].

Conceptual design entails three basic tasks. The tasks are concept generation, concept evaluation and concept selection [5]. Of the many methods of concept generation, morphological matrix approach has proved to be outstanding especially when quantity, variety and novelty [10] are of concern [11]. In a morphological matrix, the design problem is systematically defined in terms of functions and subfunctions which the artefact to be produced is expected to fulfil [11]. Then solution principles (SPs) which could be in terms of structures or physical effects, that can perform each subfunction, are proposed for each subfunction [5], as shown in Fig. 4. The solution variants (SVs) which are the combinatorial chains of SPs across different rows of the matrix, are the concepts that can perform the overall function [5].

In any morphological matrix with m_1, m_2, m_3, ---- m_x SPs in rows 1, 2, 3, ------- x respectively, the total number of theoretical SVs that could be generated is $m_1 \times m_2 \times m_3 \times ---- m_x$ [12]. However, not all such SVs are feasible concepts. This is because some of the SPs in the SV chains are not compatible. Pahl et al., [12] asserted that the morphological approach enables large expansion of the design space. Nonetheless, no logical relation has been developed in the literature, to enable complete exploration of its design space. As such many of the designers that apply the morphological matrix methods employ random sampling of the SVs in concept generation [13].

Nevertheless, several attempts were made to develop computer-based SVs exploration for conceptual design [11] [14] [15]. Still, most of them entail manual screening of the SPs either before [11] or during [15] the SV chain formation. In a study, Arnold, Stone, and McAdams [14] developed an automatic catalogue-based SPs generation method. They developed a system that compare functions and elicit components from the catalogue that matches each subfunction to develop the morphological matrix. However, identifying the SVs that contains incompatible SPs was manually done by designers by screening each of the SVs. Similar to this, are the works of Ölvander, Lundén, and Gavel [11] and Kang and Tang [15] While the former considered selective assertion of SPs into the morphological matrix, SVs with incompatible adjacent SPs, are manually screened by designers in the later.

Furthermore, some scholars have proposed representation schemes for physical effects in terms of motion of mechanisms or nature of the physical effects [2) 16) 17)]. For instance, Chakrabarti and Bligh [16)] represented physical effects as type which could be force, torque voltage etc. they also represented its orientation using the Cartesian coordinates, while the sense is either + or -. However, a generic representation for SPs (structures) is lacking in the literature. Therefore, in this study, a representation of the physical features of the SPs which is termed physical parameter (PP) is proposed. The procedure for eliciting PPs out of a morphological matrix is developed. The procedure is generic. With the PPs, vectorial numerical values are generated. Such numerical values form logical relations that enable complete extraction of SPs out of a morphological matrix. To demonstrate the applicability of the approach, the design of river cleaning machine was used as case study.

Furthermore, the Pugh decision matrix is one of the most popular when it comes to concept evaluation and selection [5) 18)]. The method entails screening the alternative concepts against a benchmarking concept. This method has been adopted by many designers. Besides, it has been modified to make weighted factors where numerical performance values are attached to each concept. Such numerical values are summed up and concepts with the highest score was adopted as preliminary design [13) 18)]. Nevertheless, evaluating each SPs for the chosen evaluation variable is proposed in this work to reflect the quality of combinatorial evaluation.

Moreover, the selection procedure to be applied in this work is optimisation based. For the optimisation to reflect a realistic combination of selection criteria that combine both variables that require minimization (e.g., cost) and those that require maximization (e.g., efficiency). Unlike in a similar work [11)] in which the objective function is only a minimization function.

The scheme for conceptual design developed in this work is tested on conceptual design of river cleaning machine. River cleaning is necessary to remove debris out of both large and small bodies of water. Most large bodies of water are connected to medium and small streams. By implication, the anthropogenic debris collected by small streams, find their ways into the larger water bodies [19)]. Other sources of debris are greenhouse solid wastes from building sector [20)]. Such wastes cause emission of gasses which could be threat to both aquatic and terrestrial lives [21)]. In attempt to maintain sanity of rivers, Mohammed et al., [22)] developed a trash collector, comprising of a trash trap, belt conveyor and a discharge bin. They built an electronic control system for the river cleaning machine. A single concept was proposed in their work. However, there are several SPs that can perform each of the subfunctions in the design. Four subfunctions were identified from the design of river cleaning machine. The subfunctions and the respective SPs that can perform them are arranged to develop the morphological matrix shown in Fig. 4.

This work entails decomposing the functional requirements of a river trash removal machine. Thereafter, SPs to each subfunctions are proposed, and arranged in line with the respective subfunction, in a morphological matrix. From a morphological matrix, several concepts (SVs) can be generated. The SVs are screened, evaluated, and optimized, based on a framework developed, to select the optimum concept.

2. Methodology

Since the focus of the approach is morphological based, the process begins with function decomposition, then generation of alternative SPs. The established subfunctions and SPs are used to compose morphological matrix. Subsequently, Compatibility factors (physical parameters) are determined and allocated to each SP. Matrices are developed to represent the physical parameters (PPs) of each SP in the morphological matrix. The number of such matrices that are developed for a design depends on the number of PPs that are identified.

Then, the SVs are screened by comparing the (PPs) of adjacent SPs in a combinatorial solution chain. SVs that are composed of compatible SPs are feasible concepts, while those that have incompatible SPs are non-feasible. The feasible concepts are subjected to an optimisation process. This yields a set of optimum concepts, and the concept with the highest score among the optimum, is selected as a preliminary concept. Furthermore, the scheme is implemented using a MATLAB programme. The programme only receives number of subfunctions, number of alternative SPs for each subfunction, PPs and evaluation variables (EVs) of each SP as inputs. Upon processing, optimum set of concepts are given, in terms of their combinatorial solution formulation.

Functional decomposition is done by creating a chain of subfunctions that can achieve the main function [5) 15)]. For instance, the main function of river cleaning machine is to remove trashes from the surface of a river. To achieve this, the trash needs to be arrested, transferred from the point of arrest to a receptacle or the riverbank. All these are subfunctions. Subfunctions are labeled as F_1, F_2….F_n, where n is the total number of subfunctions in the functional model.

Furthermore, alternative solution principles (SPs) are generated for each subfunction [9)17)]. The designer is free to include any possible SPs for each subfunction. This approach enables designers at all levels of design experience to participate in conceptual design. At this stage, less emphasis is placed on the compatibility of the SP with other SPs.

The next stage is the development of a morphological matrix [11)18)]. It comprises of an arrangement of subfunctions and their respective SPs in a matrix form [5)]. The alterative SPs can be represented using drawings [13)] or writings [11)]. In the morphological matrix in Table 1, F_1 to F_r represent the subfunctions, while their respective SPs are represented as A_1 to A_s, B_1 to B_s and so on.

Theoretical concepts or combinatorial solution or SVs are thereafter formulated, from the morphological matrix [12]. SV is a chain of SPs, that comprises of one SP, from each row of a morphological matrix [5]. For instance, (A_1, B_2, C_3,…Z_2) is a combinatorial chain elicited from Table 1. Several combinatorial chains can be formed from a morphological matrix. Theoretically, a total of $m_1 \times m_2 \times m_3 \ldots . \times m_n$ SVs can be generated from a morphological matrix [12], where n and m represent the number of subfunctions in the matrix and the number of SPs for each subfunction respectively. For instance, the morphological matrix of the river cleaning machine in Fig. 4 will produce a total of $5 \times 5 \times 5 \times 5 (625)$ SVs. All the SVs are arranged in a concept matrix termed G-matrix. The elements of a G-matrix are tagged with G. Nonetheless, in the real sense, the number of feasible SVs, that can be generated from the morphological matrix is less. Not all SPs of a subfunction, can match with SPs of an adjacent subfunction. For the SPs to be compatible, they must have similarities in some characteristics. Such characteristics are termed physical parameters (PPs).

Table 1: Morphological matrix.

Subfunctions	Solution Principles (SP)				
F_1	A_1	A_2	-	-	A_s
F_2	B_1	B_2	-	-	B_s
!	!	!	!	!	!
!	!	!	!	!	!
F_r	Z_1	Z_2	-	-	Z_s

To assign PPs to a set of SPs for a subfunction in a morphological matrix, functional features of the SPs that differentiate one from the other are examined. The PPs of a set of SPs, for the same subfunction are examined, to identify the similarity and dissimilarly in all their functional features. Based on the differences in the functional features of the SPs, PPs are formulated. If this is adroitly composed, the PPs derived from a set of SPs will be the PPs they possess for them to provide a function. Conversely, the set of PPs derived from other sets of SPs will serve as PPs that is required for them to interact with the set of SPs from which the PPs are derived. The elements of the PPs are given numerical values which are vectorial.

This procedure is contained in Fig. 1. Starting from the first row of the morphological matrix, all the features that differentiate one SP or a set of SPs from the others are examined and noted. These features are checked on the elements in the other rows if they influence their compatibility. The row is further examined to check if there are other differences. When the possible differences are all examined, the next row is examined, and the same process is repeated. Meanwhile, the PPs in the previous iterations are checked on the subsequent rows until they are exhaustively considered before searching for PPs in the next rows. When all the rows have been considered, the PPs generated are given numerical values. Then, the numerical values are assigned to each of the SPs.

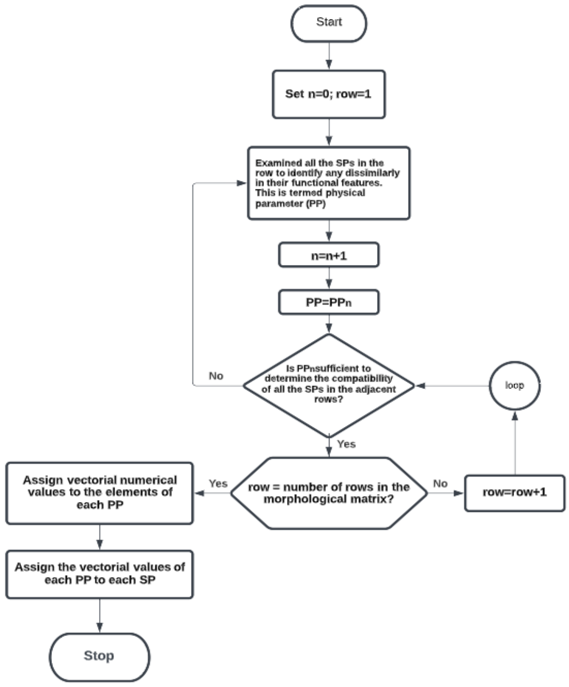


Fig. 1: Procedure for determination of physical parameters

The elements of the PPs are assigned numerical values which are vectorial. If the PP has two elements for example, one of the elements is given +1 as its numerical value while the other is given -1. A third value is added which is termed universal. Universal PP are given 0 as numerical value. Still using the SPs in Table 2 as example, the PP is 'energy source for the propulsion' the first element is 'gasoline' and can be given a numerical value of +1 while the second element is 'electricity' with a numerical value of -1. The third element is 'universal' which is given 0 as its numerical value,

Table 2: morphological matrix for a motor cycle [12]

Functions	Solution Principles		
Propulsion F_1	Combustion engine A_1	Electric motor A_2	Hybrid propulsion A_3
Store electrical energy F_2	Lead battery B_1	NiCd battery B_2	Li-ion battery B_3
Store gasoline F_3	Gasoline tank C_1	No tank C_2	
Support driver F_4	Steel frame D_1	Aluminum frame D_2	Carbon fibre frame D_3
Brake F_5	Disc brake E_1	Drum brake E_2	Regenerative electrical brake E_3

For instance, in the morphological matrix for a motorcycle shown in Table 2, only one PP is sufficient to check the compatibility of the SPs in all SVs. It can be observed that from the first subfunction (propulsion), the feature that differentiate the gasoline from the electric motor and the hybrid propulsion is the source of input energy. Two sources are identified which are gasoline and electricity.

To assign PPs to the SPs in Table 2, A_1 is +1, A_2 is -1 while A_3 is 0. All the elements of F_2, are 0. C_1 is +1 while C_2 is -1. The remaining SPs are 0 except E_3 which is -1.

Subsequently, The SVs are screened based on 3D space matrix method. PPs of adjacent SPs in an SV are checked for similarity of PPs. The SVs that contain SPs with similar PPs are the feasible concepts. Those that contain SPs with dissimilar PP are screened out. Further syntheses are carried out on the feasible concepts.

The 3D space matrix is a graphical representation of the SVs screening process. The vertical axis (Z axis) represents the SPs that are contained in the SV to be screened. Furthermore, the PPs are arranged in both the X and the Y axes alternatively. As shown in the design of river cleaning machine in Fig. 5, PP_1 is on X axis while PP_2 is on Y axis. For more than two PPs, PP_3 is on X axis while PP_4 will be on Y axis and so on. For a morphological matrix of a very simple form such as that of Table 2, the third axis is hidden.

For any of the SPs in the SV chain, the numerical values of the PPs are plotted based on magnitude and direction. However, 'universal' has 0 as PP value. It can be given same value as that of the remaining SPs in the chain for the given PP. Thereafter, the rectangle formed after plotting the 3D graph are compared for similarity in magnitude and direction. If all the rectangles are similar, then the SV is considered feasible. Otherwise, it is not feasible.

Furthermore, performance values are allocated to each SP, and subsequently weighted factors are determined for each, by multiplying their performance values, to the weight factor of each EV[23].

The weighted factors for each SP are normalized. Normalisation is aimed at unifying the beneficial status of all the EVs. Some of the EVs are identified to be beneficial while some are nonbeneficial. Beneficial EVs are those that their higher values are desirable, while non-beneficial EVs are those that their lower value is desirable. For instance, EVs like manufacturability, efficiency, safety, maintainability, reliability, and durability are all beneficial because their higher values are desirable. Conversely, EVs like cost and material, wear rate and the like are nonbeneficial because their lower values are desirable [24]. The factors are normalized using Eq. 2 for beneficial factors but Eq. 1 for non-beneficial factors 25).

$$C_{ij} = \frac{C*Min(X_{ij})}{(X_{ij})} \quad (1)$$

$$C_{ij} = \frac{C*(X_{ij})}{Max(X_{ij})} \quad (2)$$

In Eq. 1 and Eq. 2, C_{ij} represents the normalized weighted factor for SP in row i and column j of the morphological matrix. C is the weight factor of the EV. Moreover, X_{ij} is the performance value of SP in row i and column j of the morphological matrix for the respective EV. Then, $Min(X_{ij})$ / $Max(X_{ij})$ is the Minimum/Maximum performance value for the respective EV among all the SPs. Normalizing the EVs enables the use of a single objective function for the multivariable optimisation model. The weight of the EVs of all the SPs in an SV are summed up to obtain the weighted factor of each concept.

Furthermore, the SVs formed are arranged in a matrix. The matrix is termed concept matrix or G-matrix. All analyses on the concepts are done in the G-matrix. Besides, the weighted factor of each concept for each EV form different G-matrices. This is shown in Fig. 2 as the G_1, G_2 to G_e, where e is the total number of EVs used in the design.

Moreover, the optimum concept is determined using the optimisation model is indicated in Eq. 3. The model is a weighted multi-objective optimisation [25]. The uniqueness of the optimisation model developed for this work is that the constraint is based on the weighted factor of a benchmark. The performance value for one of the SVs within the design space is set as benchmark. This gives a reflection of the weighted Pugh decision making method. Besides, the objective functions are combination of both minimization and maximization. The combination is possible by Normalisation which is done using Eq. 1 or Eq. 2. The concepts obtain after the optimisation screening, are the set of optimum concepts. The one with the highest score among the optimum concepts is selected as the preliminary design concept.

Maximise:

$$\mathrm{F}(G_{ij}) = G_1(i,j) + G_2(i,j) + --- + G_e(i,j) \quad (3a)$$

Subject to:

$$H(G_1) > a;\ H(G_2) > b;\ H(G_3) > c;$$
$$---H(G_e) > d;\ H(G_{ij}) > 0; \quad (3b)$$

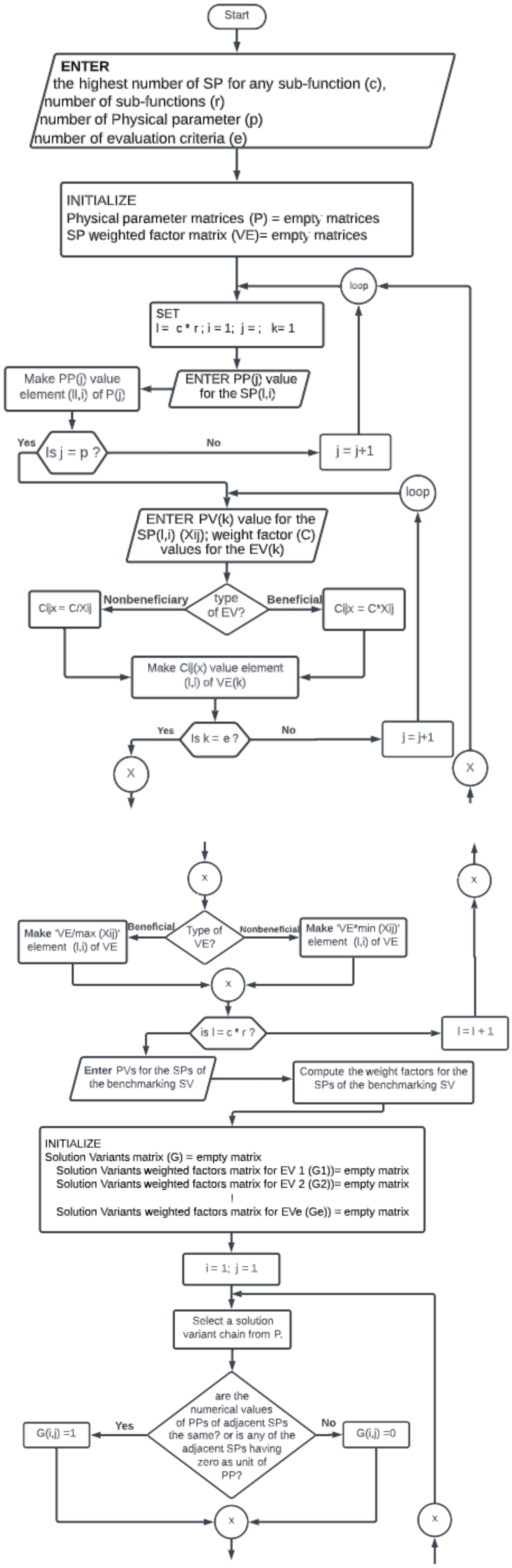
In Eq. 3, the objective function is to maximize the sum of the combination of weighted factors of EVs of the SVs [$\mathrm{F}(G_{ij})$]. $G_1(i,j)$ to $G_e(i,j)$ are the weighted factors of EVs from the first to the last. In addition, $H(G_1)$ to $H(G_e)$ are the weighted factors of EVs for the benchmarking SV from the first to the last. The entire elements of the G-matrix are subjected to the test based on the objective function and constraints in Eq. 3. The SV with the highest score among the optimal SVs is selected as the preliminary design.

The scheme for morphological matrix based conceptual design developed in this work, is implemented in MATLAB environment. In the computer programme developed for implementing the scheme developed for this study, conditional statements are made to check compatibility of all the PPs of all adjacent SPs in the SV.

As shown in Fig. 2. The main inputs of the programme are the number of subfunctions in the design, the number of alternative SP for each subfunction, the numerical values for the PPs and performance values for each EV for each SP. Weighted factors and PP matrices are made empty at the initial. The programme accepts numerical values for the PPs and performance values for each of the SPs. Weighted factors are computed for each SP for each EV, and they are normalized based on Eq. 1 and Eq. 2. Additionally, the weighted factors for the SPs in the benchmarking SV are also inputted.

Subsequently, the G-matrices are initiated as empty matrices. As explained earlier, the G-matrices are the SV matrix and the SV weighted factors matrices. The first screening is based on PP comparison. This is the 3D space matrix-based screening. The aim is to enable complete extraction of the feasible concepts out of the morphological matrix. In the programme, the numerical values of the PPs for adjacent SPs in an SV chain are compared to accept their compatibility if they are the same in magnitude and direction or one or both have zero as its numerical value. Such SVs with compatible SPs are the feasible SVs while the SVs with incompatible adjacent SPs are the non-feasible SV. The feasible SVs are given unitary value in the G matrix while the non-feasible SVs are given zero.

The optimisation-based screening is done by testing each EV of each SV against that of the benchmarking SV. For those that fulfil the condition the corresponding element of the G-matrix is made unitary. Those that do not fullfil the condition are made zero. Finally, the SV with the highest score is selected as the preliminary design.



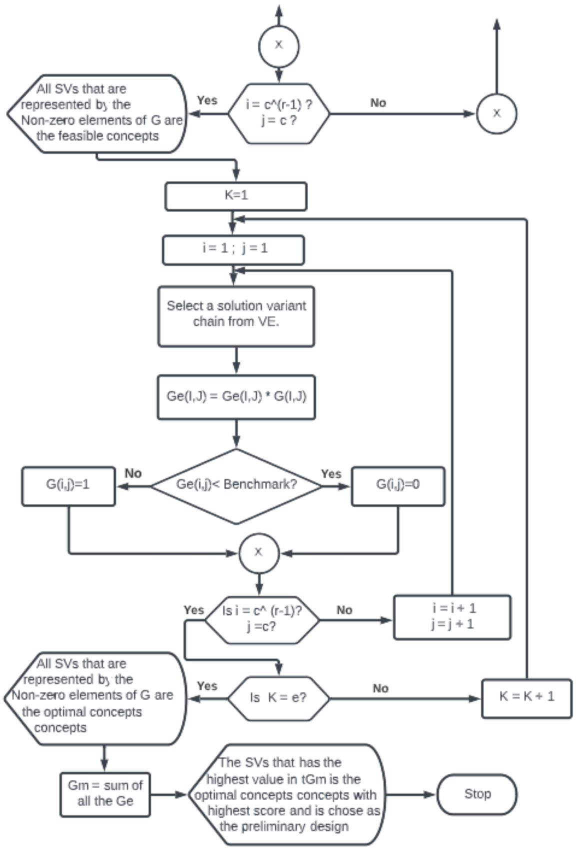


Fig. 2: Flowchart of the computer programme for the conceptual design framework developed in this study.

3. Results

This section entails, the detail of the implementation of conceptual design procedure, developed in this study. Conceptual design of river cleaning machine is used as a case study. The main function of the artifact is decomposed. Then SPs are found for the subfunctions obtained. With both the subfunctions and the SPs, morphological matrix was created. Thereafter, PPs and weighted factors were determined for each SP. With the PPs, the compatibility of the adjacent SPs in an SV was checked. This logical procedure can be graphically represented as a 3D space matrix.

Subsequently, SVs that contain SPs with compatible PPs are chosen as feasible concepts, while those that contain incompatible SPs are considered as infeasible concepts. The weighted factors are found for the feasible concept. The optimisation objective function and constrain relations were applied to the SVs to elicit the SVs with optimality. Finally, the SV with the highest score of total weighted factor is selected as the preliminary design.

3.1 Functional decomposition

The main function of the river cleaning machine is 'to remove trash from the surface of a river'. The main function can be decomposed as shown in Fig. 3. Considering the operational sequence for clearing trash from a river, the first step is to input the trash into the machine. This yields the first subfunction (F_1) which can be tagged as "to collect trash". The next sequence of operations is receipt and storage of energy (electrical, or chemical), converting the energy (into mechanical energy), then applying the energy to trash movement. This set of operations yields the second subfunction (F_2), which is described as 'to transfer trash'. The third, fourth and fifth subfunctions are F_3, F_4, and F_5 respectively. As indicated in Fig. 3, five subfunctions are developed from the main function. Nevertheless, the first four subfunctions are used for the design synthesis. F_5 is directedly connected to a lower functional level.

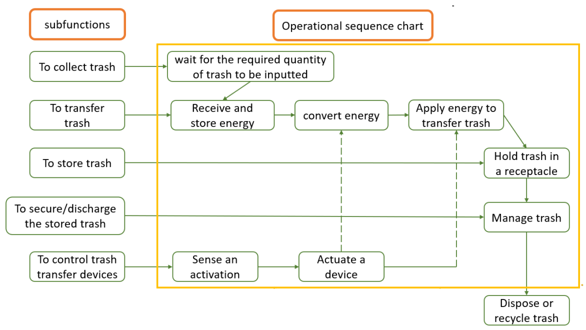


Fig. 3: The function decomposition of a river cleaning machine via operational sequence

3.2 Building of morphological matrix

Five alternative SPs are found for the first subfunction (i.e., 'to collect trash'). The five SPs that can perform the first subfunction are described, in terms of their structures in first row of Fig. 4. The first SP for the first subfunction (A_1) suggests 'the use of a floating barrier to trap the trash'. The second SP for the same subfunction (A_2), suggests collecting the trash using a rotating blade. The third SP (A_3) suggests 'collecting the trash in a skimming filter'. Then the fourth (A_4) suggests 'the use of a hydraulic arm to harvest the trash', while the fifth (A_5) suggests 'trapping the trash' just like A_1. For the rest of the subfunctions, the SPs are equally generated in the same manner. The SPs for the second, third and fourth subfunctions are labelled B_1 to B_5, C_1 to C_5, and D_1 to D_5 respectively. Generating the SP can be based on any method. It could be done by a one-man designer or by a group of designers.

The morphological matrix developed, for the river cleaning machine, is as shown in Fig. 4. The SPs for each subfunction are in the same row with it.

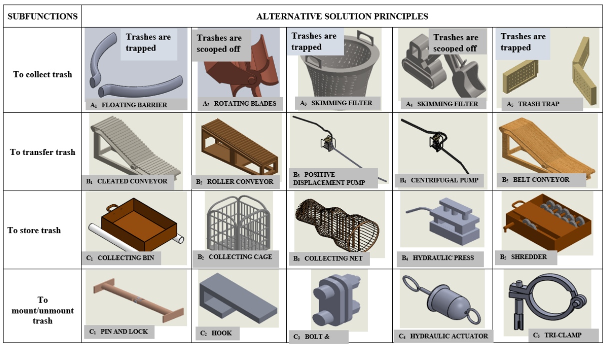


Fig. 4: Morphological matrix for conceptual design of river cleaning machine

3.3 Creating physical parameters matrix

As indicated in Table 3, three PP are derived from Fig. 4. The first PP is derived from the set of SPs in row 1 (SP to subfunction 1). It is observed that the trash arresting areas are either opened or screened (A_3 is screened while the remaining SP in row 1 are open). As such, the first PP (PP_1) is "trash arresting area" which is a provided PP for SP in row one. In addition, it is observed that, based on PP derived from SP in row one (i.e., "trash arresting area"), the SP in row two are also distinct, in the required "trash arresting area" of SP in row one, that they can connect or work with. So, "trash arresting area" is a required PP for SP in row two. This implies that, SP in row two can work with SP in row one, with either open, screened or both kind of "trash arresting area". As such, the third alternative is considered as universal. As indicated in the first row of Table 3, for the first PP (i.e., "trash arresting area"), screened is given a value 1, open -1 while universal is given 0.

The same procedure as described above, is used to obtain the second (PP_2) and the third PP (PP_3). Vectors of PP are thereafter generated, for each of the SP in the Morphological matrix. Thus, as shown in Table 4, PP of A_1 is represented by the vector [-1, 0, 0]. The first, second and third element of the vector stand for 'Trash arresting area', 'trash transfer path' and 'trash discharge area' respectively. Consequently, the PP vector for A_1 can be interpreted as 'A_1 has an open trash arresting area, it can work with SP with any kind of trash transfer path or trash discharge area'.

Table 3: Generating values for physical parameters of solution principles for conceptual design of river cleaning machine

Physical parameter	Equivalent Values		
	1	2	3
Trash arresting area (PP_1)	Screened =1	Open =-1	Universal= 0
Trash transfer path (PP_2)	flat conveying= 1	Suction=- 1	Universal =0
Trash discharge area (PP_3)	Net/box screened =1	Solid open box =-1	Universal= 0

Table 4: Generating physical parameters vectors for solution principles of river cleaning machine

Functio ns	Physical parameters (PP) of solution variants				
	1	2	3	4	5
F1	[-1, 0, 0]	[-1, 1, 0]	[1, -1, 0]	[-1, 1, 0]	[-1, 0, 0]
F2	[-1, 1, -1]	[-1, 1, -1]	[0, -1, 1]	[0, -1, 1]	[-1, 1, -1]
F3	[0, 0, -1]	[0, -1, 1]	[0, -1, 1]	[0, -1, 1]	[0, 0, -1]
F4	[0, 1, -1]	[0, 1, -1]	[0, 1, -1]	[0, 1, -1]	[0, -1, 1]

3.4 Determination of weight factors for solution principles

Performance values are determined for each of the SPs. The performance values for the SP of the river cleaning machine are shown in Table 4. Four EV are considered which are efficiency, manufacturability, repairability and cost. These four EV are chosen as extract from requirements based on author's experience. The performance values are converted into normalized weighted factors using Eq. 1 or 2. Efficiency, manufacturability and repairability, which are beneficent EV are normalized using Eq. 1, while cost which is a non-beneficent variable is normalized using Eq. 2.

Table 4: Performance value assertion for each solution principles for each EV

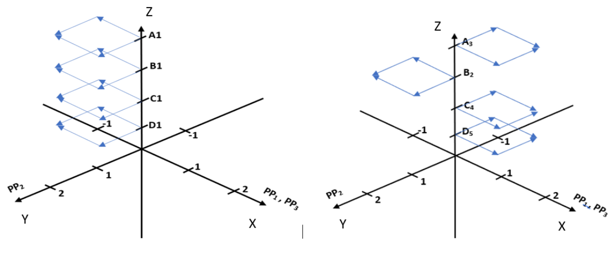
SP	efficiency	manufacturability	repairability	cost
A_1	10	2	10	3
A_2	8	3	8.5	2.5
A_3	3	5	8.5	2
A_4	6	8	2	10

A_5	9	6	8	3.5
B_1	6	3	8	4
B_2	4	5	6.5	5
B_3	10	8	2.5	7
B_4	8	7	2.5	6
B_5	3	2	8	4
C_1	5	4	9	4
C_2	2	3	7	2.5
C_3	1	2	7.5	1.5
C_4	6	5	5	4.5
C_5	7	6	5	5
D_1	8	2	9	2
D_2	4	1	10	0.5
D_3	5	3	9	2
D_4	7	6	6	3
D_5	4	3	8	1.5

3.5 3D space matrix-based solution screening

As shown in Fig. 5, the PP are arranged alternatively on the two horizontal axes. PP_1 is placed on the X-axis, PP_2 on Y-axis then PP_3 on X-axis and so on. The screening starts with the first element of the concept matrix and is done to all the elements. As shown in Fig. 5a, the first element of the G-Matrix (i.e. [A_1, B_1, C_1, D_1]) is arranged on the Z axis. The PP are labelled as PP_1, PP_2, PP_3…...PP_n. The X and Y axes are marked from 1 to the highest numerical values of the PP. in the case of the river cleaning machine, the PP have only 3 numerical values which are 0, 1, -1.

Two SV ([A_1, B_1, C_1, D_1] and [A_3, B_2, C_4, D_5]) are chosen to demonstrate the procedure. As shown in Fig. 5a, PP_1 is plotted first, based on size and direction from the origin. For A_1 and B_1, PP_1 is 1 unit in the negative direction. For C_1, PP_1 is zero (i.e., universal). The unit and direction of the PP for any SP with real number is chosen. If the unit of the PP is zero for all SV, then the same unit and direction is chosen for all. Therefore, the unit and direction of PP_1 of B_1 is chosen for C_1. Therefore, PP_1 for C_1 and D_1 is 1 unit in the negative direction. The same procedure is applied to plot all other PPs, for each of the SVs. SVs with rectangles that has all edges, similar in magnitudes and direction, and are all in the same quadrant, are acceptable as feasible concepts. Those that do not fulfil this condition are screened out.



(a) (b)

Fig. 5: 3D Matrix-based solution matching.
(a) matching solutions (b) unmatching solutions.

3.6 Concept optimisation and selection

Using the optimisation model in Eq. 3, the optimum concept is determined. The concept generation, screening and optimization process is carried out using a programme written in MATLAB. The input required for the system is the number of subfunctions, the number of SP for each subfunction, the number of PP for the design and the PP and the performance value of each SP.

Upon running the programme, a total of 114 feasible concepts are obtained from 625 theoretical concepts. Furthermore, a set of seven concepts are obtained, after the optimisation, which are the ones that are optimum, based on the constraints test. The set of optimum concepts are shown in Table 5. Furthermore, from Table 5, it can be observed that the concept having the highest score among the set of optimum concepts is [A_1 B_1 C_1 D_2]. The concept with the highest score is indicated by a path in the morphological matrix as shown in Fig. 6.

The concept comprises of four elements. The first element which is the floating barrier (A_1) is relatively cheap. Besides, it has a wide area to statically arrest the trash and guide same towards its narrow path. This makes it very efficient in arresting the trash. Furthermore, it is easy to be manufactured as common PVC pipe could be cut and capped to make it.so is it easy to repair.

The other elements in the combinatorial chain, have good qualitative value for efficiency, manufacturability repairability and cost. Though not equally distributed, the blend of their attributes makes the concept the optimum.

Table 5: Scores of the optimum set of solutions

Concept	Efficiency	manufacturability	Repairability	Cost	Total Score
A_1 B_1 C_1 D_2	0.6250	0.7875	0.9250	0.3542	2.6917
A_1 B_1 C_5 D_2	0.6750	0.7500	0.8250	0.3479	2.5979
A_1 B_1 C_1 D_1	0.7250	0.7375	0.9000	0.1667	2.5292
A_1 B_5 C_1 D_1	0.6500	0.7625	0.9000	0.1667	2.4792
A_1 B_1 C_1 D_3	0.6500	0.7125	0.9000	0.1667	2.4292
A_2 B_1 C_1 D_1	0.6750	0.7125	0.8625	0.1750	2.4250
A_1 B_2 C_1 D_1	0.6750	0.7125	0.8625	0.1604	2.4104

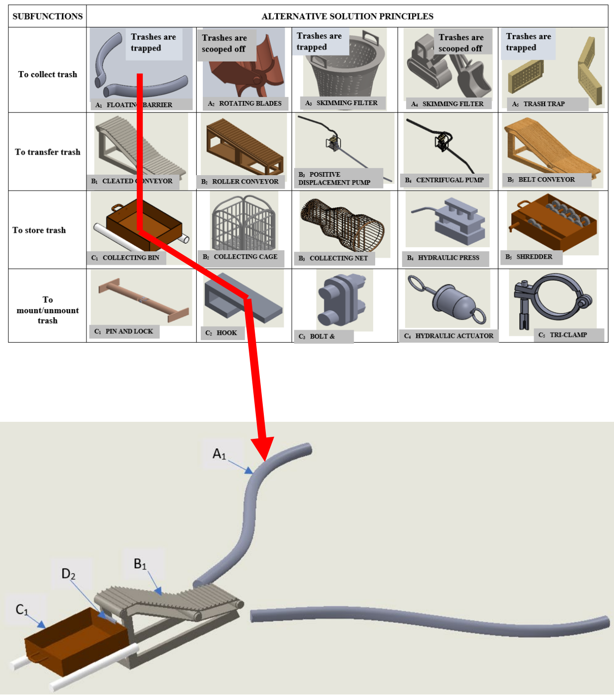


Fig. 6: Solution Chains of the Optimum SVs

3.7 Discussion

As can be seen in Fig. 24, the morphological matrix developed comprises of four subfunctions and five solution principles. A total of 5^4 (625) solution variants (concepts) are obtained. These are theoretical concepts because not all the solution principles within the chains of combinatorial solutions are feasible. For example, concept [A_3 B_2 C_1 D_1] is not feasible. This is because, A_3 has a 'screened' 'trash arresting area' while B_2 requires 'open' 'trash arresting area'. As such, under the physical parameter 'trash arresting area' A_3 and B_2 which are adjacent solution principles within the concept [A_3 B_2 C_1 D_1] have different unit values of physical parameter. With the use of the principle of 3D matrix-based solution screening, solution variants in which not all the adjacent solution principles are having compatible physical parameters are screened out. The 625 theoretical solution variants have been screened. A total of 114 feasible solutions are obtained.

It can be observed that many SVs can be obtained from the morphological matrix. Using the prevalent method of random selection of few SVs for evaluation and selection of preliminary design [13], the design space expansion which is the main advantage of using the morphological matrix is not exploited. By random selection of few concepts many feasible concepts are neglected.

Furthermore, it can be observed that using this approach, the designer has the freedom to suggest any kind of SPs while building the morphological matrix. The feasible concept generation process can screen out theoretical solution variants that contains SPs that are not matching. By so doing the quality of the design is improve based on quantity and variety [10].

In addition, the approach is capable of automatic screening of the SVs that are formed out of any morphological matrix. It is an improvement on existing morphological matrix-based automated conceptual design [11][14]. The process is based on logical relations that are matrix based and are solved using MATLAB. This adequately solves the problem of inexhaustive exploration of the morphological matrix design space as mentioned by Pahl et. al., [12]. Upon identification of PPs which has been shown through examples to be easy especially when the morphological matrix has been ordered and the functional synthesis has been properly done.

In addition, the results obtained from the multi-objective optimization-based concept selection indicates a blend of strengths and weaknesses of adjacent solution concepts. The total weight factor for the cost of a concept, is the sum of the weighted factors for the costs of each constituent solution principles that make the concept. The same is applicable to efficiency, manufacturability and repairability. For instance, the weighted factor for the efficiency of concept [A_1 B_1 C_1 D_2] is 0.625. This value is the sum of the units of efficiencies for the constituent SP. The weighted factors are 0.25, 0.15, 0.125 and 0.1 for A_1, B_1, C_1 and D_2 respectively. It could be observed that the efficiency of D_2 is very low. However, combinatorial effect enabled the summing up of the weighted factors to obtain high weighted factor for the concept.

Furthermore, with application of normalization equations (Eqn. 1 and 2), both variables that requires minimization (e.g., cost) and those that require maximization (e.g., efficiency) were combined. The result in Table 5 indicates that concept A_1 B_1 C_1 D_2 has the highest score among the optimum set of solutions. However, the concept is the strongest based on cost, repairability and manufacturability but weakest in efficiency. The combination of the variables in which it is strong and those in which it is weak give a total score that is greater than others.

3.8 Conclusion

The systematic approach to conceptual design developed in this work, enables designers of different level of experience, to participate effectively, in the design work. As demonstrated in the design of river cleaning machine, the approach permits random input of solution principles, into the morphological matrix. Then with the logical relation rendered by the PP based 3D matrix screening, solution matching is done, for eliciting feasible concepts. Furthermore, the optimization approach allows the selection of the optimum concept, based on both beneficial and non-beneficial evaluation variables.

Moreover, the approach enhances the process of concept generation, evaluation, and selection. It supports the implementation of a computer support tool for conceptual design generation. To achieve this, an interactive computer programme written in MATLAB was developed. This approach will further enhance conceptual design process for all categories of designers. Furthermore, the work could be enhanced, by incorporating a means of evaluating the solution principles based on their features. As such, by sketching the solution principles in the CAD environment, performance values for each evaluation variables, could be elicited. This is the next line of work from here.

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Nomenclature

SP	solution principle
SV	solution variant
PP	physical parameter
EV	evaluation variable

References

1) Y. L. Huo, X. B. Hu, B. Y. Chen, and R. G. Fan, "A product conceptual design method based on evolutionary game," *Machines*, **7** (1) 18 (2019). doi:10.3390/machines7010018.
2) B. He and S. Huang, "Functional synthesis of mechanisms under cost consideration," *J. Engineering Manuf.,* **230** (1) 91–99 (2014). doi:10.1177/0954405414542138.
3) H. Zhang, X. Han, R. Li, S. Qin, G. Ding, and K. Yan, "A new conceptual design method to support rapid and effective mapping from product design specification to concept design," *Int. J. Adv. Manuf. Technol.*, **87** 2375–2389 (2016). doi:10.1007/s00170-016-8576-6.
4) B. Helms and K. Shea, "Computational synthesis of product architectures based on object-oriented graph grammars," *J. Mech. Des. Trans. ASME*, **134** (2) 1-14 (2012). doi:10.1115/1.4005592.
5) D. G. Ullman, *The Mechanical Design Process*, 4th ed. New York: McGrawHill, (2010). doi:10.1017/CBO9781107415324.004.
6) Y. Chen, P. Feng, B. He, Z. Lin, and Y. Xie, "Automated conceptual design of mechanisms using improved morphological matrix," *J. Mech. Des. Trans. ASME*, **128** (3) 516–526 (2006). doi:10.1115/1.2180807.
7) A. Chawla and J. D. Summers, "Function ordering within morphological charts: an experimental study," *Proceedings of the ASME 2018 Int. Des. Eng. Tech. Conf. Comp. Info. Eng. Conf. IDETC/CIE* 2018 August 26-29, 2018, Quebec City, Quebec, Canada, **7** 1–12 (2018). doi:10.1115/DETC2018-86184.
8) A. Chakrabarti and T. P. Bligh, "An approach to functional synthesis of solutions in mechanical conceptual design. Part II: kind synthesis*," Res. Eng. Des. - Theory, Appl. Concurr. Eng.,* **8** (1) 52–62 (1996). doi.:10.1007/BF01616556.
9) S. Pugh, *Total Design: Integrated Methods for Successful Product Engineering*, First. England: Addison-westley Publishing Company Inc, (1991).
10) W. Sluis-thiescheffer, T. Bekker, B. Eggen, A. Vermeeren, and H. De Ridder, "Measuring and comparing novelty for design solutions generated by young children through different design methods," *Des. Stud.*, 43 (2006) 48–73, (2016). doi:10.1016/j.destud.2016.01.001
11) J. Ölvander, B. Lundén, and H. Gavel, "A computerized optimization framework for the morphological matrix applied to aircraft conceptual design," *Comput. Des.*, 41 (3) 187–196 (2009). doi:10.1016/j.cad.2008.06.005
12) G. Pahl, W. Beitz, J. Feldhusen, and K. H. Grote, *Engineering design: A systematic approach*, 3rd English Edition. London: Springer-velarg London Limited, (2007).
13) N. Angie, B. Paul, P. Nandy, M. Thierry, A. Nasruddin, L. Pascal, A. Idrus, E. Patrice, Y. Ardiyansyah, T. Anne-lise, "A Preliminary Conceptual Design Approach of Food Waste Composter Design," Evergreen, 8 (2) (2021).
14) C. R. B. Arnold, R. B. Stone, and D. A. Mcadams,

"MEMIC : An Interactive Morphological Matrix Tool for Automated Concept Generation," *Proceedings of the 2008 Industrial Engineering Research Conference J. Fowler and S. Mason, eds* 01/01/2008, (2008).
15) Y. Kang and D. Tang, "Matrix-based computational conceptual design with ant colony optimisation," *J. Eng. Des*., **24** (6) 429–452 (2013). doi: /10.1080/09544828.2012.756461.
16) A. Chakrabarti and T. P. Bligh, "A scheme for functional reasoning in conceptual design," *Des. Stud.*, **22** (6) 493–517 (2001). doi:10.1016/S0142-694X(01)00008-4.
17) B. He, W. Song, and Y. Wang, "Computational conceptual design using space matrix," *J. Comput. Inf. Sci. Eng.*, 15 (1) 1–7 (2015). doi:10.1115/1.4029062
18) N. Rashid, M. Nuri, K. Hudha, and S. A. Mazlan, "Design and Simulation of a New Single Actuator Double Acting Electro-Mechanical Continuously Variable Transmission," *Int. J. Mech. Eng. Robot. Res.*, 8 (1) 114–120 (2019). doi:10.18178/ijmerr.8.1.114-120
19) G. A. L. Barboza, A. D. Vethaak, B. R. B. O. Lavorante, A. Lundebye, and L. Guilhermino, "Marine microplastic debris: An emerging issue for food security , food safety and human health," *Mar. Pollut. Bull.*, **133** 336–348 (2018). doi:10.1016/j.marpolbul.2018.05.047.
20) B. Paul, P. Nandy, M. Thierry, A. Nasruddin, L. Pascal, A. Idrus, E. Patrice, Y. Ardiyansyah, T. Anne-lise., "Design of a Solar AC System Including a PCM Storage for Sustainable Resorts in Tropical Region Design of a Solar AC System Including a PCM Storage for Sustainable Resorts in Tropical Region," *Evergreen*, **6** (2) 143–148 (2019). doi:10.5109/2321009.
21) A. Abel, D. S. Machado, S. Hempel, M. C. Rillig, W. Kloas, and C. Zarfl, "Microplastics as an emerging threat to terrestrial ecosystems," *Glob Change Biol* **24** (4) 1405-1416, (2017). doi.org/10.1111/gcb.14020.
22) M. N. Mohammed, S. Al-Zubaidi, S. H. Kamarul Bahrain, M. Zaenudin and M. I. Abdullah, "Design and development of river cleaning robot using IoT technology," *16th IEEE International Colloquium on Signal Processing & Its Applications (CSPA)* 28-29 Feb. 2020, Langkawi, Malaysia, 19533887 84–87 (2020). doi: 10.1109/CSPA48992.2020.9068718.
23) H. Ma, X. Chu, D. Xue, and D. Chen, "A systematic decision-making approach for product conceptual design based on fuzzy morphological matrix," *Expt. Sys. App*. **81** 444-456 (2017). doi: 10.1016/j.eswa.2017.03.074.
24) C. Renzi and F. Leali, "A Multicriteria Decision-Making Application to the Conceptual Design of Mechanical Components," *J. Multi-criteria Decis. Anal.*, **111** 87–111, (2016). doi:10.1002/mcda.1569.
25) M. Mathew and S. Sahu, "Comparison of new multi-criteria decision-making methods for material handling equipment selection*," Manag. Sci. Lett.*, **8** 139–150 (2018). doi:10.5267/j.msl.2018.1.0043.