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Conceptual Design of Continuously Variable Transmission System Using Morphological Matrix-based Tool

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Key words: Continuously Variable Transmission, Conceptual Design, Solution Principles, Solution variant, Morphological Matrix

Abstract

Morphological matrix-based concept generation is known for high novelty, quality, quantity, and variety. However, many of the solution variants (SVs) that are extract-ed from it, contain solution principles (SPs) that are practically incompatibles. A computer based conceptual design tool that is based on morphological matrix is used to generate, evaluate and select concept for the design of continuously variable transmission (CVT) system. The results showed that, morphological matrix of CVT contain 1000 theoretical SVs. Upon screening, 37 feasible concepts with 1 optimum SV were obtained. This research validates the development of a computer-based supporting tool, to automate conceptual design synthesis, which can accept randomly proposed SPs therefore, enhancing the conceptual design capabilities, independent of the designers' experience.

Introduction:

Conceptual design is a phase in product life cycle, where emphasis is on transformation of the function that an artefact is expected to perform, into forms that can fulfil such functions (Helms and Shea 2012). Three main tasks that are involved in conceptual design are concept generation, concept evaluation and concept selection (Pugh 1991). Of the many known methods of concept generation (Hernandez, Schmidt, and Okudan, 2013; Fu et al., 2015; Fu et al., 2015; Daly et al., 2016; Narsale et al., 2019), the morphological matrix meth-od (Pahl et al. 2007) is one of the most effective, when novelty is the focus. This is because, it enables exhaustive generation of large number concepts (Chawla and Summers 2018; Duran-Novoa et al. 2019). As claimed by Ullman (2010), the more the number of feasible concepts generated in a design, the more the chances to develop a good concept.

Furthermore, morphological matrix based conceptual design, entails decomposition of the main function, to obtain the simplest form of the functional element (Yuan et al., 2017; Sallaou and Fadel, 2018; Fiorineschi, Frillici, and Rotini, 2018), for which design concepts can easily be generated (Chakrabarti and Bligh, 2001; Chen et al., 2006; Kang and Tang, 2013;). Such generated design concepts are termed solution principles (Weiss and Gilboa, 2004; Pahl et al., 2007). Solution principles are arranged in rows against the respective sub-functions, in the morphological matrix (Pahl et al. 2007). From the morphological matrix, combinatorial chains of solution principles are made across the rows. In doing so, one solution principle is chosen from each row, to form each combinatorial chain of solution principles called solution variant (Pahl et al., 2007; Ölvander et al., 2009). Such solution variants are the generated concepts.

On the other hand, despite the of Pure electric vehicles (PEVs) have longstanding benefits to customers and environment, yet the initial cost is high and driving range per charge is unsatisfactory. These present significant barricades for its commercialization at large-scale.

Attainment of sustainable and reliable specific energy via battery technology is still at crawling state. Improvement of the powertrain efficiency is therefore eminent in order to sustain the adoption of electric vehicles.

The ideas of implementing various multi-speed transmissions to PEV to lift the average working efficiency of motor and improve the driving capability have been proposed by academic and industry in recent years. A redesigned two-speed automatic transmission was A continuously variable transmission (CVT) is a mechanical transmission, with a variable output speed and a continuous speed ratio. The term infinitely variable transmission (IVT) or CVT system refers to transmission systems with infinite values of velocity ratios (VRs) with a predesigned range of values (Rashid et al. 2019). It provides smooth and continuous variable output power to increase the convenience of mechanical operations and improve mechanical efficiency (Wu et al., 2018).

CVT has several advantages like absence of shock due to gear shift which enables smooth acceleration and comparatively good fuel efficiency compared to all step variable transmission systems (SVTS) (Mayet et al. 2019). Nonetheless, it has disadvantages like low mechanical efficiency when compared to all SVTS (Mayet et al. 2019) and high-cost com-pared to manual transmission. as such researchers have of resent shown interest in its improvement (Verbelen et al. 2017).

LITERATURE REVIEW

The most essential element of a CVT that mainly differentiate it from an automatic step transmission (AMT) is the variator. Several designs of variators have evolved over time (Ruan et al., 2018). The most importance function of the variator, is to vary the output torque to sooth the requirement of the driveline. The change of VR is prompted by a system that continuously varies the effective diameters of the transmitting elements (Wu *et al.*, 2018). Theoretically, such a transmission, enables better operation from the points of the thermal engine. Therefore it enables a reduction of fuel consumption and emissions (Shreyas et al., 2018). However, the efficiency of the conventional (hydraulic actuated) CVT during quasi-stationary operation is typically lower than the efficiency of a classical discrete gearbox, which leads to higher fuel consumption (Mayet et al., 2019). Many designs of CVT are available. The most common of all is the belt and split pulley variator type (Linares et al., 2010). Other types are the cone (Li & Song, 2013) type and the toroidal type (Verbelen et al., 2020).

The most common of them is the split pulley in which either one or both halves are moveable (Setlur et al., 2003). As the half cone of the pulley moves, the effective diameter form by the belt on the pulley changes, causing a change in velocity ratio. Other designs have two conical pulleys that are linked to each other via a belt, chain, or ring. In this design changing the VR is effected by moving the belt, chain or ring along the length of the cones (Bell et al., 2011). Furthermore, Rashid et al. (2019) developed a single actuator dual acting CVT, using an electro-mechanical system. Increasing the range of the effective diameter of the variator pulley, in other to increase the VR range. They asserted that the range of VR in existing designs is 0.38 to 2.64. Their design was able to generate a higher range of 0.3 to 3.0. However, the process of conceptual design adopted was not elaborate enough to give room for more concepts that could be reasoned on, to elicit the best solution. **Error! Reference source not found.**1 shows some of the various mechanisms for CVT. The major dividing line among the concepts are:

The variating element: from **Error! Reference source not found.**1, in A the variating element is a flexible element (i.e., belt or chain) which is moved along the surface of the pulleys to create different VRs. In B the variating element is the movable half pulleys which are moved in or out to change the pitch diameter thereby changing the VR. In C and D, the variating elements are the cylindrical and spherical discs respectively which are oscillated in-between the toroid to create VRs.

Transmission element: from **Error! Reference source not found.**1, in A the transmission element is a short flexible element (i.e., belt or chain) which transmit motion between the two pulleys. In B the transmission element is a long flexible element (i.e., belt or chain) which transmit motion between the two pulleys. In C and D, the variating elements are the cylindrical and spherical discs respectively which rotate in between the toroid to transmit motion.

The type of element on the input and output shaft: from **Error! Reference source not found.**, the elements on the input/output shafts are pulley, split pulley and toroid for A, B and C and D respectively.

Relationship between input and output shaft: from **Error! Reference source not found.**, in A and B the input and output shaft are parallel to each other. In C the shafts are in-line with each other, while in D, the shafts are perpendicular to each other.

Motion of the variating element: in A and B the variating elements reciprocate, while they oscillate in C and D.

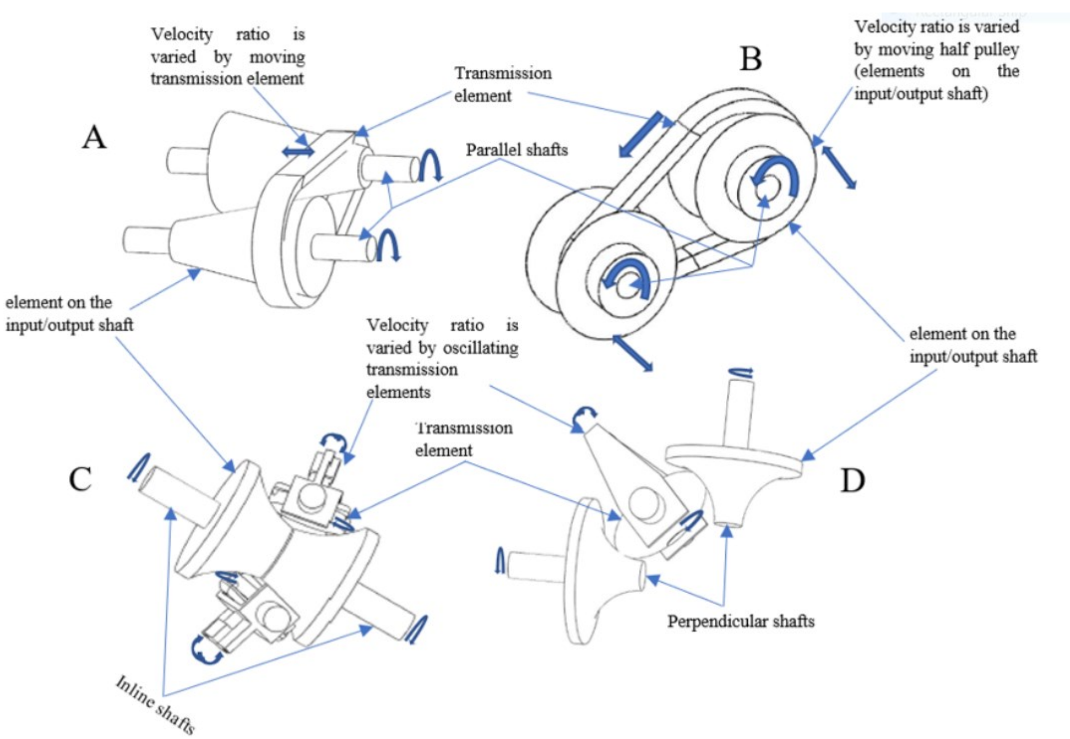

Figure 1 Continuously Variable Transmission (CVT) Systems (a) Push Belt (b) Split Pulley (c) Double Cylindrical Toroid (d) Spherical Toroid (Balogun et al., 2022)

METHODOLOGY

The methos materials and Equipment used in this study are explained in the following subheading. The subheadings are chronologically arranged in the order of the work that the study entail. It starts from the framework upon which the design is based and explains the application of the framework in the conceptual design of CVT.

MORPHOLOGICAL MATRIX-BASED FRAMEWORK FOR CONCEPTUAL DESIGN

The framework developed in a previous work for conceptual design, is indicated in Figure 2. The approach in the framework is a morphological matrix-based conceptual design process. Morphological matrix comprises of decomposed functions (sub-functions) and their respective SPs, arranged in rows to form a matrix. In this work many matrices are developed out of the morphological matrix. The principal Morphological matrix, which contains functions and SPs, is termed sub-function/SPs matrix. The term solution principle (SP) has been used by many scholars, to refer to the solutions to the problem posed by each sub-function (Pahl et al. 2007; Chakrabarti et al. 2011). SP can either be physical effects (He, Song, and Wang 2015) or structures (Angie et al. 2021). In this work the term SP is used for structures. Besides, the conceptual design of river cleaning machine is used as example throughout this chapter, to enable easy comprehension of the framework. Furthermore, other matrices that are elicited from the morphological matrix are: the compatibility determinant (CD) matrices and the SPs weighted factors matrices. CDs are factors that differentiate one SP from the others. In this study, they are used to determine compatibility of adjacent SPs in a solution variant. With the determination of the CDs, such structures that are not connectible are screened out. In addition, matrices for the weighted factors of each SP, for each evaluation variables (EVs), are elicited from the morphological matrix. In this work, four EV were considered. As such, four weighted factors matrices are produced. Each of the matrices of the weighted factor, contains elements, that are the weighted factors of the SPs, for the respective EVs.

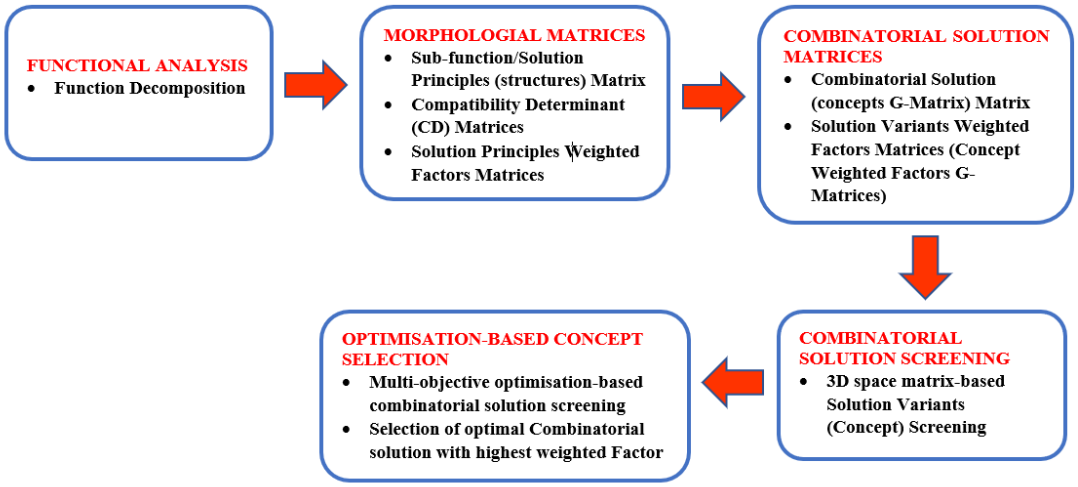

Figure 2 Framework for Morphological Matrix-Based Conceptual Design (Balogun et al., 2023)

The framework is discussed extensively in previous works (Balogun et al., 2023). It includes functional analysis and morphological matrix synthesis. This entails development of morphological matrix and eliciting solution variants out of it. Furthermore, relationship is established between the formation of the solution variants and the solution principles that are contained in them (Balogun et al., 2022). Attainment of this indicates the fulfilment of the first objective of this research work.

Moreover, for the purpose of screening the solution variants to fish out the feasible solution variants, the compatibility of the solution principles that are contained in them are tested. To enable such test, a method for determining the compatibility of adjacent solution principles in a solution variant is established. In addition, the evaluation is based on categorisation of the evaluation criteria, which are de-noted as evaluation variables in this work. The evaluation variables are categorised as beneficial and non-beneficial. Beneficial variables are those whose higher values are desirable. Examples of beneficial variables are efficiency, manufacturability, accuracy, safety etc. all these are often desired to be high. Conversely, non-beneficial variables are those whose lower values are desirable. Examples of non-beneficial variables are cost, material consumption, level of maintenance etc. All these are often desired to be low. This addresses the third objective of the research. Additionally, the framework entails the development of model for determining optimum solution variant based on multiple evaluation criteria. This makes it a multi-objective optimisation problem. With this aspect of the framework, the third objective is attained. Furthermore, the computer programme developed is meant to aid the implementation of the framework. The programme also serves as a supporting tool for morphological matrix based conceptual design. The programme is built based on the framework and the relations that are contained in it.

MORPHOLOGICAL MATRIX-BASED CONCEPTUAL DESIGN OF CVT

Meanwhile, the conceptual design of CVT using the framework developed in this study is fully discussed here. Continuously variable transmission (CVT) is a transmission system used in automobile and other applications, for enabling transmission of engine torque to the drive line, at infinitely variable velocity ratio. The main difference between an automatic step transmission system and a CVT system, is the use of variator in CTV, in place of the step gears in the automatic step transmission system. Therefore, the conceptual design of CVT focuses on the design of variators. The conceptual design of CVT was done following the procedure laid down in this work. All the required data was obtained and inputted into the programme. The results obtained formed basis for discussion and validation of the framework and the computer supporting tool developed.

FUNCTIONAL SYNTHESIS AND GENERATION OF SOLUTION PRINCIPLES FOR CVT

The main function of CVT is 'to transmit engine torque to the drive line at infinitely variable speed, based on the required driveline torque'. The main function was decomposed to four sub-functions as indicated in Figure 3. Furthermore, SPs were generated for each of the sub-functions. Thereafter, morphological matrix was composed as shown in Figure 3, to indicate the sub-functions and their respective SPs.

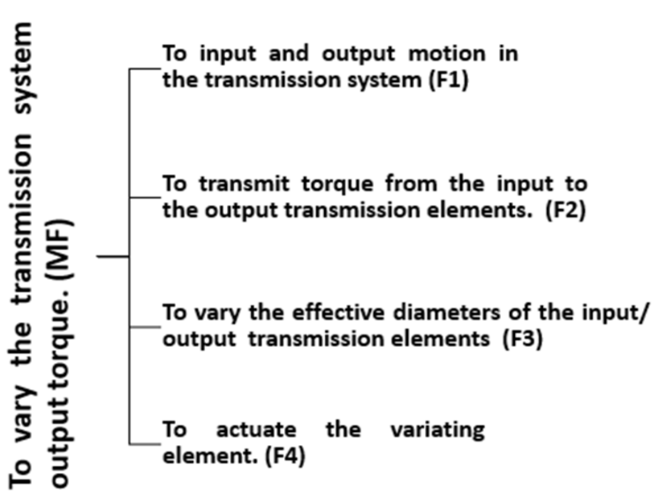

Figure 3 Functional Decomposition for CVT

The first sub-functions F_1 'to input and output motion in the transmission system', implies the functional requirement of the CVT system, to receive input torque from the engine, and release-controlled torque to the driveline. As shown on the morphological matrix in Figure 4.4, five components were identified that can perform this function. The five components which are the SPs for F_1 are represented as S_{11}, S_{12}, S_{13}, S_{14} and S_{15} in Table 1. Equally, the second sub-function (F_2) 'to transmit torque from the input to the output elements' represents the requirements for connecting the transmission element on the input shaft to the transmission element on the output shaft. Eight components are identified for F_2 which are the SPs for it. The proposed SPs for F_2 are represented as S_{21}, S_{22}, S_{23}, S_{24}, S_{25} S_{26}, S_{27} and S_{28} as shown in Table 1.

Similarly, F_3, 'to vary the effective diameters of the input or output transmission elements' implies altering the pitch diameters of the transmission elements. Generally, the velocity ratio of any transmission systems is changed when the pitch diameter of the input or output element is altered. Five variating elements for F_3 and their motions, are indicated in Figure 4.. The SPs for F_3 are represented by S_{31}, S_{32}, S_{33}, S_{34} and S_{35} as shown in **Error! Reference source not found.**. Correspondingly, F_4 'to actuate the variating element' stands for the functional requirement of the element that is used to achieve the variation of effective diameter. Five candidate SPs were also proposed for F_4. The SPs to F_4 are indicated with the respective components in Figure 4., and as S_{41}, S_{42}, S_{43}, S_{44} and S_{45} in**Error! Reference source not found.**.

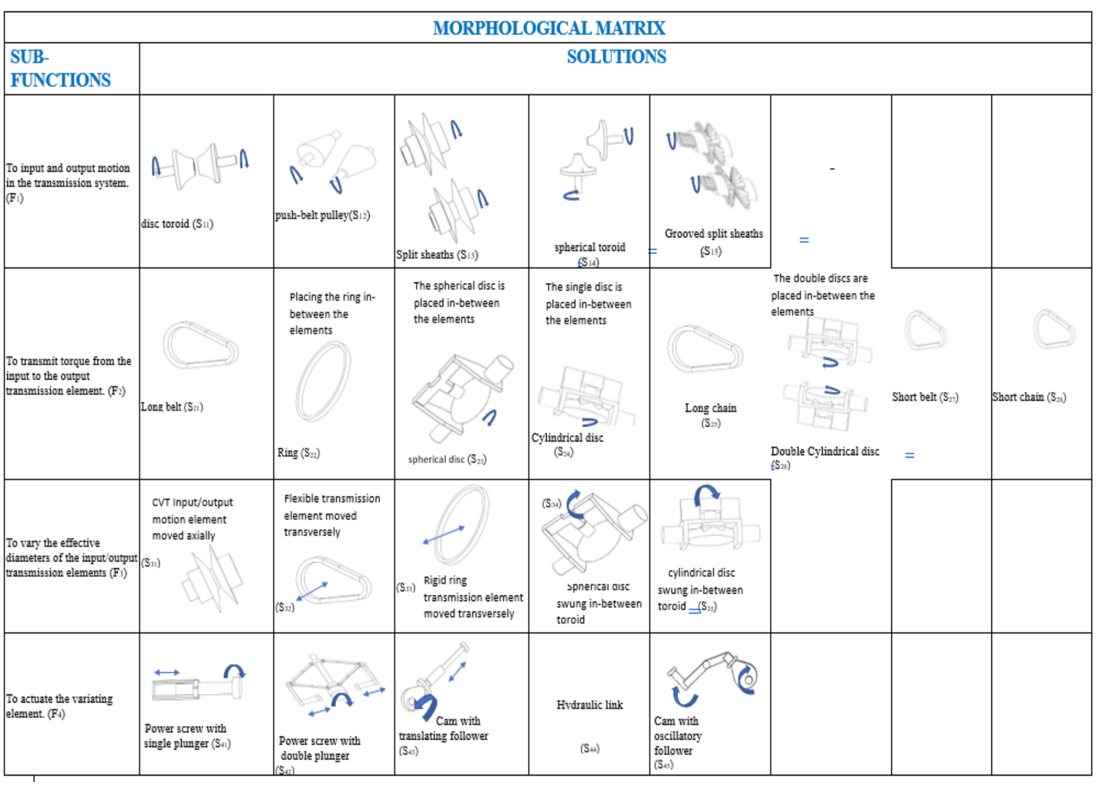

Figure 4. Morphological Matrix for Conceptual Design of CVT

Table 1 Representation of Morphological Matrix of CVT

Sub-functions	Solution Principles							
F_1	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	-	-	-
F_2	S_{21}	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}	S_{27}	S_{28}
F_3	S_{31}	S_{32}	S_{33}	S_{34}	S_{35}	-	-	-
F_4	S_{41}	S_{42}	S_{43}	S_{44}	S_{45}	-	-	-

DETERMINATION OF COMPATIBILITY DETERMINANT AND PERFORMANCE VALUES FOR CVT

Four CDs are identified, as shown in Table 2. Observing the SPs of F_1, it is noticed that the orientation of shafts of the elements that input/output motion is different. Based on this a CD is formulated, termed 'orientation of transmission shaft'. This is the first CD (CD_1). To CD_1 five elements are deduced. Some of the shafts are 'parallel with wide gap', some are 'parallel with narrow gap', some are 'in-line' while some are 'perpendicular'. The fifth element is the 'universal' element. Therefore, the five elements of CD_1 ('orientation of transmission shaft') are ['universal', 'parallel with wide gap', 'parallel with narrow gap', 'in-line', 'perpendicular'] respectively represented with units [0, 1, -1, 2, -2]. In the same vein, from the SPs of F_2, the transmission elements are noted to differ in their flexibility. Hence, the second CD (CD_2) is termed 'rigidity of linking element'. Three elements are deduced for CD_2 which are ['universal', 'rigid, flexible'] represented in units as [0, 1, -1] respectively.

Furthermore, the third CD (CD_3) is deduced from the SPs of F_3 as 'Rigidity of the variating element'. The elements deduced for CD_3 are respectively, ['universal', 'rigid', 'flexible'] represented in units as [0, 1, -1]. Lastly, the fourth CD (CD_4) is the motion type of the variating element. CD_4 equally has three elements which are ['universal', 'reciprocating', 'oscillating'] represented in units as [0, 1, -1] respectively. The various CDs and their elements are indicated in Table 2. The CDs are attached to each SP in the morphological matrix.

Table 2 Values for the Compatibility Determinant of CVT

Compatibility Determinant	Elements Representation and Units				
Orientation of transmission shaft	Universal (0)	Parallel with wide gab (1)	Parallel with narrow gab (-1)	In-line (2)	Perpendicular (-2)
Rigidity of linking element	Universal (0)	Rigid (1)	Flexible (-1)		

Rigidity of variating element	Universal (0)	Rigid (1)	Flexible (-1)
Motion type of variating element	Universal (0)	Reciprocating (1)	Oscillating (-1)

The numerical representation for the CDs of each SPs are shown in Figure5. The first matrix is that of CD_1 (Orientation of transmission shaft). S_{11}, S_{12}, S_{13}, S_{14} and S_{15} have 2, -1, 1, -2 and 1 respectively. It implies that the shafts of S_{11} are inline, those of S_{12} are parallel with narrow gap, those of S_{14}, are perpendicular to each other while those of S_{13} and S_{15} are parallel with wide gap. The empty cells in the first row are given the same CD numerical values. Their numerical values are higher than those of the establish CDs. This is to enable ease of manipulation of the matrices by the computer programme.

Furthermore, CD_1 for S_{21}, S_{22}, S_{23}, S_{24}, S_{25}, S_{26}, $S_{27}$and S_{28} are 1, -1, -2, 2, 1, 2, -1, -1 respectively. Since CD_1 was not derived from S_{21} to S_{28}, CD_1 is a required CD for them. SPs S_{21} and S_{25} only work with SPs S_{11} to S_{15} whose shafts are parallel with wide gap. Besides, S_{22}, S_{27}, and S_{28} can work with only SPs S_{11} to S_{15} whose shafts are parallel with narrow gap. Also, S_{23} can work with only SPs S_{11} to S_{15} whose shafts are perpendicular to each other. In the same vein, S_{24} and S_{26} can only work with SPs S_{11} to S_{15} whose shafts are inline to each other. The CDs of the remaining SPs were found in the same manner.

Another input to the supporting tool developed in this work is the performance value. Based on the framework proposed in this work, the SPs were first ranked on each EV. The four EVs are considered. Furthermore, the EVs are both function-based, and solution-based. Efficiency is a function-based EV, while manufacturability, repairability and cost are solution based. As shown in Table 3, ranking of the SP for efficiency is done among SPs for the same function. However, for manufacturability, repairability and cost the ranking is among all the SPs in the morphological matrix. For Efficiency, the SPs of sub-function F_1 are ranked as S_{15}, S_{11}, S_{14}, S_{13} and S_{12} for 1st, 2nd, 3rd, 4^{th,} and 5th respectively. Equally, S_{25}, S_{26}, S_{21}, S_{27}, S_{28}, S_{22}, S_{23} and S_{24} for 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, and 8th respectively. Conversely, the ranking of the SPs for Manufacturability is done among all the SP in the morphological matrix. There are 23 SP altogether in the morphological matrix. SPs S_{21}, S_{28}, S_{23}, S_{45}, S_{41}, S_{27}, …… S_{33}, S_{14}, and S_{31} are ranked as the 1st, 2nd, 3rd, 4th, 5th, 6th……21st, 22nd, and 23rd respectively. The ranks of each of the SPs for each EV are as shown in Table 3.

With the ranking, allocation of performance values to the SPs is enhanced. This is one of the merits of using the framework developed for this work. PVs are selected over a scale of 1 to 5. As show in Table 3, the PVs are allocated to each of the SPs for each EV. The performance values follow the same trend with the ranking. For the function-based EV, the SP with the highest rank is first given a PV. Then, the rest are given PVs in a chronological order. However, SPs of different ranks may have the same PVs. If the PVs of two SPs are within a close range, same PV may be allotted to them. That accounts for the reason why the PVs for Efficiency of the SPs for F_1 with ranks 2nd, 3rd and 4th are the same (i.e., 3). Similarly, performance values for manufacturability of S_{21}, S_{28}, S_{22}, S_{45} and S_{41} are the same (i.e., 5). They all fall under the category of 'extremely easy to manufacture'. Furthermore, S_{25} which has a rank of 7, is given 4 as PV. Therefore, S_{25} is 'very easy to manufacture'. Moreover, S_{13}, S_{12}, S_{42} and S_{43} which are the 8th, 9th, 10th, and 11th in rank respectively, have 3 as their PVs. This implies that they are 'easy to manufacture'. Furthermore, those with 2 as performance value are considered as 'manufacturable', while those with 1 as PV are 'difficult to manufacture'. The performance values of each SP were formed into matrices representing the PVs of the SPs for each EV. Figure 6 represents the PVs matrices for efficiency, manufacturability, repairability and cost of the SPs for RCM.

$$CD_1 = \begin{bmatrix} 2 & -1 & 1 & -2 & 1 & 3 & 3 & 3 \\ 1 & -1 & -2 & 2 & 1 & 2 & -1 & -1 \\ 1 & -1 & -1 & -2 & 2 & 4 & 4 & 4 \\ 0 & 0 & 0 & 0 & 0 & 5 & 5 & 5 \end{bmatrix}$$

$$CD_2 = \begin{bmatrix} 1 & 0 & -1 & 1 & -1 & 3 & 3 & 3 \\ -1 & 1 & 1 & 1 & -1 & 1 & -1 & -1 \\ -1 & -1 & 1 & 1 & 1 & 4 & 4 & 4 \\ 0 & -1 & 0 & 0 & 0 & 5 & 5 & 5 \end{bmatrix}$$

$$CD_3 = \begin{bmatrix} 1 & 0 & 1 & 1 & 1 & 3 & 3 & 3 \\ 0 & 1 & 1 & 1 & 0 & 1 & -1 & -1 \\ 1 & -1 & 1 & 1 & 1 & 4 & 4 & 4 \\ 0 & 1 & 0 & 0 & 1 & 5 & 5 & 5 \end{bmatrix}$$

$$CD_4 = \begin{bmatrix} -1 & 1 & 1 & -1 & 1 & 3 & 3 & 3 \\ -1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & 1 & 1 & -1 & -1 & 4 & 4 & 4 \\ 0 & 1 & 0 & 0 & -1 & 5 & 5 & 5 \end{bmatrix}$$

Figure 5Representation of CDs in Morphological Matrix of CVT.

Table 3Performance Assertion for Function and Solution Based EV for SPs of CVT

Sub-Functions	SP	Function Based EV		Solution Based EV					
		Efficiency		Manufacturability		Repairability		Cost	
		Rank	PV	Rank	PV	Rank	PV	Rank	PV
F1	S_{11}	2	3	17	1	13	2	23	5
	S_{12}	5	2	9	3	8	3	9	3
	S_{13}	3	3	8	3	9	3	10	3
	S_{14}	4	3	22	1	16	2	17	5
	S_{15}	1	4	13	2	7	3	12	4
	S_{16}		0		0		0		0
	S_{17}		0		0		0		0
	S_{18}		0		0		0		0
F2	S_{21}	3	3	1	5	1	5	3	1
	S_{22}	6	3	3	5	4	4	4	2
	S_{23}	7	3	12	2	14	2	14	4
	S_{24}	8	3	14	2	15	2	13	4
	S_{25}	1	4	7	4	6	4	6	2
	S_{26}	2	4	15	2	22	1	15	4
	S_{27}	4	3	6	5	3	4	1	1
	S_{28}	5	3	2	5	2	4	5	2

Sub-Functions	SP	Function Based EV		Solution Based EV					
		Efficiency		Manufacturability		Repairability		Cost	
		Rank	PV	Rank	PV	Rank	PV	Rank	PV
F3	S_{31}	1	4	23	1	23	1	18	5
	S_{32}	5	2	18	1	18	1	20	5
	S_{33}	5	1	21	1	17	1	16	5
	S_{34}	2	3	19	1	19	1	22	5
	S_{35}	3	3	20	1	20	1	19	5
	S_{36}		0		0		0		0
	S_{37}		0		0		0		0
	S_{38}		0		0		0		0
F4	S_{41}	2	4	5	5	5	4	2	1
	S_{42}	4	3	10	3	11	3	7	2
	S_{43}	3	3	11	3	12	3	11	3
	S_{44}	1	5	16	1	21	1	21	5
	S_{45}	5	3	4	5	10	3	8	3
	S_{46}		0		0		0		0

	S_{47}	▯	▯	▯	▯
	S_{48}	▯	▯	▯	▯

$$E \quad \begin{bmatrix} 3 & 2 & 3 & 3 & 4 & 0 & 0 & 0 \\ 3 & 3 & 3 & 3 & 4 & 4 & 3 & 3 \\ 4 & 2 & 1 & 3 & 3 & 0 & 0 & 0 \\ 4 & 3 & 3 & 5 & 3 & 0 & 0 & 0 \end{bmatrix}$$

$$M \quad \begin{bmatrix} 1 & 3 & 3 & 1 & 2 & 0 & 0 & 0 \\ 5 & 5 & 2 & 2 & 4 & 2 & 5 & 5 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 5 & 3 & 3 & 1 & 5 & 0 & 0 & 0 \end{bmatrix}$$

$$R \quad \begin{bmatrix} 2 & 3 & 3 & 2 & 3 & 0 & 0 & 0 \\ 5 & 4 & 2 & 2 & 4 & 1 & 4 & 4 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 4 & 3 & 3 & 1 & 3 & 0 & 0 & 0 \end{bmatrix}$$

$$C \quad \begin{bmatrix} 5 & 3 & 3 & 5 & 4 & 0 & 0 & 0 \\ 1 & 2 & 4 & 4 & 2 & 4 & 1 & 2 \\ 5 & 5 & 5 & 5 & 5 & 0 & 0 & 0 \\ 1 & 2 & 3 & 5 & 3 & 0 & 0 & 0 \end{bmatrix}$$

Figure 6 Representation of PVs of the SPs in Morphological Matrix of CVT.

Furthermore, PVs are determined for each of the SPs for four optimisation variables (EVs). The four EVs; efficiency, manufacturability, repairability and cost, are represented as [e, m, r, c] respectively. Table 3 shows the ranking and PVs allocated for both function and solution based EVs. Efficiency is a function-based EV, and its ranking and PVs allocation are within SPs of the same sub-function. Besides, the ranking and performance value allocation for manufacturability, repairability and cost are withing the entire SPs in the morphological matrix. Both CDs and PVs of the SPs are the main inputs to the computer programme. The programme is designed, based on the logical relations, discussed in Chapter 3. Based on the relations, it executes screening of the concepts, evaluation of the feasible concepts, and selection of the optimum concept. Furthermore, the constraints equation was based on one of the SV, which is S_{13}, S_{21}, S_{31}, S_{44}. The weighted factors of the concept were taken as the benchmark.

RESULTS AND DISCUSSION

Upon screening based on CDs matching, 37 feasible concepts were generated as indicated in
Table 4. Besides, the optimum concept and its various weighted factors and total score are shown on Table 5. Furthermore, the optimum concept is indicated on the morphological chart with the linking line in Figure . Concept S15 S25 S31 S41 is the optimum concept. It is a combination of grooved spit sheaths linked by chain and moved in and out by a screw and nut device to achieve change of effective diameter as shown in Figure .

Table 4 Generated Feasible Concepts after 3D Matrix-based Screening for CVT Design

S/N	Concept	S/N	Concept	S/N	Concept
1	S_{11} S_{24} S_{35} S_{41}	14	S_{12} S_{27} S_{32} S_{44}	27	S_{14} S_{23} S_{34} S_{43}
2	S_{11} S_{24} S_{35} S_{43}	15	S_{12} S_{28} S_{32} S_{41}	28	S_{14} S_{23} S_{34} S_{44}
3	S_{11} S_{24} S_{35} S_{44}	16	S_{12} S_{28} S_{32} S_{43}	29	S_{14} S_{23} S_{34} S_{45}
4	S_{11} S_{24} S_{35} S_{45}	17	S_{12} S_{28} S_{32} S_{44}	30	S_{15} S_{21} S_{31} S_{41}
5	S_{11} S_{26} S_{35} S_{41}	18	S_{13} S_{21} S_{31} S_{41}	31	S_{15} S_{21} S_{31} S_{42}
6	S_{11} S_{26} S_{35} S_{43}	19	S_{13} S_{21} S_{31} S_{42}	32	S_{15} S_{21} S_{31} S_{43}
7	S_{11} S_{26} S_{35} S_{44}	20	S_{13} S_{21} S_{31} S_{43}	33	S_{15} S_{21} S_{31} S_{44}
8	S_{11} S_{26} S_{35} S_{45}	21	S_{13} S_{21} S_{31} S_{44}	34	S_{15} S_{25} S_{31} S_{41}
9	S_{12} S_{22} S_{33} S_{41}	22	S_{13} S_{25} S_{31} S_{41}	35	S_{15} S_{25} S_{31} S_{42}
10	S_{12} S_{22} S_{33} S_{43}	23	S_{13} S_{25} S_{31} S_{42}	36	S_{15} S_{25} S_{31} S_{43}
11	S_{12} S_{22} S_{33} S_{44}	24	S_{13} S_{25} S_{31} S_{43}	37	S_{15} S_{25} S_{31} S_{44}

12	S_{12} S_{27} S_{32} S_{41}	25	S_{13} S_{25} S_{31} S_{44}
13	S_{12} S_{27} S_{32} S_{43}	26	S_{14} S_{23} S_{34} S_{41}

Table 5 Optimum Concept for CVT Design

S/N	Concept	Efficiency	Manufacturability	Repairability	Cost	Total score
1	$S_{15}S_{25}$ S_{31} S_{41}	0.8000	0.6500	0.6000	0.4875	2.5375

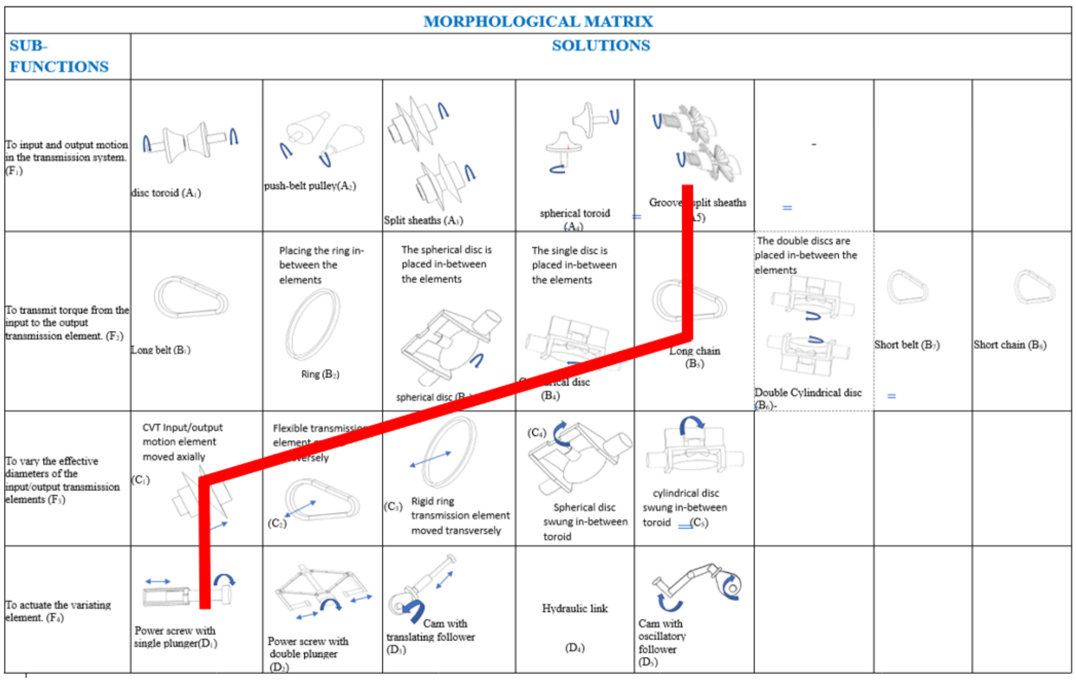

Figure 7 Solution Chain of the Optimum SV

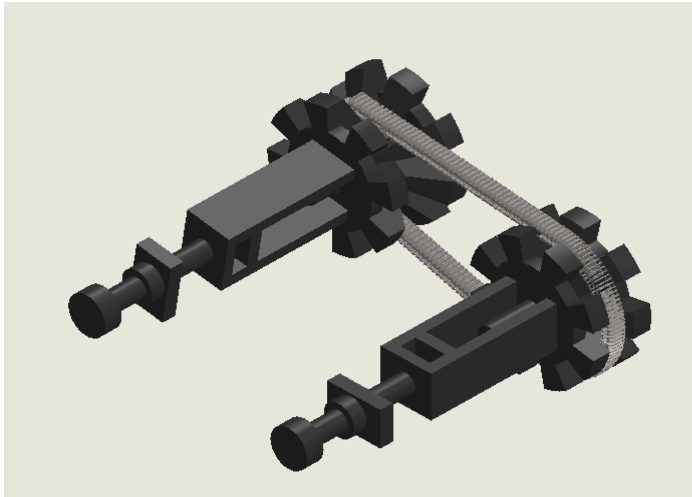

Figure 8 The Optimum Concept for CVT Selected Using CACDSO

The morphological matrix for the CVT design in the first case study has four subfunctions, and maximum number of eight SPs for (F_2). Therefore, it has 8 columns and 4 row (i.e., $c = 8$ and $r = 4$). Consequently, the G-matrix developed from this morphological matrix is expected to have 8^{4-1} (512) columns, 8^1 (8) rows and 8^4 (4096) elements. The number of elements in the G-matrix includes both theoretical and virtual elements. The virtual elements are those that contains elements of the empty cells of the morphological matrix. The computer programme is design to navigate within the G-matrix, to numerically solve the problems. The problems range from evaluation to optimisation-based concept selection.

The result obtained after running the computer programme for the first case study, which is the conceptual design of CVT is indicated in

Table 4. The total number of theoretical concepts, that can be extracted from the morphological matrix for the conceptual design of CVT is $(5 \times 8 \times 5 \times 5)$ 1000. Yet only 37 of the 1000 extracted theoretical concepts are practically feasible. The remaining 963 concepts that are screened out, are those that contain SPs that are not matching. In the same vein, the conceptual design of river cleaning machine which is expected to yield $(5 \times 5 \times 5 \times 5)$ 625 theoretical concepts outputted 108 feasible concepts. The remaining 517 out of the 625 theoretical concepts are practically infeasible.

CONCLUSION

The use of morphological matrix in conceptual design has been accorded the advantage of high novelty, variety and variance. However, the problem of combinatorial explosion in concept generation and lack of categorization of the evaluation variables have been identified as needs for improvement. In this study, a framework developed to address these problems was applied to the conceptual design of continuously variable transmission system. The main objective is to verify the applicability of the framework. Based on the results obtained, it can be concluded that the framework is capable of producing novel design for CVT.

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