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Logical Design Method and its Application in the Design of a Compressed Air Engine

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Logical Design Method and its Application in the Design of a Compressed Air Engine

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Abstract- The logical design method developed in this paper stems from the first two phases and part of the third phase of the mechanical engineering design process. This research work had as research goal; developing a method that will facilitate the commencing of any design project in mechanical engineering. The approach used here is proven to be sustainable as it builds up constructively the design in question using theoretical tools and some demonstrative/figurative techniques that gradually highlight just the essential components necessary to the design in question. The first phase of the method is a mere identification of the problem which should be seen in the introductory chapter as the problem statement then elaborated in the literature review before being summarized under the subtitle of the identification of the need/problem in the body of the designing project proper. Though the lengthy introduction and literature review for the case study was not put on this paper, the summary of the identification of the need is what we see and the impact of that exercise to the steps that follow is eminent in the end results. The second phase; the definition of the problem, is studied in details on this paper with some tools applied for a better interpretation of the results. In the third phase, the synthesis; just the functional analysis, automation of the functioning of the design and conceptual sketches are elaborated in the application demonstration. The end result of the use of this method is the logical design of a compressed air engine. This clearly unveils the design of an engine that is powered and lubricated solely by compressed air.

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I. Introduction

Many engineering creations happen to be results of accidental findings which put to question the very essence of the engineering activities which is obviously to create something useful. Working on the bases of the generalized mechanical design engineering process(Kovacevic), this research work has been able to put together a systemic method that will permit any engineer with a right sense of duty to develop a "Logical" design of whatever item he or she plans to create. This research work equally demonstrates the success of this approach as it presents how this unique method was used to realize a logical design of an engine powered and lubricated solely with compressed air. The paragraphs that follow consist of first the general method then the application example before the conclusion.

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II. Method of Logical Design

Like every engineering project, activities start with the presentation of a problem or need. This method gives an approach on how this need can be fully developed to give solutions that are concrete and sustainable; through creating logical designs. This method is developed into three phases as can be seen below.

a) Identification of need (problem)

As this may sound, this phase involves the identification of the need of the design in question. Work for this phase normally starts in the introduction; as the problem statement is expressed; it then continuous in the literature review where the recent developments and limitations of such an undertaking are conveyed. Then all these are formally represented in a figurative identification of the need using a "Bull with Horn" representation (Granger).

b) Definition of problem

At this phase of the design process, the expected service functions of the solution to the above need will be spelt out under the identification of the service functions. This should be figuratively displayed using an "Octopus diagram"(AUDRY and TAILLARD). Closely followed should be a characterisation of these service functions and then establishment of a hierarchy of the service functions which is visualized on a "Bar chart". Until this level, the designing process should be done following strictly the simplest possible language as is recommended by the "Occam's Razor Principle" (Craig). It should be noted that even at this level of the work there might be some unidentified needs that might call for further modifications to be done in the first phase.

c) Synthesis

This phase initiates the detailing of the complexity of the design as is recommended by the Occam's Razor Principle (Craig). Here is studied the synthesis of the scheme, that is, connecting possible elements deemed essential to the design. This phase starts with a functional analysis systems technique (FAST)(Kaufman); which details the designer(s) choice, or set of choices on how the major service functions will be executed, and this is displayed on a FAST diagram. This should be done bearing in mind the "Simplicity versus Complexity" and the "Independent functions" Principles of mechanical design (Craig). The interaction between the different elements identified in the lowest order function of the FAST diagram should be automated using the "GRAFCET" technique and then displayed using a "GRAFCET diagram". With the principle of functioning of the engine achieved, sketches of possible elements should be realised and this should be based on the designer(s) creative thoughts alongside some design principles like; "Saint-Venant's" principle, "Symmetry" Principle, "Triangulate for Stiffness" Principle, "Maxwell and Reciprocity" principle, "Stability" principle, "Avoid Bending Stresses" Principle, "Manage Friction" Principle, and "Self Principles"(Craig). The initial dimensions of these sketches should respect the Golden Rectangle Rule of (1.618:1). A sketched assembly should then be established permitting a visualization of the interaction of the various elements. This stage marks the end of the logical designing process.

III. Case Study of Compressed Air Engine

a) *Identification of need*

i. *Raison-d'etre of the research work (design)*

- A long lasting solution to the climate change, and other consequences of the excessive pollution of human activities of nowadays.
- A long lasting solution to the air pollution of the cities as a result of the ever increasing use of non-economic and highly polluting means of transport.
- A solution to global warming, particularly the cities.
- A solution to the non-economic use of the ever reducing stock of fossil fuels.
- The need for a more efficient engine for the cities.
- Need to design an efficient compressed air engine that is fully characterised and has clear power enhancement parameters.

ii. *Design Purposes*

- Zero CO_2 polluting engine.
- Zero Heart polluting engine.
- Engine powered and Lubricated solely by compressed air.
- Engine operating with almost no sound, very silent.
- Engine with very high mechanical efficiency.
- Engine with low parts count.

iii. *Expression of Need*

The expression of the need of this design is summarized in the "Bull with Horns" below.

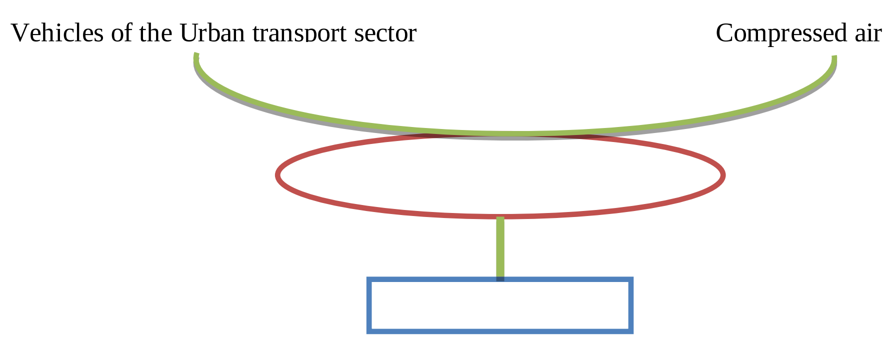

Fig. 1: Expression of the Design Need

b) *Definition of problem*

Under the definition of the problem, the need was further detailed out into some elementary service functions that contribute in one way or several ways to the accomplishment of the design purposes. Here the service functions were identified, characterised and then hierarchized.

i. *Identification of the Service Functions*

The identification of the service functions was facilitated by the construction of an octopus diagram. Here, the engine was placed in its environment of functioning and all the players that are expected to have a principal or constraint influence to its functioning, related to it with respect to their functional contributions.

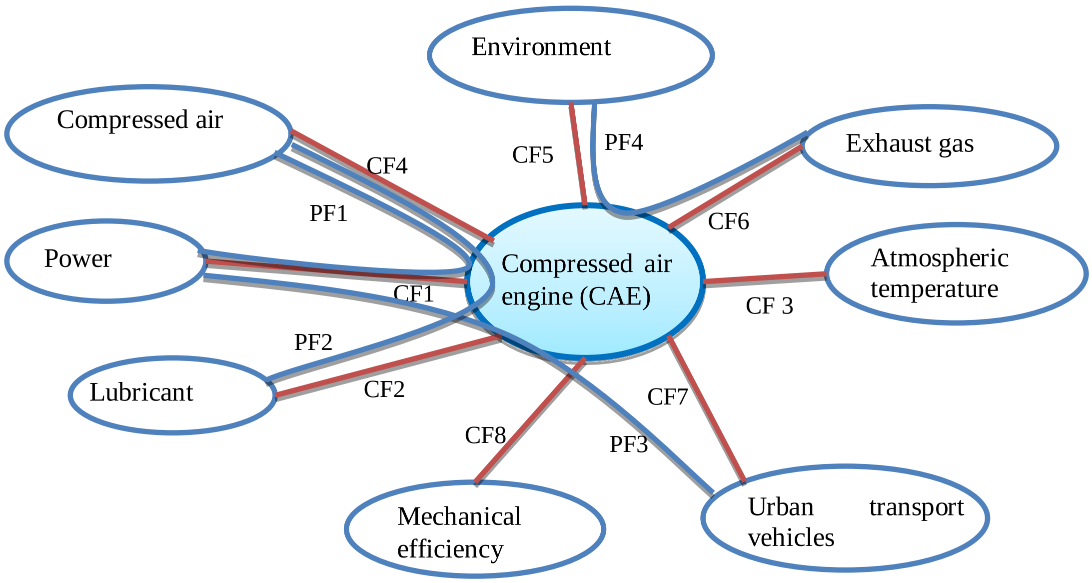

Fig. 2: Octopus diagram

Constraint functions (CF)

CF1: Need power to energize its moving parts

CF2: Use lubricant for low friction movement of parts

CF3: Operate at constant atmospheric temperature to guarantee isothermal expansion

CF4: Operate 100% with compressed air

CF5: Use environment as an energy sink for the Third Law of Thermodynamics

CF6: Exhaust gas is air at atmospheric temperature and pressure

CF7: Fit comfortably in urban transport vehicles

CF8: Operate at very high mechanical efficiency.

Principal functions (PF)

PF1: Potential energy stored in compressed air to be transformed to power, to run engine

PF2: Part of partially expanded compressed air to be used as lubricant

PF3: Power to be sufficient to run urban transport vehicles

PF4: Exhaust gas completely emitted to the environment.

ii. *Characterization of the Service Functions*

The characterization of the service functions was done according to the proportion of the injected air that is needed for a proper realization of each service function and the influence on a scale of 100%, of a service function on the overall design of the engine.

Table 1: Characterization of service functions

Service function	Injected air %	Influence %	Product
CF1	100	90	9000
CF2	10	40	400
CF3	100	10	1000
CF4	100	100	10000
CF5	100	100	10000
CF6	100	60	6000
CF7	100	20	2000
CF8	10	80	800
PF1	100	90	9000
PF2	10	90	900
PF3	100	50	5000
PF4	100	60	6000

These characteristics were then used to deduce the relative influence of the service functions at the level of hierarchi zing the service functions.

iii. *Hierarchi zing the Service Functions*

For a better appreciation of the service functions, the figures from the characterization of the service functions above was used with their product values rounded up to the closest 500s.

Table 2: Inter-service function appreciation masses

	CF2	CF3	CF4	CF5	CF6	CF7	CF8	PF1	PF2	PF3	PF4	Mass	%
CF1	CF1/36	CF1/18	CF4/2.5	CF5/2.5	CF1/3	CF1/9	CF1/18	CF1/2	CF1/18	CF1/3.5	CF1/3	110.5	15.4
	CF2	CF3/4	CF4/40	CF5/40	CF6/24	CF7/8	CF8/4	PF1/36	PF2/4	PF3/20	PF4/24	0	0
		CF3	CF4/20	CF5/20	CF6/12	CF7/4	CF3/2	PF1/18	CF3/2	PF3/10	PF4/12	8	1.1
			CF4	CF4/2	CF4/3.5	CF4/10	CF4/20	CF4/2.5	CF4/20	CF4/4	CF4/3.5	128	17.9
				CF5	CF5/3.5	CF5/10	CF5/20	CF5/2.5	CF5/20	CF5/4	CF5/3.5	128	17.9
					CF6	CF6/6	CF6/12	PFI/3	CF6/12	CF6/2.5	CF6/2	70.5	9.8
						CF7	CF7/4	PF1/9	CF7/4	PF3/5	PF4/6	20	2.8
							CF8	PF1/18	CF3/2	PF3/10	PF4/12	8	1.1
								PF1	PF1/18	PF1/3.5	PF1/3	110.5	15.4
									PF2	PF3/10	PF4/12	8	1.1
										PF3	PF4/2.5	55	7.7
											PF4	70.5	9.8
											total	717	100

Table 3: Pareto table of the service functions

№	Functions	% of mass	Cumulated %
1	CF4	17.9	17.9
2	CF5	17.9	35.8
3	CF1	15.4	51.2
4	PF1	15.4	66.6
5	CF6	9.8	76.4
6	PF4	9.8	86.2
7	PF3	7.7	93.9
8	CF7	2.8	96.7
9	CF3	1.1	97.8
10	CF8	1.1	98.9
11	PF2	1.1	100
12	CF2	0	100

A histogram representation of this hierarchy was the drawn as is below.

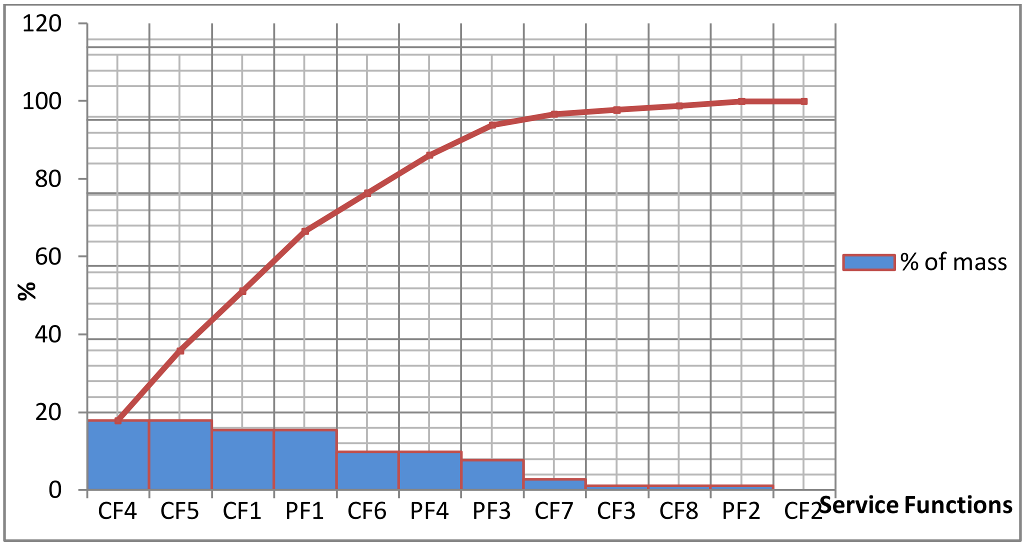

Fig. 3: Pareto display of the hierarchy

This Pareto display of the service functions was seen to highlight six service functions with over 80% of the design satisfactions, these included;

- CF4: Operate 100% with compressed air
- CF5: Use environment as an energy sink for the Third Law of Thermodynamics
- CF1:Need power to energize its moving parts
- PF1:Potential energy stored in compressed air to be transformed to power, to run engine
- CF6:Exhaust gas is air at atmospheric temperature and pressure
- PF4:Exhaust gas completely emitted to the environment
- The conclusion drawn from this was that these service functions have to be of utmost importance in the design process.

c) *Design synthesis*

The design synthesis phase included FAST, GRAFCET and then a figurative conception study.

i. *Functional analysis structure technique (FAST)*

Using the FAST method (Kaufman), a more complex functional analysis of a design model of the compressed air engine was done, as was recommended in the Occam's Razor Principle(Craig). A portray of the set of technical design choices for the accomplishment of the different principal service function was vividly represented on a FAST display, this was in accordance to the "Simplicity versus Complexity" principle.

The FAST display was seen as a logical representation of the way the designer chose to accomplish a compressed air engine with the ability to satisfy appropriately the different service functions.

The highest order function of the FAST display was "Power Urban Vehicle", and the next highest order function depended on the different service functions, starting with the principal ones. The lowest order functions were simplified representations of how much the design wished to render the design complex. It was done in accordance to the "independent function" principle.

From the FAST display, was extracted the following key components that play a major role in the functioning of the compressed air engine;

1. A reusable insulated compressed air storage cylinder (SC).
2. A multivariable transmitter for measurement (MT).
3. Throttle like valve (TV).
4. High pressure good heat conduction metallic pipe network (MP).
5. Adjustable metallic slot timer (ST) with inject slot (IS) and exhaust slot (ES).
6. Quasi fixed volume reception chamber (RC), equally called the pre expansion chamber; enclosed by the slot timer and a lid.
7. Enclosed poor heat conduction stator or casing, hexagonal cross section.
8. Poor conduction inlet manifold (IM) separate routes, some leading to EC (Primary Passages (PP)), while others the inner surface of the rotor (Secondary Passages (SP)).
9. Light metallic wings.
10. Dense metallic fixed axial rotor assembly.
11. The wings together with the inner walls of the stator and outer walls of the rotor enclose the expansion chamber (EC).
12. Exhaust manifold and stator lid (EM).

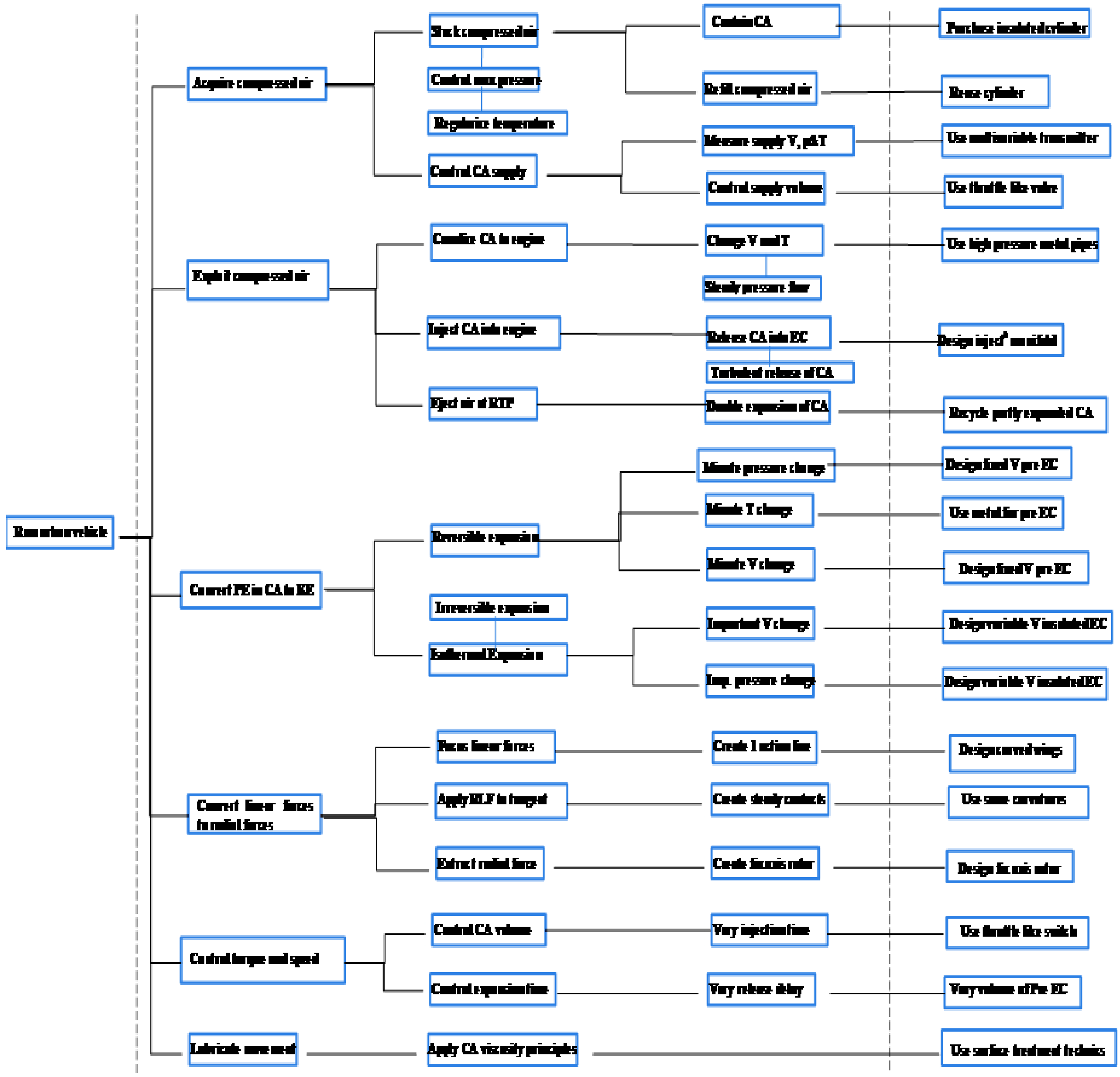

Fig. 4: FAST Diagram of compressed air engine

ii. *Automation of compressed air engine operation*

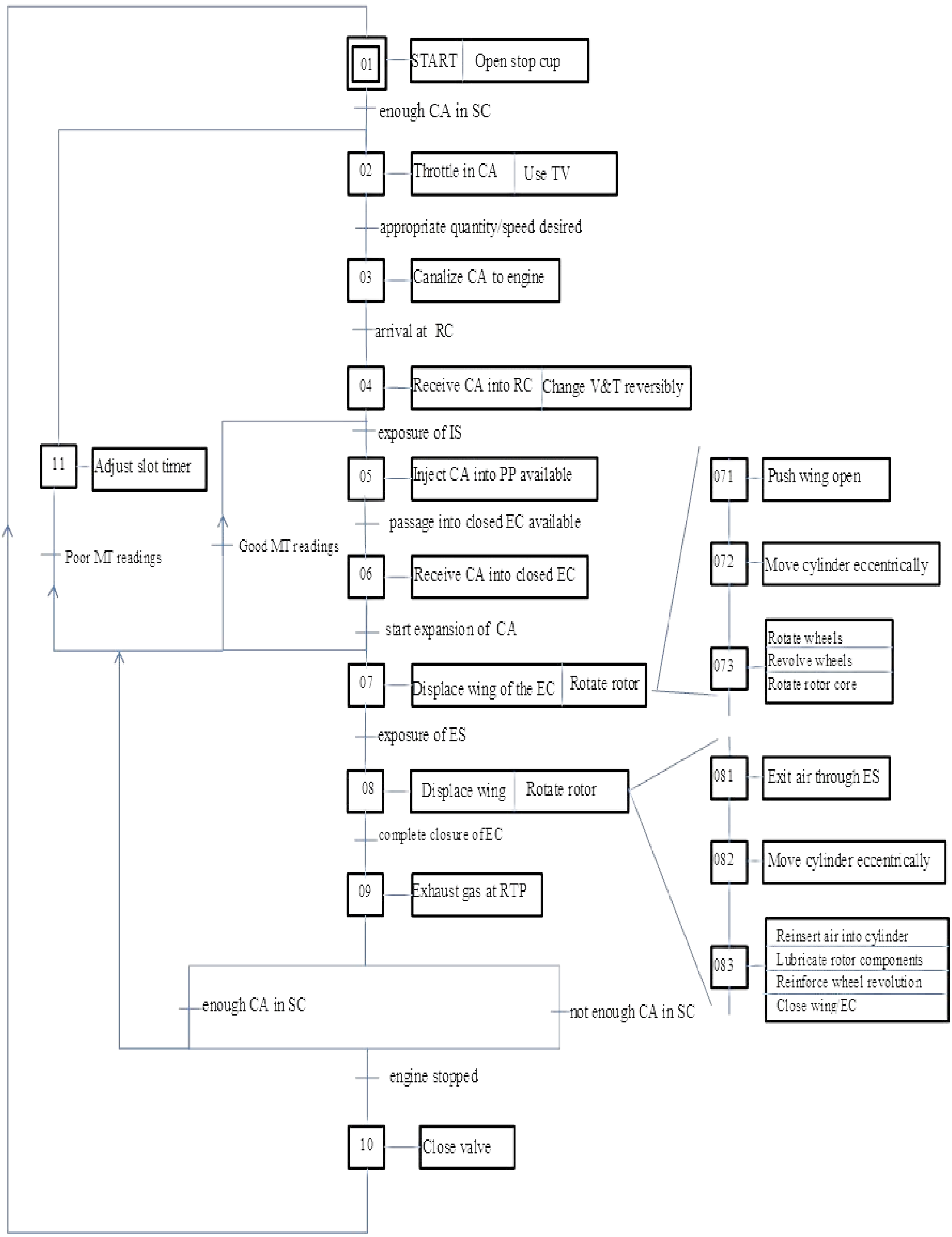

Fig. 5: GRAFCET diagram of compressed air engine

Bearing in mind the "independent function", "self", "Maxwell and Reciprocity" and "symmetry" principles of mechanical design; a model of automated process of the operation of this engine was derived using the GRAFCET technique.

Given this engine design was expected to operate mechanically and parts count reduced to a minimum, all the sensors were eliminated. The operation was expected to be continuous with momentary interventions done only by the operator.

The operation process of this engine was taken to be initiated with the opening of the stop-cup which was then followed by an iterative process of running and adjustment of the engine with operator intervention or not for an economic operation of the engine.

iii. *Structural conceptual sketches of the compressed air engine*

With a close appreciation of mechanical design principles like; ; "Saint-Venant's" principle, "Symmetry" Principle, "Triangulate for Stiffness" Principle, "Maxwell and Reciprocity" principle, "Stability" principle, "Avoid Bending Stresses" Principle, "Manage Friction" Principle, and "Self Principles"(Craig), an understanding of the functioning and automation of the engine, the next step involved conceptual structural sketches of the main component parts of the engine and their assembly.

iv. *Structural conceptual sketches of the component parts*

The Golden Rectangle Rule (1.618:1) ,discovered by Pythagoras was used in the realisation of sketch concepts so that they had greater chances of being realizable and with this understanding and the principles of symmetry, the design process of the component parts of the engine started from the outside working inwards. This made the stator of the engine the first component part sketched.

d) Engine stator

The stator constituted the foundation/framework of the compressed air engine, and from Occam Razor, this part being the first to be sketch was simply designed. As this part equally was the framework of the engine and from the self-principle which reinforces the use of the triangulate for stiffness principles, to render the engine ridged to withstand the reciprocating bombardment it has to support were applied to give a rigid framework for the engine. These principles alongside the Golden Triangle Rule and the principle of symmetry yielded the essential sketch of the stator.

e) Adjustable metallic slot timer

Made out of a good conductor material, the slot timer was designed to act as the 'camshaft' of this engine. It was made to initiate the injection and exhaust processes by conducting the compressed air in and out of the available expansion chamber. This part due to the goal of low parts count was designed compact. The designing of this part equally took into consideration the self-principle, the simplicity versus complexity principle and the St. Venant principle. The resulting adjustable slot timer was a conic structure that is assembled directly on the rotor arm by fixing and it had to fit perfectly in the inlet manifold such that it seals the slots exposing only one at a time to the reception chamber while connecting the inlet slot and exhaust slots of another.

f) Rotor arm

The rotor arm was a compact piece designed to fully execute the transmission task of converting momentary lateral translations into smooth uniaxial rotation. The rotor arm was seen to be unique in its design and was one of the pieces that defined the uniqueness of this engine. When assembled with the rotor wheels, an almost friction free rotor was expected produced.

g) Inlet manifold

The inlet manifold was a compact piece of work though stagnant it was seen to operate smoothly the transition from the inlet to the exhaust. Its compact nature assured a zero energy loss at for that operation and also reduced the part count not forgetting the limitation of moving parts thus it increased the sustainability of the engine.

h) Exhaust manifold

The exhaust manifold was a simple piece design for two main purposes; seal the different chambers and assure a complete exhaust of the decompressed air.

i) Wings

The triangulate for stiffness principle, self-principle and the principle of symmetry result to concept that whenever a design consists of triangulated forces that are symmetrical with clearly identified lines of action, the stiffer and more sustainable it becomes. The wings were designed such that their contact with the rotor was a single line or a point when viewed as a cross section. This reduced loses due to friction and it also directed the radial forces to the centre of rotation and so assuring a self-annulment of the radial forces thus a better equilibrium of the engine in functioning contributing to the sustainability of the engine.

The design of the other parts of this engine were meant to assure the proper functioning of the above six principal parts. It should be noted that the dimensions of these parts were just tentative for these sketches were conceived solely on the bases of the functional understanding of the engine. These shapes were equally meant to assist in the mathematical conception as they were destined to be used to choose the coordinates best appropriate.

j) Structural conceptual sketch of the assembly

This assembly was established following strictly the concept represented on the GRAFCET diagram on how the engine was going to operate. The assembly was restricted only to the engine as the study had as interest to create first an ideal engine before the other elements could be added.

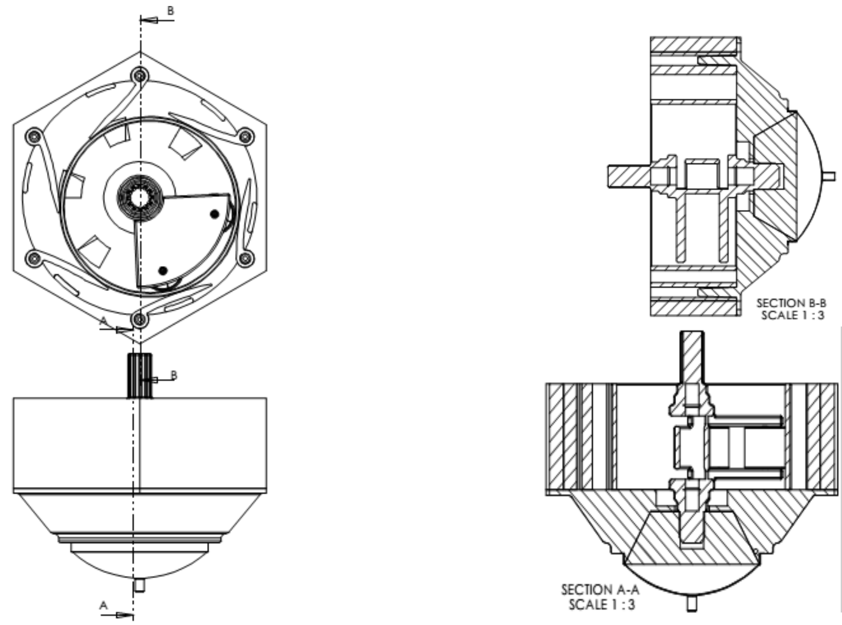

Fig. 6: Assembly sketch

IV. Conclusion

With the logical design of the engine set, the next step could be the kinematics studies closely followed by dynamic studies to complete the conceptual design of the compressed air engine in question. This method of realising logical design made sure none of the systems functions were left out and the end result was proven to be satisfactory.

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