Chapter

Principles for Designing Green, Lean, and Smart Microfactories: Chicken as a Model

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Abstract

Industrial revolutions have gone through four phases: steam, electricity, electronics, and Industry 4.0. Through all these four industrial revolutions, efficiency, productivity, quality, and automation have been greatly improved. However, the manufacturing processes created by humans have had disastrous consequences on the environment leading to a gigantic "climate change" problem. To mitigate climate change, engineers, and manufacturers all over the world have stepped up the research into cradle-to-cradle designs and sustainable manufacturing practices inspired by the designs and value cycles in nature. Bio-inspired designs have been gaining momentum to create products and manufacturing methods that are eco-friendly. All manufacturing (of a fruit, an organism such as a human baby) in nature happens in microfactories such as a womb, a leaf, a flower, or a chicken oviduct whose products are eggs. The product (egg) and the manufacturing process (chicken oviduct) are both green (eco-effective), lean (built with minimal resources), and smart (sensors and Internet of Things). Using a chicken as a model, this book chapter presents a set of metrics for green, lean, and smart attributes, which engineers can use to design products and microfactories.

Keywords: biomimicry, eco-efficiency, eco-effectiveness, lean, IoT, sustainability, cradle-to-cradle, microfactory design

1. Introduction

In the last three centuries, we have experienced four industrial revolutions. At the end of the eighteenth century, the steam engine powered the first revolution. Almost a 100 years later, electricity powered the second one leading to the proliferation of mass production lines. Nearly another 100 years later, the adoption of electronics, IT systems, and robotics sparked the third revolution [1].

The emergence of the fourth industrial revolution, labeled "Industry 4.0" or "I4.0" or 4IR," was discussed for the first time in public at the Hanover Trade Fair in 2011 [2]. Since then, I4.0 has been revolutionizing industries by embracing the technologies offered by tools such as AI, advanced robotics, and cyber-physical systems.

Through these four industrial revolutions, efficiency, productivity, quality, and automation have greatly improved the delivery of products and services to customers. However, the manufacturing processes created by humans have had disastrous consequences on the environment due to "climate change." To mitigate climate change, engineers and manufacturers worldwide have stepped up the research into cradle-to-cradle designs and sustainable manufacturing practices. Bio-inspired designs have been gaining momentum to create products and manufacturing methods that are eco-friendly.

Life has been thriving on the earth for 3.5 billion years. In just the past 200 years, starting with the invention of the steam engine, the four industrial revolutions ushered a pattern of destruction to our home called "The Earth." We can see the dangers of climate change as portrayed by the documentary "Six Degrees" by National Geographic, as massive amounts of greenhouse gases are released into the atmosphere raising the average temperature of the Earth [3]. The other dangers are plastic pollution and loss of biodiversity. One recent book by Bill Gates starts with the chapter "51 billion to zero." [4] It states,

> *"There are two numbers you need to know about climate change. The first is 51 billion. The other is zero. Fifty-one billion is how many tons of greenhouse gases the world typically adds to the atmosphere every year. Although the figure may go up or down a bit from year to year, it's generally increasing. This is where we are today. Zero is what we need to aim for. To stop the warming and avoid the worst effects of climate change—and these effects will be very bad—humans need to stop adding greenhouse gases to the atmosphere."*

The conclusion is very clear: Our current design and manufacturing methods are unsustainable and dangerous to the environment and, therefore, to ourselves ultimately. We need to learn and imitate nature's design principles and manufacturing methods.

The United Nations Department of Economic and Social Affairs has created a set of 17 Sustainable Development Goals (SDGs) as a blueprint for peace and prosperity in countries [5]. In the last few decades, companies across the world have been attempting to make their factories green, lean, smart, and green. "Green" refers to technologies and practices for sustainability. "Lean" refers to lean product design, lean manufacturing, and lean service. "Smart" refers to leveraging Industry 4.0 technologies. A seminal book "Biomimicry: Innovation Inspired by Nature," by Janine M. Benyus led to the creation of the Biomimicry Institute [6]. Biomimicry looks to nature for solving design problems in a regenerative way. Biomimicry is about learning from nature and applying that knowledge to design, make and operate products, systems, businesses, and cities that are compatible with the sustenance of the earth. The author proposed nine principles of biomimicry: (1) Nature runs on sunlight, (2) Nature uses only the energy it needs, (3) Nature fits form to function, (4) Nature recycles everything, (5) Nature rewards cooperation, (6) Nature banks on diversity, (7) Nature demands local expertise, (8) Nature curbs excesses from within, and (9) Nature taps the power of limits [7].

Another book "Cradle to Cradle: Remaking the Way We Make Things" by William McDonough and Michael Braungart suggests several strategies to design products and systems that can be used and reused again and again, imitating nature's circular economy to attain the principles of cradle-to-cradle life cycles [8]. The essential principles of cradle-to-cradle design emphasize a shift from humanity's "cradle-to-grave" to nature's "cradle-to-cradle" with a deep understanding of Technical and biological metabolisms. This requires a system that does not create monstrous hybrids such as landfills but plans for efficient separation of technical and biological nutrients and recycles them endlessly, just as nature does.

Similarly, Gregory Unruth, the author of the book "Earth, Inc.: Using Nature's Rules to Build Sustainable Profits," gives five eco-minded rules called "bio-sphere rules" for the sustainable design of products and processes [9]. These five rules are (1) Materials parsimony, (2) Value cycle, (3) Power autonomy, (4) Sustainable product platforms, and (5) Function over form [10]. They aim to create closed-loop business processes. Currently, we see a great interest in learning the principles from nature and applying them in design and manufacturing to realize nature's "cradle-to-cradle" approach to sustainability. In recent times research into bio-inspired design has been gaining momentum [11]. Thousands of new eco-friendly products are designed, developed, and patented [12]. A significant amount of time and resources are spent on nature-inspired biomaterials such as Chitin and Chitosan [13]. Innovations are happening in 3D printing (additive manufacturing) technologies to bring it closer to nature's manufacturing methods in terms of sustainability [14]. There is an urgent need to create a framework to achieve the sustainable development goals (SDGs) proposed by the United Nations Organization (UNO).

Nature produces a variety of products, such as grains, nuts, fruits, vegetables, herbs, wood, eggs, and meat, all in microfactories. A close observation of nature shows that all its products and manufacturing methods are green, lean, and smart. Most of the products of nature are manufactured in microfactories. For example, a plant manufacturing tomatoes, a bird producing eggs, and a womb assembling a baby. To expand on this discussion, we analyze a product of nature, the "egg," and the microfactory of nature, the "chicken" for their green, lean, and smart features.

2. Green, lean and smart product and production system: a framework

Everything that nature creates—for example, a chicken egg—happens in a lights-out factory [15]. Even a human baby is entirely created in the dark factory of the mother's womb. **Figure 1** presents an IDEF (Integration Definition) [16] model of the egg production process. There are four parameters in IDEF representation of a system: Input, output, mechanism, and constraints or controls. The inputs are cereal grains, water, air, minerals and vitamins, and feed additives such as antioxidants and organic minerals. The outputs are eggs, urine, and feces. The mechanism that converts inputs into outputs is the biological body of the chicken. Constraints and controls are the availability of resources such as chicken feed, water, and suitable living conditions.

The feed sustains the female chicken and aids in its growth. A chicken turns a portion of the feed into follicles in its ovary. These tiny follicles travel through the chicken's approximately 70 cm long oviduct. As a follicle travels through the oviduct, many parts of the egg, including membranes, albumen, chalazae, and shell, are added by processes similar to nano and additive manufacturing. The whole process is executed within the oviduct factory. This 70 cm-long microfactory typically produces an egg a day during the breeding season. Depending on the bird species and seasons, the number of eggs per clutch and the frequency of egg delivery vary.

A matrix with five parameters, as shown in **Table 1**, is to study, appreciate, and explore any object in Nature [17]. These five parameters will be used to study the

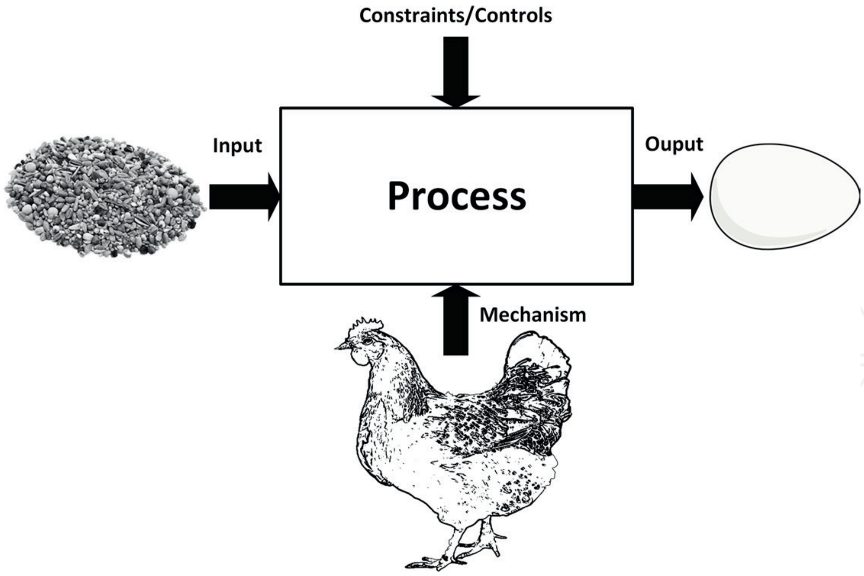

Figure 1.
Chicken input-output IDEF model.

Parameter	Form	Function
Model	Chicken Body. Egg shape (Ovoid).	Produce eggs. Provide a link between one generation and the next.
Metric	Green metrics. Lean metrics. Smart metrics.	Achieve eco-effectiveness. Use minimum materials, labor, and resources. Protect the egg and chicken body.
Mentor	Nature.	Provide insights.

Table 1.
Five parameters.

"chicken egg" and the "chicken body" as a "green, lean, and smart" microfactory to draw insights for the bio-inspired design of future products and factories.

Nature as Model: "Biomimicry, biomimetics, bio-inspired design" is a new science that studies nature as the model to imitate its ways and take inspiration from its designs and processes to find solutions to human needs. For example, taking inspiration from a leaf, scientists and engineers have created solar cells to meet human energy needs.

Nature as a measure (Metric): Nature has learned, through its 3.8 billion years of evolution, what works, what fits, and what lasts. Biomimicry uses ecological standards to benchmark our innovations.

Nature as a mentor: Biomimicry introduces a shift in thinking from "what we can extract from nature" to "what we can learn from nature." As physicists, chemists, engineers, and biologists explore nature, they are discovering nature's super-intelligent.

Form: Form is the visible shape or configuration of something. Or it is a particular way in which a thing exists or appears.

Function: The purposes for which a living or non-living thing exists. It implies a definite action or a particular kind of work (**Figure 2**).

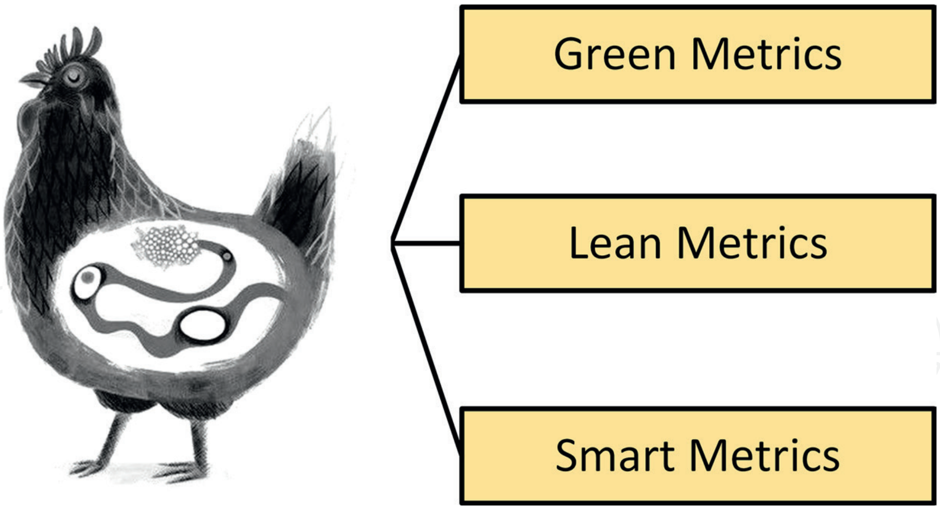

Figure 2.
Three sets of metrics of the egg and the chicken microfactory.

3. Green, lean, and smart product: chicken egg as a model

An egg is a reproductive unit that develops into a new individual like the one that produced the egg. Although very different from other cells of the chicken body, an egg is a single cell. The intelligence and love ensconced in an egg are infinitely mysterious for the following reasons [18]:

1. An egg is a large single cell.
2. An egg survives outside the animal's body, while no other cells can survive outside the body.
3. The egg is nature's remarkable and versatile invention that encapsulates everything necessary to create new life.
4. The egg has carried life from one generation to the next for millions of years.
5. There is no definite answer to the old riddle: "Chicken first or the egg first."

Consider a chicken egg manufactured by nature in the oviduct of a chicken. An egg has various parts, as shown in **Figure 3**, and each part fulfills one or more functions. All components of an egg are essential for its function. As a food source, an egg is a complete powerhouse. All parts of an egg are designed to support life and provide nourishment. With their unique combination of essential vitamins, minerals, fatty acids, and amino acids, it is hard to ignore the health benefits of eggs. All the parts of an egg are organic and upcyclable. Of more than 100 elements, nature chose to use just four—carbon, hydrogen, oxygen, and nitrogen—to produce all living things. These four elements, with the addition of a little sulfur and phosphorus, can account for 99% of the weight of all living things on the planet. The major parts of an egg and its functions are presented below.

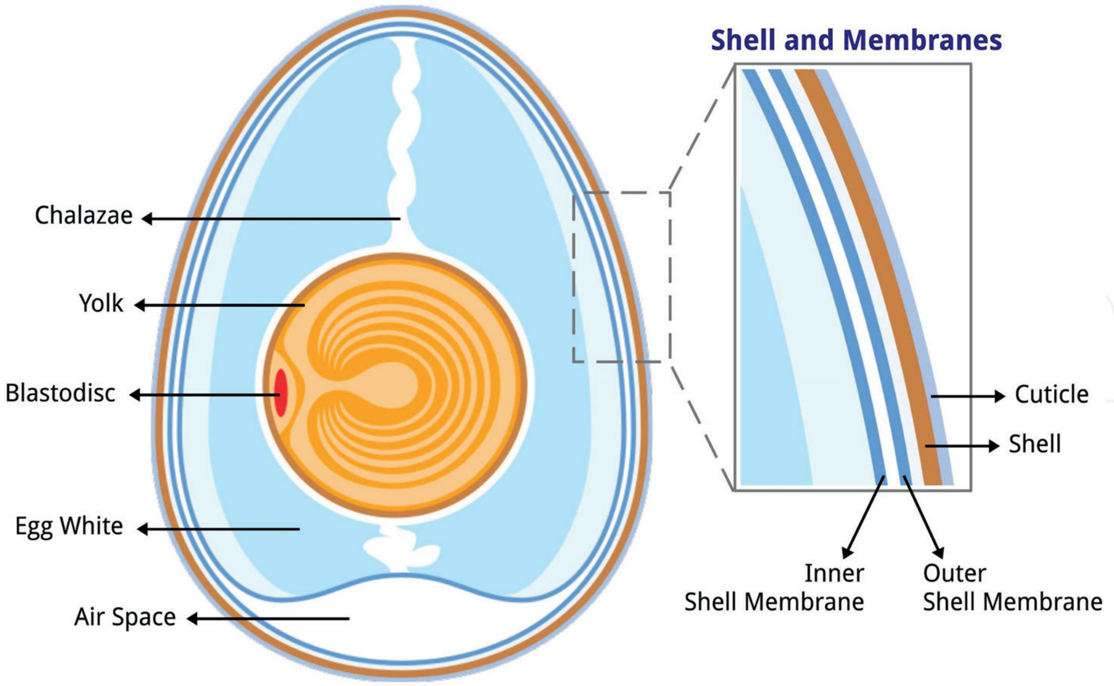

Figure 3.
Chicken egg and its parts.

3.1 Bloom

Description: Bloom, known as the cuticle, is the natural protective coating on the eggshell that seals the eggshell pores. Bloom dries and flakes off.

Functions: Seals off egg pores. Prevent the entry of harmful bacteria and dust into the shell. Reduces moisture loss from the egg.

3.2 Shell

Description: The chicken eggshell is 95–97% calcium carbonate crystals stabilized by a protein matrix; without the protein, the crystal structure would be too brittle to keep its form. The organic matrix is thought to play a role in the deposition of calcium during the mineralization process. The structure and composition of the eggshell formation require enough calcium deposition within hours, which must be supplied via the hen's diet. An eggshell contains between 7000 and 17,000 semipermeable pores. Shells come in an array of colors, from blues and greens to whites, browns, and often including specks.

Functions: The avian eggshell holds the parts of the egg and protects the egg against damage and microbial contamination. At the same time, it prevents desiccation, provides calcium for embryogenesis, and regulates gas and water exchange for the growing embryo.

3.3 Outer egg membrane

Description: The outer membrane is a translucent, film-like gel that nestles immediately next to the eggshell. Is partially made of keratin.

Functions: Outer membranes facilitate the porous activities of eggs. They operate as a bacterial barrier and air molecule vent permitting oxygen, nitrogen, carbon dioxide, and other gaseous particles to flow in and out.

3.4 Inner egg membrane

Description: Inner membrane is the second translucent protein barrier tucked right below the outer membrane. The inner membrane shelters the albumen (egg white). It is partially made of keratin, a fibrous amino acid. It is robust, water-insoluble, and microscopically dense, and acts as a sturdy protective shield.

Functions: This inner egg membrane is the strongest of the egg's protective layers. It blocks bacteria and holds the egg white and other contents together.

3.5 Air cell

Description: Air cell rest opposite the pointed end of an egg, nestled into the more rotund and spacious bottom curve. A freshly laid egg is hot at around 105°F. As the egg cools in the environment, the air cell is formed.

Functions: Air cell stores the oxygen required for a developing embryo. Without this oxygen pocket, a fertilized embryo cannot mature. Air cell assists in maintaining proper internal conditions for the egg. The cascade of chemical interactions that take place between the air cell gases and the rest of the egg's fluids and proteins rely on oxygen transfer for their stability and quality. Air pockets are universal and essential parts of an egg that keep it healthy and whole, with a stable shelf life.

3.6 Albumen

Description: Albumen, known as egg white, is a translucent fluid that makes up over 60% of an egg's interior weight. Albumen is 10% protein and 90% water. Egg white fluid consists of four segmented layers, with each alternating between a thin and thick consistency. This mix of consistencies provides protein-packed egg whites with a robust template that holds over 40 different amino acids. Chalaziferous White is the first and most central layer of the albumen. It rests around an egg yolk, restraining the yolk's movement to the center of the egg. Besides proteins, egg white contains micrograms of calcium, folate, choline, selenium, magnesium, phosphorus, and potassium; it does not contain fats.

Functions: It holds protein-based nutrients and compounds that aid in overall embryo growth if the egg was fertilized. During embryo development, folate and choline support cell growth, DNA replication, and hormone production. At the same time, calcium and magnesium build and activate hundreds of distinct enzymes to regulate blood sugar, blood pressure, nerves, muscles, and bone development.

3.7 Chalazae

Description: Chalazae are the long, stringy, fibrous little squiggles that run through and around an egg's yolk. Chalazae permeate the two ends of the yolk. It is made up of strong fibrous proteins.

Functions: They preserve the structure and safety of the yolk. They operate like yolk scaffolding, or like ropes that anchor the yolk's outer casing, supporting and balancing the yolk's movements.

3.8 Vitelline membrane

Description: This is a protective covering around the yolk. It is made up of two layers—the inner layer 1–3.5 μm thick, and the outer layer 0.3–0.5 μm. Vitelline membranes are made up of glycoproteins and other proteins.

Functions: Vitelline layer protects the yolk from cracking and seeping fluid inside the egg. It keeps the egg's central yolk separate from the albumen. A cracked internal vitelline membrane will destroy the egg. The vitelline membrane is also responsible for protein binding during the fertilization process. Without the signals and receptors held within its inner and outer layers, an egg cannot initiate the development of an embryo. It acts as a gatekeeper for hormones and substances to either pass into the yolk or remains blocked.

3.9 Yolk

Description: Egg yolk contains saturated fat, fatty acids, minerals, and fat-soluble vitamins A, D, E, B6, B12, Iron, Calcium, Phosphorous, Lutein, Zeaxanthin, Choline, and protein.

Functions: The major function of the egg yolk is to provide nutrients for a developing poultry embryo.

3.10 Blastodisc

Description: Blastodisc, also known as a germinal disc, is the embryo-forming portion of an egg with discoidal cleavage usually appearing as a small disc on the upper surface of the yolk mass.

Functions: A fertilized blastodisc (now called the blastoderm) grows and becomes the embryo. As it grows, the embryo feeds on the yolk as a food source.

Part name	**Functions (verb + noun)**
Bloom	Seal-off egg pores. Prevent entry of harmful bacteria. Prevent entry of dust. Reduce loss of moisture.
Shell	Hold all parts of the egg. Allow gas exchange. Provide calcium (to the developing embryo).
Outer egg membrane	Prevent harmful bacteria. Allow gas exchange.
Inner egg membrane	Hold egg-white and other contents. Block bacteria.
Air cell	Store oxygen. Give long shelf life. Aid in the growth of an embryo into a chick.
Albumen	Supply water and proteins (to the developing embryo).
Chalazae	Prevent yolk movement.
Vitelline membrane	Keep the yolk separated. Bind proteins (during the fertilization process). Allow or prevent hormones (during embryo development).
Yolk	Provide nutrients (to the developing embryo).
Blastodisc	Become embryo.

Table 2.
Summary of functional analysis of an avian egg.

Attribute	Description/specifications
Shape	Ovoid.
Weight	50–70 g.
Design Blueprint	DNA, a few nanometers in size.
Product BOM (Bill-of-materials)	About 15 major parts, about 1000 parts (counting proteins, fats, etc.).
Materials	Calcium, Oxygen, Hydrogen, Nitrogen, Water.
Calorific Value	70 calories (in a 50 g egg).
Composition	A 50 g (1.8 oz) medium/large chicken egg provides approximately 70 calories (290 kJ) of food energy and 6 g of protein. Boiled eggs provide significant amounts of several vitamins and minerals, including vitamin A (19% Daily Value (DV)), vitamin B12 (46% DV), riboflavin (42% DV), and vitamin D (15% DV), choline (60% DV), pantothenic acid (28% DV), zinc (11% DV), and phosphorus (25% DV).
Recyclability, Circular Economy	All parts are organic that are upcycled by nature.
Product recall	No customer complaints or product recalls.
Closed-loop system	The egg, when hatched, turns into a new factory (chicken) that can produce more eggs as per the blueprint (DNA) of the egg.

Table 3.
Product attributes.

In **Table 2**, we summarize the functions of the parts of an egg. We use the standard notation of writing the function with a verb and a noun. For example, for the part "bloom" the verb is "seal-off" and the noun is "egg pores." In **Table 3**, the product (egg) attributes are listed.

When we examine "egg" as a product for its green, lean, and smart attributes, the following conclusions emerge.

Green: All the materials that are used to manufacture an egg are organic. There are no toxic materials that might pollute or damage the environment. When an egg is discarded into nature, all the materials decompose by the actions of microbes except the shell which is made of calcium carbonate. Some animals and birds might consume eggshells as a calcium supplement. There is no waste. All the materials are upcycled.

Lean: Egg shape and all the parts are made of a minimum number of materials and labor to fulfill specific functions summarized in **Table 2**. It is evidently a lean design.

Smart: The materials in an egg protect the egg by preventing harmful bacteria at seven different levels in a hierarchical manner [19]. Its design allows good trade-offs between different functions; for example, the pores in the eggshell allow the passage of gas molecules but not liquid material.

4. Green, lean and smart microfactory: chicken body as a model

The oviduct of a chicken is a factory that produces eggs. An oviduct is the hen's reproductive system. It is a long spiraling tube. There are five major stages in the manufacturing of an egg. These stages and the cycle times of each stage are shown in **Figure 4** [20]. The journey of the chicken egg starts as an egg yolk. First, a follicle or the oocyte (still unfertilized) is made in the ovary, and as it moves through the oviduct by a small distance, it may be fertilized internally (life is created) by a

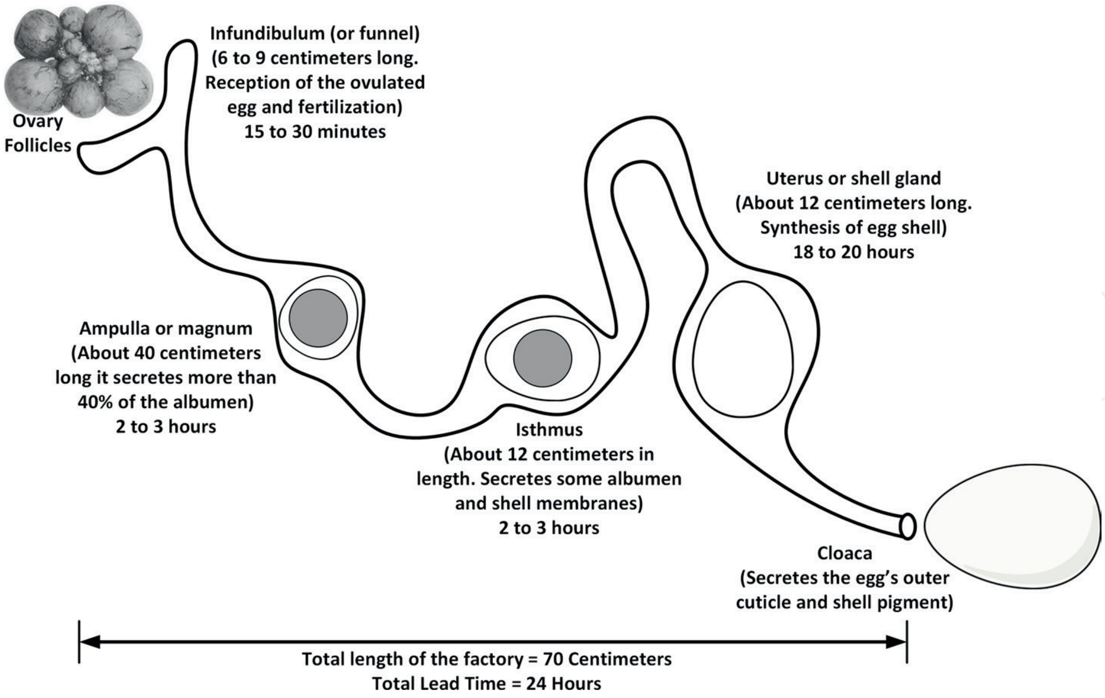

Figure 4.
Manufacturing stages of a chicken egg production in oviduct.

sperm (stored inside the hen) and compacted into a spherical shape. Once the yolk attains a predetermined size and shape, its growth of stops. This process takes about 30 minutes. The yolk continues down the oviduct (whether it is fertilized or not) and is covered with a membrane (called the vitelline membrane), structural fibers, and layers of albumin (the egg white). This part of the oviduct is called the magnum. As the egg goes down through the oviduct, it is continually rotating within the spiraling tube. This movement twists the structural fibers (called the chalazae to hold the yolk in the center of the egg, against the forces of gravity), which form rope-like strands that anchor the yolk in the thick egg white. This process of two chalazae anchoring each yolk, on opposite ends of the egg takes about another 2 hours. Then, two egg membranes made of keratin, are wrapped around the albumen to keep it in an ovoid shape. Then in the lower part of the oviduct, the synthesis of eggshell takes place, which takes about 20 hours. The shell is made of calcite, a crystalline form of calcium carbonate. Eggshell is not a solid wall, but porous with about 7000 to 17,000 holes. These pores allow the exchange of gases during the development stage. The cloaca secretes the egg's outer cuticle and shell pigment. Then, the egg is ejected out of the hen's body. Eggs are usually laid blunt end first. An air space filled with Oxygen forms when the contents of the egg cool and contract after the egg is laid. The embryo consumes this Oxygen as it grows into a chick during the hatching process.

Material transforms while moving through the tubular factory with minimum energy requirements in the conversion process. The oviduct is like a moving workshop, a silent and lights-out factory, where an egg is manufactured, at the rate of one egg every 24 hours. An egg, when hatched, transforms into a new factory (chicken) that can produce more eggs, with the egg's DNA blueprint. All parts of an egg are fully upcyclable. No part causes any damage to the environment (except the large-scale waste from the industrial poultries). A discarded egg putrefies and decomposes enriching the soil. Other birds and animals eat leftover eggshells to supplement their calcium intake. The chicken body and the "oviduct assembly line" are made of

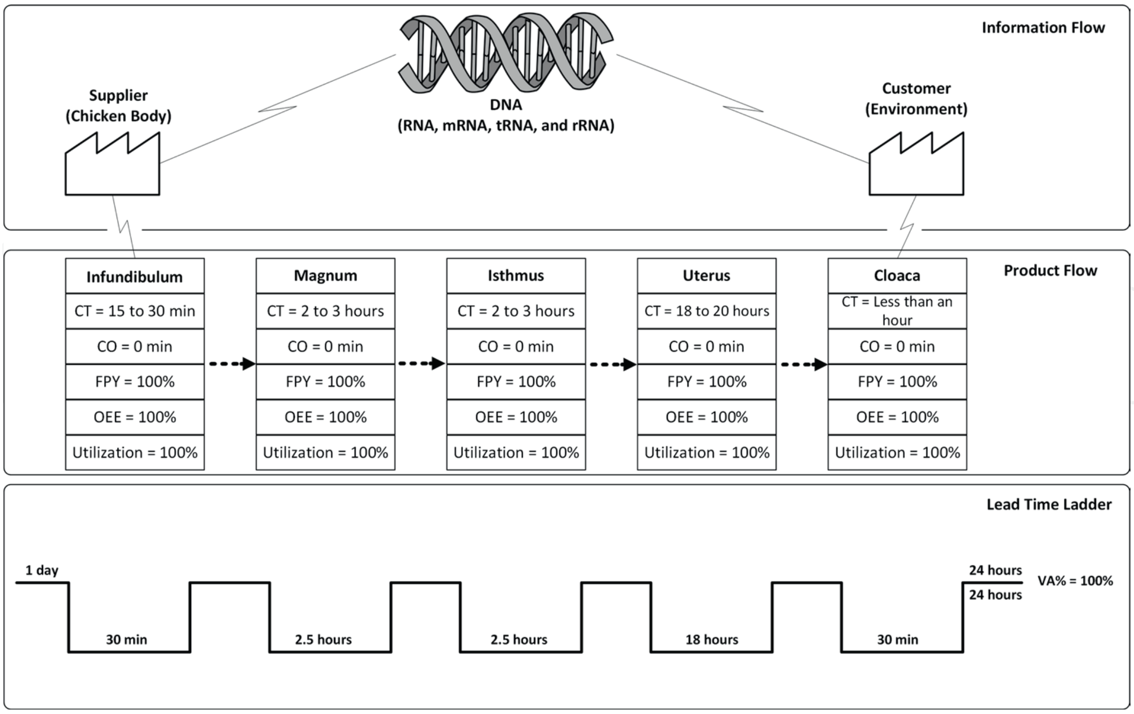

Figure 5.
Value stream map (VSM) of a chicken egg production process.

biomaterials that are easily decomposed and upcycled. Considering that both the product (egg) and the manufacturing system (chicken body) are zero-waste systems, they can serve as models of a circular economy.

A Value Stream Map (VSM) of this manufacturing process in the oviduct is presented in **Figure 5** [21]. The inventory of protein, fat, calcium, and amino acids is approximately sufficient for just one day. The inventory in the chicken's body lasts for about a day, which is 24 hours. For the next day, for the next egg, fresh feed must be taken in by the chicken. There is no storage space for, say, many days of inventory. Some chickens might be fattened up, but there is a limit on how much a chicken can eat and store, which cannot be more than the inventory for a couple of days. From the inventory "turns" point of view, if a chicken is laying 400 eggs during the egg-laying period in a year, the number of inventory turns is 400. Because each egg is produced with a one-day worth of inventory, 400 is a very high number, far beyond what has been achieved by any human-built factory. The value addition percentage is also close to 100% which has not been matched even by the best lean manufacturers in the world. The physical, green, lean, smart, and operational attributes of this factory are summarized in **Tables 4**–**8**.

These characteristics listed in **Tables 4**–**8** clearly make it evident that the chicken body viewed as a microfactory is a green, lean, and smart manufacturing system. The chicken body is a lights-out factory with no workers, no supervisors, no machines, no tools, and no technology experts. The chicken body is made of environmentally benign biomaterials, and hence, it is green. All materials of a chicken's body are completely upcyclable. Millions of sensors in a chicken's body are connected to a central nervous system. When we apply the concepts of lean, Industry 4.0, or sustainability, we get answers that confirm that the chicken microfactory is extremely lean, highly automated, and 100% green. The lights-out score of this microfactory will be the highest compared to any human-built factory embracing the principles of green, lean, and smart. From the moment the first single-celled organism was born,

Metric/Attribute	Description
Shape	Long, flexible, and spiraling tube with an expandable cross-sectional area, and several bends to reduce overall space.
Factory length	60–70 cm.
Factory weight	2–5 kg (whole chicken).
Factory lifespan	5–10 years
Manufacturing process, tools, accessories, machines, furnaces, containers, etc.	The technology used is nanotechnology which involves bottom-up manufacturing with self-assembly, hierarchy, and massive parallelism; it is something more efficient than the current additive manufacturing (AD), or 3D and 4D printing technologies.

Table 4.
Microfactory physical attributes.

Metric/Attribute	Description
Material choice	Parsimonious biomaterial palette: Calcium, Oxygen, Hydrogen, Nitrogen, Water.
Energy	Renewable energy for the factory (chicken) comes from the grain produced by plants using sunlight.
Pollution	Zero pollution.
Upcyclability of factory (chicken) and product (egg)	100% upcyclable; the entire factory is made of organic materials which become food for animals and trees after the death of a chicken.
Power of platform	Nature uses the "Oviduct" platform for almost all bird species for producing eggs.

Table 5.
Microfactory attributes (green).

Metric/Attribute	Description
Process parameters	No high temperatures, no elevated pressures, or no caustic chemicals
Noise	No noise, no sound (zero decibel level).
Ambient lighting (electricity bill)	No lighting lights-out factory).
Maintenance	Self-repair.
Office staff	No offices or staff.
Material handling equipment	Muscles move the work-in-process (WIP) to the next stage.
Quality assurance staff	Built-in quality assurance with no quality control inspection.
Inventory turns	400 per year (approximately).
Cycle time (CT)	15 minutes to 20 hours.
Value addition (VA)	Close to 100%.
Kanbans	Leptin and Ghrelin hormones.
Changeover times (CO)	Not applicable (a chicken body is a focused factory producing a single product).
Overall equipment effectiveness (OEE)	Close to 100%.
Lead time (LT)	24 hours (for one egg).

Metric/Attribute	Description
First pass yield (FPY)	99.97% (3 Sigma).
Defect rate	Extremely low.
Scrap and rework	No scrap and no rework.
Visibility management (dashboards etc.)	A dark factory where chemicals control the flow of work-in-process (WIP).
Product recall	Close to zero.

Table 6.
Microfactory attributes (lean).

Metric/Attribute	Description
Sensors (Factory 4.0 and Industry 4.0)	Millions of sensors.
Connectivity (IIoT, PLCs, SCADA, etc.)	Central nervous system (CNS) of the chicken body.
Real-time information	Yes (to the chicken's brain).
Automation level	Highly automated.
Autonomy	Autonomous and self-cognitive factory.
Digital maturity score (strategy, operations, technology, culture, customer service, etc.)	100 (on a scale of 0 to 100).
Forecast accuracy	Close to 100%.
Order cycle time	24 hours for one egg.
Fill rate	Close to 100%.
Customer satisfaction	Close to 100%.

Table 7.
Microfactory attributes (smart).

Metric	Chicken microfactory (nature)
Size	Small and compact.
Cost	Very low.
Profit margin	About 30% on chicken meat and eggs.
Portability	Highly portable (one can carry the factory to wherever one wants to).
Scalability	Highly scalable. One can have one chicken or a hundred or even some thousands (in 2019 it is estimated that the leading countries produced 1225 billion eggs accounting for about 157 eggs per person per annum).
Upcyclability	The whole chicken becomes a part of nature as food and nutrients for other life forms after death.

Table 8.
Chicken body microfactory attributes.

about 3.5 billion years ago, nature has been using only green and lean principles in its creation. The key to nature's "lean" processes are nanotechnology and self-assembly which do not require enablers like machines, tools, workers, and supervisors. Nature's factories are significantly more efficient than the best factories in our industrial world like Toyota, GE, Dell, or Apple. Nature's factories score much higher scores on "green, lean, and smart" metrics than the best modern factories. Similarly, nature's products are designed intelligently with nature-friendly materials, manufactured efficiently with no pollution, and upcycled completely after their useful life. In this sense, nature factories and products are perfectly created for the circular economy.

5. Green, lean, and smart factories

Lean manufacturing and later lean thinking have revolutionized the manufacturing and service sectors. Intellectuals and business leaders such as Frederick Taylor, Henry Ford, Sakichi Toyoda, Kiichiro Toyoda, Taiichi Ohno, Shigeo Shingo, Masaki Imai, Edward Deming, Joseph Juran, Kaoru Ishikawa, and James Womack have contributed to the knowledge of lean. The publications of the International Motor Vehicle Program (IMVP) [22] at MIT, Cambridge, MA, and the Lean Enterprise Institute (LEI) [23] have further promoted the implementation of lean across the globe. As lean thinking continued to spread to every country in the world, leaders have been adapting the tools and principles beyond manufacturing, to supply chain, logistics and distribution, services, retail, healthcare, construction, maintenance, and even government. The first report "Industry 4.0 and the Internet of Things" was published by Hannover Messe in 2013 [24]. With the advent of Factory 4.0 and Industry 4.0 technologies, lean is further fine-tuned to gain more productivity, efficiency, and quality. Hundreds of companies have been implementing Industry 4.0 technologies, and many smart manufacturing hubs are established all over the world. Recent advances in biomaterials and new technologies such as 3D printing and 4D printing [25] have been shifting design and manufacturing closer to a circular economy and bio-inspired manufacturing methods [26, 27].

Millions of products (grains, fruits, vegetables, fibers, eggs, etc.) in nature are manufactured in focused factories. For example, a tomato plant that produces vegetables, or an almond tree that produces nuts, or a bird that produces eggs are focused factories. The basic concepts and characteristics underlying the focused factories are simplicity and repetition that give consistent delivery performance [28]. Chicken body is like a focused factory which produces a single product (egg) at low cost, high quality, with consistent lead times, and with low investment. In this chapter, an attempt is made to look at the chicken oviduct as a model for sustainable design and manufacturing. The preliminary analysis presented in this chapter shows that "chicken microfactory" can serve as a benchmark "green, lean, and smart" metrics for human-built products and manufacturing systems.

6. Principles of microfactory design

Microfactory is a small-to-medium scale, highly automated, and technologically advanced manufacturing setup, which has a wide range of process capabilities [29]. A microfactory either refers to a local capital-lean facility used for the assembly of a complex product or a small manufacturing system (normally automated) for producing small quantities of products. The Mechanical Engineer Laboratory (MEL) of Japan proposed the term "microfactory" in 1990. Currently, microfactory describes the small-to-medium scale, highly automated manufacturers like Arrival Ltd., an electric vehicle manufacturer headquartered in London, UK. The main advantages of microfactory are saving a substantial amount of space, energy, materials, time, and upfront capital costs [30]. Many companies are establishing microfactories leveraging new technologies. For example, Local Motors is a pioneer in establishing a microfactory for automotive production. In 2010, the company established its first microfactory for the commercial production of Rally Fighter cars in Phoenix, Arizona [31]. Microfactories have been built in many sectors, including automotive, apparel, consumer goods, food and beverage, electronics, and electronic waste recycling.

Microfactories are small high-tech manufacturing units located close to customers. These can even function as retail outlets for customized products. In the garment industry, some of the microfactories are producing clothes customized for the users. For instance, customers can send their preferred designs using the manufacturer's app and can receive a perfectly styled and fitted dress the next day from the manufacturer. The following are the benefits of microfactories:

- Capital costs are less.
- Distribution systems are less costly and more efficient.
- Mass customization is economically feasible.
- Investment risk is low.
- Breakeven volumes are low.
- Profit margins are high.

The supply chain complexity also gets simplified with microfactories responding to a pull market: only after getting confirmed orders from the customer, are the products manufactured. The following principles can be used in designing products and microfactories.

Products:

1. Use biomaterials.
2. Avoid toxic, non-renewable, non-recyclable materials.
3. Minimize the variety of materials.
4. Minimize part count.
5. Use generative design and 3D printing technologies.
6. Design for eco-effectiveness.
7. Use Internet-of-Things (IoT) to maximize the useful life of the products.
8. Design for disassembly, recycling, and upcycling.
9. Provide a product passport for tracking and recovery.

Manufacturing processes:

1. Design for eco-efficiency.
2. Use renewable energy to run the manufacturing processes.
3. Leverage digital technologies.
4. Use technologies such as product configurators, augmented reality, virtual reality, mixed reality, and Cobots.
5. Use the Industrial Internet of Things (IIoT), digital twins, and related cyber technologies.
6. Minimize transportation.
7. Locate microfactories close to the customer.
8. Leverage the technologies for mass customization.
9. Design for dismantling and reusing the materials and machines of microfactories.

Divergent, a company located in California, is a good example of a microfactory. It developed its own Divergent Adaptive Production System (DAPS) which is a complete software-hardware solution designed to replace traditional vehicle manufacturing. It is a complete modular digital factory for complex structures [32]. Given a set of digital requirements as input, the machine automatically engineers, additively manufactures and assembles any complex structure. The system can move seamlessly between manufacturing different vehicle models. To achieve the objectives of the circular economy, the World Economic Forum (WEF) has launched the circular car initiative [33]. The term “circular car” refers to a hypothetical vehicle with maximum material efficiency. This notional vehicle is expected to produce zero materials waste and zero pollution during the manufacturing process, product usage, and disposal. Many organizations have been exploring similar approaches toward a circular economy. For example, the production of rechargeable batteries, in their journey from mine to electric vehicles, poses significant social and environmental risks. The Battery Passport is created as a digital representation of a battery that conveys information about all applicable environmental, social, and governance (ESG) and lifecycle requirements based on a comprehensive definition of a circular battery [34].

7. Conclusions

In creating products and production systems, nature has been using design blueprints embedded in DNA, nano-biomaterials, nanomanufacturing, and self-assembly processes. The industrial revolutions in the past 200 years have thrown nature into disarray. Copying and imitating nature’s designs and processes can lead to green, lean, and smart products and production systems. For example, in all flowers, fruits’ beauty, function, and non-toxic decomposition coexist in their designs. In search of a solution to a problem, an important question to ask is, “WWND—What

Would Nature Do?” Keen observation and analysis of nature can lead to creative and sustainable innovations [35]. The solution to the industry’s attempts to solve complex sustainability issues is to look at nature. In this chapter, we examined a chicken egg and chicken body from the green, lean, and smart lens to present a framework that designers of products and production systems can use for learning and benchmarking human-designed products and human-built factories.

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