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A Systematic 3D Matrix Screening Approach to Conceptual Design of River Cleaning Machine

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Abstract

In order to make conceptual design of river cleaning machine more efficient, a systematic approach which enables expansion of the design space is developed. The approach entails; functional decomposition, generation of alternative solution principles for each subfunction, formation of combinatorial solution chains, 3D space matrix-based concept screening and multi-objective concept optimisation. 625 theoretical concepts are obtained from the morphological matrices. 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. This approach is capable of yielding high novelty at minimum time while large number of concepts are developed.

Keywords: Feasible Concept, Solution Principle, Solution Variant, Physical Parameter, River Cleaning Machine

Introduction

The growth in population has a huge impact on waste generation. These wastes are at times deposited into rivers (Guerranti et al., 2017). Nonetheless, at times, such trashes migrate from land (Abel et al., 2017) through freshwater bodies, to other bigger water bodies. This results in pollution of water bodies. Many rivers in Malaysia in 2017, were categorised as dead rivers, due to high concentration of debris in them (Mohammed et al., 2020). Marine litter emanate from sources like; sediments from the beach and neighbouring environment, thrown off packages and the like. Plastic material is one of the most lethal materials, to both terrestrial and aquatic habitat. Close to a half billion tons of plastic, are produced annually. While some of the plastics are recycled after use, many are thrown off as trashes. Such trashes litter not only the land, but also the water bodies (Lebreton et al., 2018). Even those plastics that are classified as biodegradable, still undergo disintegration, and form microplastics mostly about 5mm in size (Abel et al., 2017). Besides, during the transport process, the debris wear off and become micro particles that are harmful to the aquatic habitat (Wan et al., 2019). Microplastic pollution is lethal to both terrestrial and aquatic ecosystem (Abel et al., 2017; Guerranti et al., 2017). Many of the marine organism absorb it via direct injection or absorption alongside a prey (Barboza et al., 2018).

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(Wagh & Munde, 2018; Bauer-civiello et al., 2019). In hydro electricity generating plants, there is need to ensure that, the water that enters the turbine is particles free. While smaller particles cause increase of load on the turbine vanes, larger materials may block the inflow of water, thereby reducing the efficiency of the system (Wagh & Munde, 2018). The Malaysian government came up with River of Life (RoL) project to enhance the economic values of the Klang River by cleaning the connected rivers, making master plans and beautifying them. Several devices were procured to ensure that, the rivers in the RoL region are clean (Wagh & Munde, 2018).

Many efforts were made to design devices for ridding streams of anthropogenic debris or trapping them,

from entering into places, where they could harm life or facilities. Kandare *et al.* (2018) developed a river cleaning machining in which trashes are collected in an open bracket and transferred to the storing box via an inclined cleated conveyor and flat conveyor. Their concept is simple and efficient; however, machine needs to be moved all-round the stream to collect the trashes. Besides, Wagh and Munde (2018) developed a trash trap, for preventing debris from entering into a hydro-power generating plant. In their design, trapping basket and rack are used to hold the trash against entering into the plant. Another design of river cleaning machine, is that of Sayyad *et al.* (2019). They used a screened box as the storing box, and double cleated conveyor for transferring from the trash collection area. Moreover, Pawar *et al.* (2019) developed a river cleaning machine in which transfer of trash is via belt conveyor. The device is fitted with a remote-control system. In another design, electrical power used for trash conveyance is via solar 12. Furthermore, Mohammed *et al.* (2020)(Mohammed et al., 2020) 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. Unlike the design of (Sayyad et al., 2019), in which the storage box is a screen, their storage box is a solid box.

Conceptual design has been accorded the most significant stage in the design process (Woldemichael & Hashim, 2009). In fact, 70% of the life cycle cost of products, is influenced by the conceptual design stage(Huo et al., 2019) (Zhou et al., 2019). Furthermore, conceptual design affects the impact of the product on the environment(Fitzgerald et al., 2010). For these reasons, sixty to seventy percent of the design cost, is often expended at the conceptual design stage (He & Huang, 2014; Fitzgerald et al., 2010; Uddin et al., 2014). Conceptual design process, can be considered as the transformation of design specification(Zhang et al., 2016) - which is given as requirements list-(Pugh, 1991) into one or more concepts, that can satisfy these requirements(Garbatov et al., 2018) for further development(Lønmo, 2014). During the conceptual design phase, design problems are formulated(Lønmo, 2014), possible solutions to the problems are generated (Chakrabarti & Bligh, 2001), then the seemingly best solution is selected (Lønmo, 2014) after evaluating the various solutions variants (SV) (Pahl et al., 2007).

This work entails decomposing the functional requirements of a river trash removal

machine. Thereafter, solutions to each subfunctions (solution principles) are proposed, and arranged in line with the respective subfunction, in a morphological matrix. From a morphological matrix, several concepts can be generated, by combining the solution principles (SP) in a chain of one SP from each row of the morphological matrix. Such concepts are called combinatorial solution or solution variants (SV). The SV are screened, evaluated and optimized, based on a framework developed, to select the optimum concept.

LITERATURE REVIEW

The growth in population has a huge impact on waste generation. These wastes are at times deposited into rivers (Guerranti et al., 2017). Nonetheless, at times, such trashes migrate from land (Abel et al., 2017) through freshwater bodies, to other bigger water bodies. This results in pollution of water bodies. Many rivers in Malaysia in 2017, were categorised as dead rivers, due to high concentration of debris in them (Mohammed et al., 2020). Marine litter emanates from sources like; sediments from the beach and neighboring environment, thrown off packages and the like.

Plastic material is one of the most lethal materials, to both terrestrial and aquatic habitats. Close to a half billion tons of plastic, are produced annually. While some of the plastics are recycled after use, many are thrown off as trashes. Such trashes litter not only the land, but also the water bodies (Lebreton et al., 2018). Even those plastics that are classified as biodegradable, still undergo disintegration, and form microplastics mostly about 5mm in size (Abel et al., 2017). Besides, during the transport process, the debris wear off and become micro particles that are harmful to the aquatic habitat (Abel et al., 2017). Microplastic pollution is lethal to both terrestrial and aquatic ecosystem (Abel et al., 2017; Guerranti et al., 2017). Besides, organic wastes though are biodegradable, can lead to emission of toxic gasses (Syafrudin et al., 2021). Many of the marine organism absorb all the harmful products via direct injection or absorption alongside a prey (Lebreton et al., 2018). Most of the conceptual design of river cleaning machine entail four functional units. The functional units are trash arresting unit, trash transfer unit, trash storage unit, and the securing element. (Wagh and Munde, 2018; Pawar et al. 2019).

METHODOLOGY

Since the focus of the approach is morphological-based, the process begins with function decomposition, then generation of alternative SP. The established subfunctions and SP are used to compose morphological matrix. Physical parameters are allocated to each SP. Then, the SV are screened by comparing the physical parameter (PP) of adjacent SP in a combinatorial solution chain. SV that are composed of compatible SP are feasible concepts, while those that have incompatible concepts 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 SP for each subfunction, and PP and evaluation variables (EV) 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(Bin et al., 2010). 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 river bank. All these are subfunctions. Subfunctions are labeled as F_1, F_2…..F_n, where n is the number of subfunction in a functional model.

Furthermore, alternative solution principles (SP) are generated for each subfunction(Chakrabarti & Bligh, 1996). The designer is free to include any possible SP for each subfunction. This approach enables designers at all level of design experience to participate in conceptual design. At this stage, less emphasis is placed on the compatibility of the SP with other SP.

The next stage is the development of a morphological matrix. It comprises of an arrangement of subfunctions and their respective SP in a matrix form (Zwicky, 1967). The alterative SP can be represent using drawings or writings (Ullman, 2010). In the morphological matrix in Table 1, F_1 to F_r represent the subfunctions, while their respective SP are represented as A_1 to A_s, B_1 to B_s and so on.

Theoretical concepts or combinatorial solution or solution variants (SV) are thereafter formulated, from the morphological matrix (Chawla & Summers, 2018).

SV is a chain of SP, that comprises of one SP, from each row of a morphological matrix (Sarkar et al., 2015). For instance, (A_1, B_2, C_3,…Z_2) is a combinatorial chain elicited from Table 1. Several combinatorial chain can be formed from a morphological matrix. Theoretically, A total of ($M_1 \times M_2 \times M_3$ …. $\times M_n$) SV can be generated from a morphological matrix (Pahl et al., 2007), where n and M represent the number of subfunction in the matrix and the number of SP for each subfunction respectively. For instance, the morphological matrix of the river cleaning machine in Fig. 2 will produce a total of 5×5×5×5 (625) SV. All the SV 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 possible SV, that can be generated for the morphological matrix is less. Not all SP of a subfunction, can match with SP of an adjacent subfunction. For the SP to be compatible they must have similarities in some characteristics. Such characteristics are termed physical parameters (PP).

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

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

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

are carried out on the feasible concepts.

Furthermore, four evaluation variables (EV) are considered for this work. They are; efficiency, manufacturability, repairability and cost. Efficiency is dependent on function while manufacturability, repairability and cost depend on unique properties of the SP. Each of the EV is assigned a weight factor. Depending on the importance attached to each. For this work, all the four EV are of equal weight. Therefore, their weight factor is 0.25 each. Sum of all weight factors must be 1 (Mathew & Sahu, 2018). Performance values are allocated to each SP, and subsequently weighted factors are determined for each, by multiplying their performance value, to the weighted factor of each EV.

The weighted factors for each SP are normalized. Among the EV, efficiency, manufacturability and repairability are beneficial (higher values are desirable), while cost is non-beneficial (lower value is desirable) therefore, the factors are normalized using Eq. 2 for beneficial factors but Eq. 1 for non-beneficial factors. Normalising the EV enables the use of a single objective function for the multivariable optimisation model.

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

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

The weight of the EV of all the SP in an SV are summed up to obtain the weight of each concept. The G-matrix is labelled G_e, G_m, G_r and G_c for efficiency, manufacturability, repairability ang cost respectively, of the concepts. The optimum concept is then determined. The optimisation model is indicated in Eq. 3. In the model, the constraint is based on the weighted factor of a benchmark. 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. The design process is implemented in MATLAB environment.

The input variables for the programme are; the number of subfunctions, the number

of alternative SP for each subfunction, the set of PP for each of the SP, and the weighted factor for the EV of each SP.

Maximise:

$$\mathrm{F}(G_{ij}) = G_e(i,j) + G_m(i,j) + G_r(i,j) + G_c(i,j) \quad (3a)$$

Subject to:

$$H(G_e) > a;\ H(G_m) > b;\ H(G_r) > c;$$
$$H(G_c) > d;\ H(G_{ij}) > 0; \quad (3b)$$

RESULTS

This section entails, the detail of the conceptual design procedure, for river cleaning machine, based on the framework developed for this work. The results obtained are equally illustrated and discuss therein.

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. 1. 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. 1, 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.

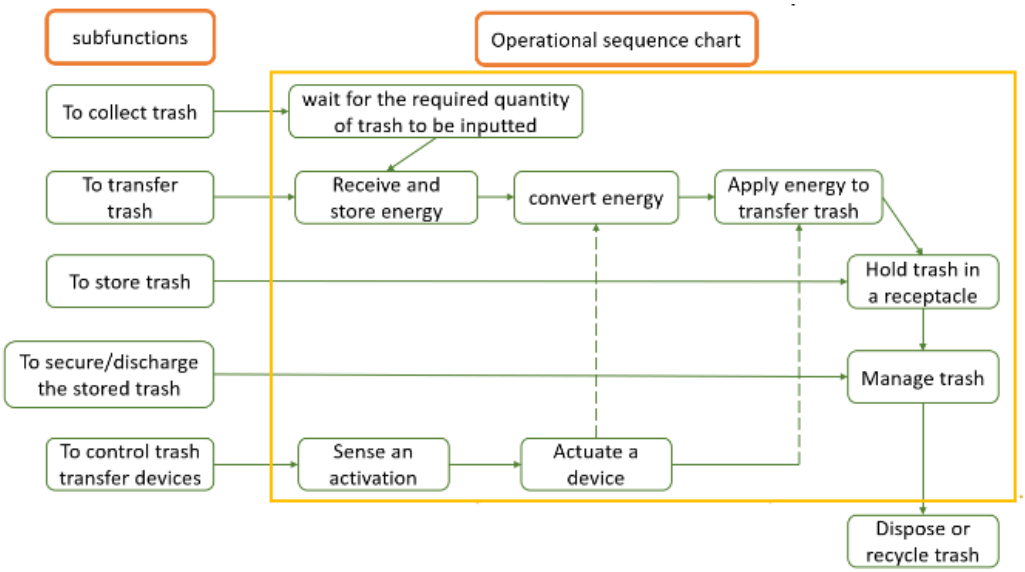


Fig. 1: The function decomposition of a river cleaning machine via operational sequence (Balogun et al., 2022)(Balogun et al., 2022)

Generation of Solution Principles (SP)

Five alternative SP are found for the first subfunction (i.e. 'to collect trash'). The five SP that can perform the first subfunction are described, in terms of their structures in first row of Fig. 2. 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 A1. For the rest of the subfunctions, the solution principles are equally generated in the same manner. The SP 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.

Morphological Matrix development

The morphological matrix developed, for the river cleaning machine, is as shown in Fig. 2. The SP for each subfunction are in the same row with it.

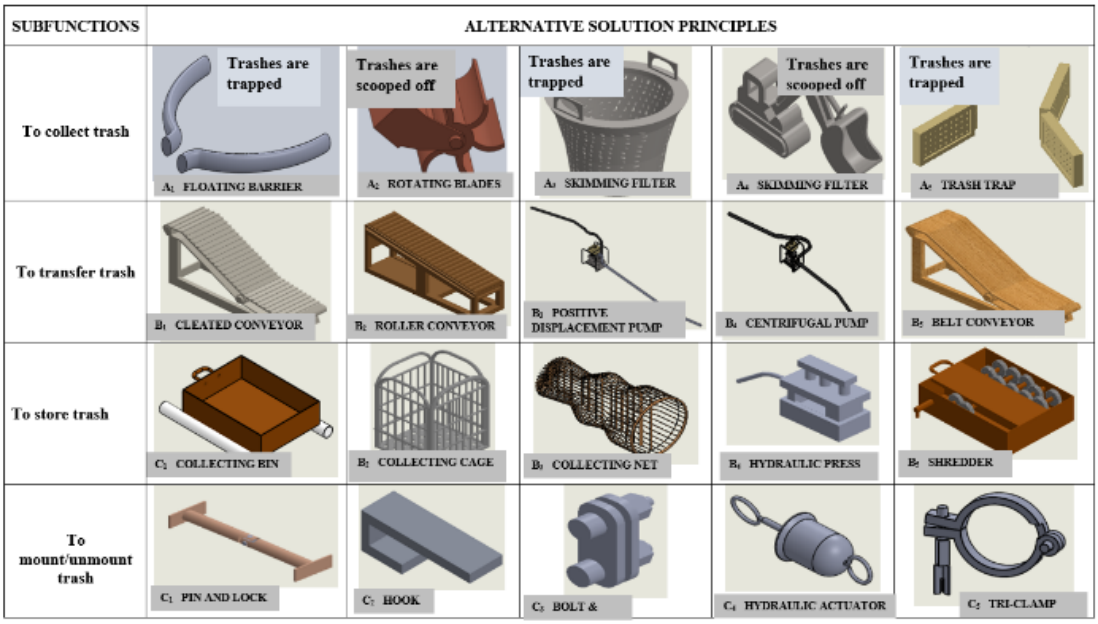


Fig. 2: Morphological matrix for conceptual design of river cleaning machine

Creating Physical Parameters Matrix

As indicated in Table 2, three PP are derived from Figure 2. The first PP is derived from the set of SP 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 1, 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 3, 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 2: 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 3: Generating physical parameters vectors for solution principles of river cleaning machine

Functions	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]

Determination of weight factors for solution principles

Performance values are determined for each of the SP. The performance values for the SP of the river cleaning machine are shown in Table 4. Four EV are chosen which are; efficiency, manufacturability, repairability and cost. 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 solution-based EC

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

3D space matrix-based solution screening

As shown in Fig. 3, 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. 3a, 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 from the G-Matrix to

demonstrate the procedure. As shown in Fig. 3a, 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 PP1 of B1 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 PP, for each of the SV. SV 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.

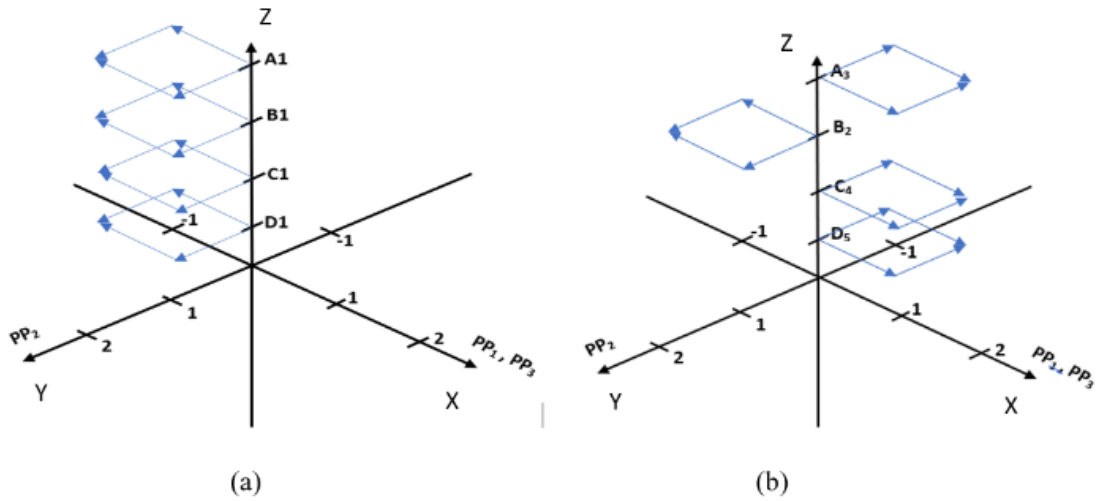


Fig. 3: 3D Matrix-based solution matching.
(a) matching solutions
(b) unmatching solutions.

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 programmes, 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 concept having the highest score [A_1 B_1 C_1 D_2] among the set of optimum concepts, is indicated by a path in the morphological matrix as shown in Fig. 4. 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.

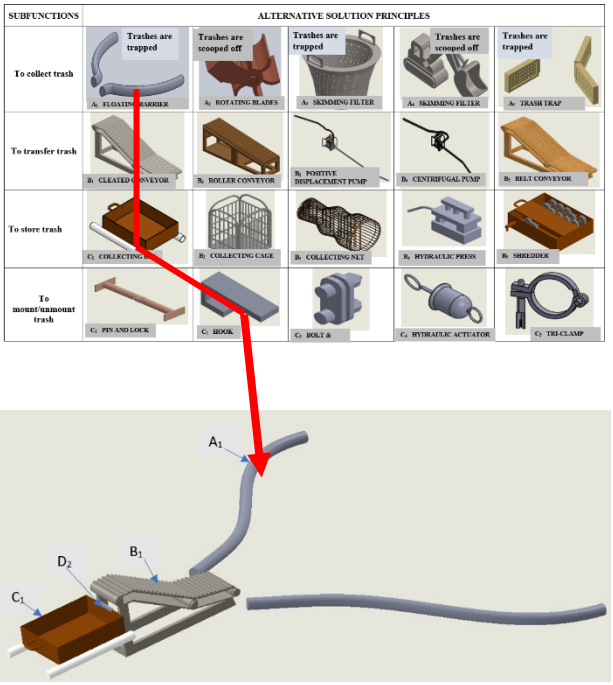


Fig. 4: Solution Chains of the Optimum SVs

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

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