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An Analysis of Uncoupled Designs in Chicken Egg

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Abstract**—**Nature has perfected her designs over 3.5 billion years of evolution. Research fields such as biomimicry, biomimetics, bionics, bio-inspired computing, and nature-inspired designs have explored nature-made artifacts and systems to understand nature’s mechanisms and intelligence. Learning from nature, the researchers have generated sustainable designs and innovation in a variety of fields such as energy, architecture, agriculture, transportation, communication, and medicine. Axiomatic design offers a method to judge if a design is good. This paper analyzes design aspects of one of the nature’s amazing object: chicken egg. The functional requirements (FRs) of components of the object are tabulated and mapped on to nature-chosen design parameters (DPs). The ‘independence axiom’ of the axiomatic design methodology is applied to analyze couplings and to evaluate if eggs’ design is good (i.e., uncoupled design) or bad (i.e., coupled design). The analysis revealed that eggs design is a good design, i.e., uncoupled design. This approach can be applied to any nature’s artifacts to judge whether their design is a good or a bad. This methodology is valuable for biomimicry studies. This approach can also be a very useful teaching design consideration of biology and bio-inspired innovation.

Keywords**—**Uncoupled design, axiomatic design, nature design, design evaluation.

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I. INTRODUCTION

LIFE has been on this planet for about 3.5 billion years. Throughout this long period, nature seems to follow the bottom-up approach in which a material is synthesized atomic or molecular species via chemical reactions, allowing for the precursor particles to grow [1]. The atoms/molecules are combined by means of covalent or non-covalent bonds. This technique is widely used in nature to form functional nanomaterials that are used to manufacture objects such as chicken egg, and mosquito proboscis. In fact, all living objects in nature are created by nano-assembly process. These two objects have several components, and each component fulfills a function or a set of functions. To the best of their knowledge, the authors are not aware of any research paper that evaluated the design of chicken egg by axiomatic design methodology to judge whether they are a good (i.e., uncoupled) or a bad (i.e., coupled) design. In this paper, the design of this object is evaluated by axiomatic design methodology.

II. ANALYSIS

A. Axiomatic Design

In this paper the anatomy and functionality of the selected object is analyzed using the first axiom, known as independent axiom, of the axiomatic design methodology. The second axiom of the methodology, known as information axiom, emphasizes the selection of informationally lean and functionally reliable alternative among the design solutions that satisfy the independent axiom. Considering that components of nature made objects deliver their respective functions with high reliability, it is fair to assume that the information axiom is normally satisfied. However, the discussion in this paper focuses only on the independent axiom which prescribes that a good design should have mutually independent FRs. This independence of FRs is possible only when each FR in the design has a dedicated DP [2]. When multiple FRs share a common DP, that DP creates a coupling between the FRs. When FRs are coupled, changes in one DP results in a significant impact on two or more separate FRs. Axiomatic design introduces design matrix-based analysis to both assess and mitigate the effects of coupling. There are three types of designs: (1) uncoupled design, (2) decoupled design, and (3) coupled design. In uncoupled designs, for each FR a dedicated DP can be determined to make FRs independent of one another. In decoupled design, DPs can be determined to satisfy FRs independently only if DPs are realized in certain order. In coupled design, DPs cannot be determined without affecting multiple FRs causing dependencies among FRs. According to axiomatic design methodology, the best design is a functionally uncoupled design that has minimum information content [2]. In contrast, a coupled design is least desirable.

An interesting point about the analysis in this paper is that DPs for FRs have already been determined by nature. Scientists have discovered [3]-[5] FRs over a long period spanning centuries of research. In this paper, the FRs are mapped on to DPs to check for the existence couplings. The relationship between FRs and DPs can be represented by:

$$\{FR\} = [A]\ \{DP\}$$

where [A] is the design matrix.

$$FR_i = \sum_{j=1}^{n} A_{ij}\, DP_j$$

The following sections examine designs of a nature made object—chicken egg—through the lens of independent axiom.

B. Chicken Egg

The egg is the reproductive unit, produced by the female

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which develops into a new individual. It is a single cell very different from other cells in the body. Unlike other cells, egg cell can survive outside the body. Egg is an all-in-one biological object that includes everything necessary for the creation of a new life. For millions of years, the egg has facilitated a continuum of life from one generation to the next. In birds, the eggs grow to an enormous size. At about 16 cm long, ostrich egg is often said to be the largest [3]. Synthesized by nature in the oviduct of a chicken, an egg embodies various components, each fulfilling one or more functions. All components of an egg are essential. An egg is a rich energy source as a food item. Each part—from the protective shell to the porous membranes, the stabilizing chalazae to the nutrient-dense and vital yolk—is designed to nurture and support life. With their unique combo of essential carbohydrates, vitamins, minerals, fatty acids, and amino acids, an egg supports the embryonic development of a chick. All the parts of an egg are organic and nature friendly.

Each part of an egg serves a specific function. The outermost layer of a freshly laid egg is the bloom, also known as the cuticle. It is a natural protective coating that provides a defense against bacteria. It also serves as a covering on the eggshell to seal the eggshell pores. After the egg is laid, cuticle dries and flakes off. The next layer below the bloom is the eggshell. It is a container that holds all parts of the egg. Eggshell comprises tiny crystal calcium carbonate particles. The eggshell itself comprises two layers—the outer layer, called the spongy layer, and the inner, mammillary layer. Eggshells contain between 7,000 and 17,000 semipermeable pores with more of these at the blunt end. The thickness also varies (10 to 60 μm) across shell [4]. The chicken eggshell is 95 to 97% calcium carbonate crystals that are stabilized by a protein matrix. The protein supports the crystal structure maintain its form without turning brittle. This organic matrix is believed to help calcium deposition during the mineralization process. The eggshell serves to protect the egg against damage and microbial contamination, prevention of desiccation, regulation of gas and water exchange for the growing embryo and provides calcium for embryogenesis. Next comes the outer membrane, which is a translucent film-like gel that nestles immediately next to the eggshell. Outer membranes facilitate the porous activities of eggs. They serve as a barrier to bacteria but as a permeable media for air molecules including carbon dioxide, nitrogen, oxygen, and other gaseous elements. Situated right underneath the outer membrane is the inner membrane encapsulating albumen (egg white). The inner and outer membranes are clear and translucent. They contain a common fibrous amino acid called Keratin. Being strong, robust, water-insoluble, and microscopically dense, Keratin acts as a protective shield. Keratin and protein fibers give both inner and outer membranes their gel-like consistency [4]. They are the strongest of the egg's protective layers. They block bacteria and hold the egg white and other contents together.

Between the outer and inner membranes, an air cell rest opposite the pointed end of an egg. Freshly laid egg is hot with around 105 °F. As the egg cools in the environment, the air pocket is formed. It stores oxygen required for embryo development. Without this oxygen pocket, fertilized embryo cannot mature. Air reserve help maintain proper internal conditions for the egg. Air cell gases and the egg fluids chemically interact through a series of reactions. For example, proteins maintain their stability and quality through their interaction with oxygen in cell gases. Air pockets are universal and essential parts of an egg that keep it healthy and whole, with a stable shelf life.

Beneath the inner membrane, lies albumen, commonly known as egg white. It is a translucent fluid that makes up over 60% of an egg's interior weight. Albumen is 90% water and 10% protein [5]. Egg white fluid comprises four segmented layers, with each alternating between a thin and thick consistency. This mix of consistencies provides protein-packed egg whites the robust template that holds over forty different amino acids. Located at a central layer of the albumen, Chalaziferous White stabilizes and contains yolk's movements at the center of the egg. Egg white does not contain fat. Besides proteins, egg whites contain micrograms of calcium, folate, choline, selenium, magnesium, phosphorus, and potassium [5]. The albumen provides many major functions. It holds protein-based nutrients and compounds that aids in overall embryo growth when the egg was fertilized. During the embryo development, folate and choline contribute to cell growth, DNA replication, and hormone production. Similarly, calcium and magnesium create and trigger hundreds of distinct enzymes to regulate blood sugar, blood pressure, nerves, muscles, and bone development. Then, there is Chalazae, which operate like yolk scaffolding, like ropes that anchor the yolk's outer casing, supporting, and balancing the yolk's movements. The two ends of egg yolk are surrounded by Chalazae, which are long and string-like fibrous tiny squiggle. It is made up of strong fibrous proteins. The main function of these twisted ropes is to preserves the structure and safety of the yolk.

To keep the egg's central yolk separate from the albumen, a part of the called Vitelline Membrane plays an important role. This is a protective covering around the yolk. It is made up of two layers (inner layer 1 to 3.5 micrometer thick, and the outer layer 0.3 to 0.5 micrometer) [6]. Vitelline membranes are made up of glycoproteins and other proteins. Vitelline layer protects the yolk from cracking and seeping fluid inside the egg. A cracked internal vitelline membrane will destroy the egg. During the fertilization process, the vitelline membrane binds protein. It acts as a gatekeeper to allow or not to hormones and substances into the yolk. The signals and receptors located in the inner and outer layers an egg control the initiation of the development of an embryo. In the center of the egg, is a spherical part called yolk. Egg yolk contains saturated fat, fatty acids, minerals, and fat-soluble vitamins A, D, E, B6, B12, Iron, Calcium, Phosphorous, Lutein and Zeaxanthin, Choline, and protein. The most important function of the egg yolk is to provide nutrients for a developing poultry embryo [7]. Blastodisc, also known as germinal disc, is a small disc located on the upper surface of yolk. It is responsible for formation of

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embryo in the egg. The fertilized blastodisc is called the blastoderm, which grows and becomes the embryo. As the embryo grows, its primary food source is the yolk.

The FRs and DPs of these egg parts are presented in the following design equations.

Cuticle (Bloom)

FR_1 = Seal-off egg pores to prevent dust and reduce moisture loss, FR_2 = Prevent harmful bacteria through a first-order mechanical barrier, FR_2 = Prevent harmful bacteria through a first line of chemical defense:

$$\begin{Bmatrix} \mathbf{FR_1} \\ \mathbf{FR_2} \\ \mathbf{FR_3} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \textbf{DP1}: \textbf{Cuticle Layer} \\ \textbf{DP2}: \textbf{Cuticle Microstructure} \\ \textbf{DP3}: \textbf{Proteins} \end{Bmatrix}$$

Shell

FR_1 = Hold all parts of the egg, FR_2 = Stabilize mineral matrix, FR_3 = Allow gas exchange, FR_4 = Provide calcium to the developing embryo, FR_5 = Prevent harmful bacteria through a second-order mechanical barrier, FR_6 = Prevent harmful bacteria through a second line of chemical defense:

$$\begin{Bmatrix} \mathbf{FR_1} \\ \mathbf{FR_2} \\ \mathbf{FR_3} \\ \mathbf{FR_4} \\ \mathbf{FR_5} \\ \mathbf{FR_6} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \textbf{DP1}: \textbf{Assymmetric Tapered Oval Container} \\ \textbf{DP2}: \textbf{Protein} \\ \textbf{DP3}: \textbf{Pores} \\ \textbf{DP4}: \textbf{Calcium Carbonate} \\ \textbf{DP5}: \textbf{Shell Microstructure} \\ \textbf{DP6}: \textbf{Proteins} \end{Bmatrix}$$

Outer Egg Membrane

FR_1 = Prevent harmful bacteria through a third-order mechanical barrier, FR_2 = Prevent harmful bacteria a third line of chemical defense, FR_3 = Allow gas exchange:

$$\begin{Bmatrix} \mathbf{FR_1} \\ \mathbf{FR_2} \\ \mathbf{FR_3} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \textbf{DP1}: \textbf{Microstructure of Membrane} \\ \textbf{DP2}: \textbf{Proteins} \\ \textbf{DP3}: \textbf{Gaps between Microfibers} \end{Bmatrix}$$

Inner Egg Membrane

FR_1 = Prevent harmful bacteria though a fourth-order mechanical defense, FR_2 = Prevent harmful bacteria a fourth line of chemical defense, FR_3 = Allow gas exchange:

$$\begin{Bmatrix} \mathbf{FR_1} \\ \mathbf{FR_2} \\ \mathbf{FR_3} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \textbf{DP1}: \textbf{Microstructure of Membrane} \\ \textbf{DP2}: \textbf{Proteins} \\ \textbf{DP3}: \textbf{Gaps Between Microfibers} \end{Bmatrix}$$

Albumen

FR_1 = Provide water during embryo development, FR_2 = Provide protein during embryo development, FR_3 = Act as a cushion to protect the embryo from jarring movements, FR_4 = Protect blastoderm and yolk, FR_5 = Allow production of DNA and division of cells during embryonic development, FR_6 = Contribute to strong cell membranes during embryonic development, FR_7 = Build and activate hundreds of distinct enzymes during embryonic development, FR_8 = Prevent bacterial contamination through a fifth-order mechanical barrier, FR_9 = Prevent bacterial contamination through a fifth line of chemical defense, FR_{10} = Keep yolk in central position and maintain the orientation:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_7 \\ FR_8 \\ FR_9 \\ FR_{10} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \textbf{DP1}: \textbf{Water} \\ \textbf{DP2}: \textbf{Protein} \\ \textbf{DP3}: \textbf{Layers of Albumen} \\ \textbf{DP4}: \textbf{Folic Acid} \\ \textbf{DP5}: \textbf{Cholin} \\ \textbf{DP6}: \textbf{Calcium and Magnesium} \\ \textbf{DP7}: \textbf{Chalaziferous Layer} \\ \textbf{DP8}: \textbf{Physicochemical Characteristics (Viscosity and pH)} \\ \textbf{DP9}: \textbf{Lysozyme} \\ \textbf{DP10}: \textbf{Chalazae and Thick Albumen} \end{Bmatrix}$$

Vitelline Membrane

FR_1 = Keep yolk separately from Albumen, FR_2 = Provide sperm reception for fertilization process, FR_3 = Prevent bacterial contamination through a sixth-order mechanical barrier, FR_4 = Prevent bacterial contamination through a sixth line of chemical defense, FR_5 = Establish the foundation for embryonic development:

$$\begin{Bmatrix} \mathbf{FR_1} \\ \mathbf{FR_2} \\ \mathbf{FR_3} \\ \mathbf{FR_4} \\ \mathbf{FR_5} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{Bmatrix} \textbf{DP1}: \textbf{Outer and Inner Protein Layers} \\ \textbf{DP2}: \textbf{Receptor Proteins} \\ \textbf{DP3}: \textbf{Microstructure of Vitelle Membrane} \\ \textbf{DP4}: \textbf{Antibacterial Peptides and Proteins} \\ \textbf{DP5}: \textbf{Proteins for Constructing Network of Dense Fibers} \end{Bmatrix}$$

Yolk

FR_1 = Supply food for the development of the embryo, FR_2 = Regulate storage and supply of nutrients, FR_3 = Prevent bacterial contamination through a seventh-order mechanical barrier, FR_4 = Protect from microorganism invasion through a seventh line of chemical defense, FR_5 = Form emulsion, FR_6 = Provide color:

$$\begin{Bmatrix} \mathbf{FR_1} \\ \mathbf{FR_2} \\ \mathbf{FR_3} \\ \mathbf{FR_4} \\ \mathbf{FR_5} \\ \mathbf{FR_6} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \textbf{DP1: Fat and Proteins} \\ \textbf{DP2: Proteins} \\ \textbf{DP3: Physicochemical Characteristics (Viscosity)} \\ \textbf{DP4: Antibodies} \\ \textbf{DP5: Phospholipids (Lecithin)} \\ \textbf{DP6: Pigments} \end{Bmatrix}$$

III. Discussion and Conclusions

A chicken egg looks like a simple object, but in fact, it is a complex structure designed to hold life in fertilized eggs. Number of unique parts of an egg (Bill-of-Material, or BOM), when presented at a high level, comes to about fifteen. However, a detailed BOM will include more than a thousand components. For example, the number of proteins and peptides alone exceed 1,000 in the various compartments of eggs [8]. Many more components of an egg will be identified in the future, particularly the proteins, peptides, and antibodies. By weight egg albumen and chalazae account for 60%, yolk is 30%, and shell with membranes is 10%. In a fertilized egg, the yolk supplies the nutrients, and the albumen supplies the water necessary for the development of the embryo [9].

Besides holding the contents—Albumen, Blastodisc, Yolk, etc.—egg has a multi-layer defense system to protect the life in the blastoderm. These layers are cuticle, shell, membranes, vitelline membrane, physicochemical properties of albumen and yolk. These defense layers in an egg are like a defense system of a medieval castle. Old time castles had a moat, a drawbridge, castle walls, courtyard, narrow stairways, rooms arranged to confuse the enemy, and guarded vaults. Or the egg protection system can be compared to a multi-layered cybersecurity system to prevent malware and intruders, both physical (biometric devices) and cyber (password, firewall, filters, encryption, etc.). One or two layers may be ineffective barriers to bacterial penetration in the eggs. For example, eggshell has pores that allow gas exchange during incubation. Some bacteria can easily get thru the pores on the eggshell; therefore, to build a defense against those intruders, egg design includes additional defense layers.

As shown in the design equations in the Section II, the defense system of an egg comprises seven layers mechanical and seven layers chemical barriers. Cuticle, shell, outer membrane, inner membrane, albumen, vitelline membrane, and yolk act as barriers against the invading bacteria such as salmonella, Alcaligenes, Proteus, and Pseudomonas. The cuticle and shell largely act as mechanical barriers. A small amount of proteins in cuticle and shell not only stabilize the mineral matrix but also act as chemical antibacterial barriers. The outermost layer of the eggshell, the cuticle, is an organic layer of variable thickness composed of polysaccharides, hydroxyapatite crystals, lipids and glycoprotein. The proteins such as C-type lysozyme, ovotransferrin and an ovocalyxin-32 inhibited the growth of *Staphylococcus aureus*, *Escherichia coli* D31, *Pseudomonas aeruginosa* and *Bacillus subtilis* [10]. These proteins offer antimicrobial defense.

The shell itself has many layers—the outer layer, called the spongy layer, and the inner, mammillary layer [6]. In this paper, the shell is treated as a single part and the FRs of its components are not mapped on to these DPs at a micro-level. Similarly, this paper does not address a micro analysis for other parts—membranes, albumen, and yolk. The two membranes—outer and inner—are composed of protein–polysaccharide fibers [11]. These two membranes provide physicochemical defense but allow gases to pass through. They together form an air pouch at the blunt end of the egg as the egg cools after it was laid. The air trapped in the pouch supplies oxygen the chick developing inside the egg during incubation. The fifth line of defense (after cuticle, shell, outer membrane, and inner membrane), both physical and chemical defenses against bacterial contaminations, is provided by albumen. Bacteria are often able to survive on the shell and membranes. But survival is more difficult in the albumen. Antimicrobial proteins present albumen and their in-built physicochemical properties make it difficult for bacteria to survive and multiply. These antimicrobials together with the physicochemical characteristics of egg white are very efficient to prevent bacterial growth [12]. Antibacterial properties of egg white come from its physicochemical characteristics and the presence of numerous antimicrobial proteins such as lysozyme. The egg white pH is close to neutrality at 7.6 and becomes alkaline after a few days of storage at room temperature, reaching pH values as high as 9.5. Alkalinity can directly inhibit bacterial growth and flagella synthesis. The viscosity of the thick egg white inhibits cell motility and restrains the migration of bacteria towards the yolk [14]. The egg white is a protein system with several layers consisting of ovomucin fibers. The thick and thin layers of egg white differ only in their ovomucin content. The protein fractions of egg white consist of ovalbumin, conalbumin or ovotransferin, ovomucoid, lysozyme, ovomucin, avidin, ovoglobulins, ovoinhibitor, and flavoprotein [13]. Albumen is made of water ((87–89%), protein (9.7–10.6%), Carbohydrate (approximately 1%) and traces of fat [10]. These substances will be used during the development of the embryo. Chalazae anchor the yolk and keep it from rising and touching the shell, lest the germinal disc may be damaged and life in it extinguished.

The sixth line of defense is provided by Vitelline membrane. This is a multilayered proteinaceous structure separating egg white from yolk. This membrane, approximately 0.025 mm thick [12], is home to about 137 proteins [15]. These proteins serve many functions: Keep yolk separately from Albumen, provide sperm reception, and establish the foundation for embryonic development. This membrane also allows diffusion of water and nutrients between the albumen and the yolk during embryonic development.

The last line of defense is provided by yolk, which is composed of water (48.8%), fat (32.9%), protein (16.4%), carbohydrate (0,2%) [10]. Besides the antibacterial proteins, egg yolk has antibody (IgY), a unique type of immunoglobulin which has the ability to inhibit bacteria [15]. Another anti-protease ovoinhibitor plays a significant role in antimicrobial activities in protecting the chick embryo [16]. These contents of yolk and its proteins serve many functions: supply food for the embryo during its development, regulate storage and supply of nutrients, form emulsion (to prevent mix-up), and to provide color to the chick. Thus, the defense mechanism of the egg consists of mechanical (physical) barriers and bio agents to protect the embryo.

The total number of eggs produced by the leading countries of the world is 1225 billion in 2019 [18]. That is about 157 eggs per person per year. In nature, trillions of eggs are produced in the wild. This astounding production is attributable to the simple factory called oviduct in the chicken's body. All parts of an egg are fully upcyclable—a cradle-to-cradle design [19], [20]. There is no part that causes any damage to the environment (except the large-scale waste from the industrial poultries). In fact, a thrown egg, while putrefying and decomposing, enriches the soil. Egg shell is eaten by other birds and animals to supplement calcium intake. It is a closed-loop system: Each fertilized egg hatches into a new factory (chicken) that can produce more eggs, with blueprint (DNA) embedded within.

Nature is not perfect. A small percentage of eggs are laid with defects such as eggs with misshapen, thin, porous or shell-less, mottled shells, double yolk, pee-wee, shell-less, and soft shelled. Egg quality is measured based on several parameters such as included albumen height, egg weight, yolk weight, and puncture score. There are many reasons for defective eggs. Some of these are genetic inheritance, lack of sufficient calcium, phosphorus, manganese, or vitamin D3, excess phosphorus consumption, excessive use of antibiotics, copper deficiency, manganese deficiency, high stress in the flock, age of bird, elevated environmental temperature, nutrition and poor water quality [21].

The FRs that are discovered in the last hundred years or so (and many more are yet to be discovered), when mapped onto the DPs that nature has already chosen, the egg design seems to be an "uncoupled design" which is the best design according to the theory of axiomatic design. But the design equations presented in the section B are incomplete. These equations represent the mapping of FRs and DPs are at a gross level. Much more research is needed to arrive at the specifications for all FRs and DPs. Then only one could conclude whether chicken egg is a good design or a bad design. Because of the absence of specifications, applicability of axiom 2 (i.e., information axiom) for egg design is not presented in this paper. But axiomatic design tool offers an elegant way of judging whether the design of a nature made object is a good design or a bad design.

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