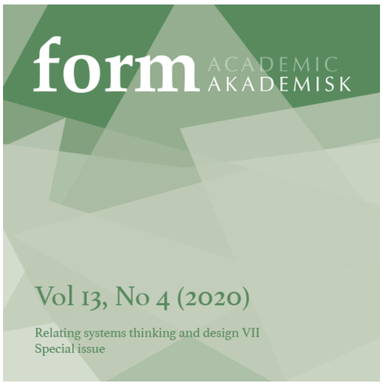


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# Integrative Systems of Production

## A framework and model for designers, based on ecosystem metabolisms and functions

***ABSTRACT***
*Different branches of design are shifting from a primary focus on artefacts as ends to concentrating on means (e.g. forms of production), with ends encompassing larger societal goals. Concurrently, humanity is facing an increasingly carbon-and-freshwater-constrained world, combined with escalating realities of climate change and ecosystem degradation; thus, our means of production must evolve. An integrative framework and model has been developed to support designers (and other stakeholders) working on regenerative systems of production. The model integrates synergistic, circular, cascading and aggregate efficiency design systems based on ecosystem concepts, as well as regenerative agriculture, the bioeconomy and the (technical) circular economy. With this integrative approach, stakeholders may develop more productive, regenerative synergies and hybrid activities that produce zero waste. The model can be applied at the micro-, meso- and macro-scales.*

*Keywords*:
Systemic design, ecological design, biomimetics, circular economy, regenerative agriculture.

**INTRODUCTION**

Over the past 15 years, the global sustainability movement has been increasing in size and rate each year (Mang & Haggard, 2016). The debate is truly starting to shift from *if* we should work on sustainability to *how* to work on sustainability (Mang & Haggard, 2016). With this increased attention, a substantial number of methodologies have been developed and put into practice; coming from different disciplines, such as biology, ecology, agriculture, chemistry, architecture, urban planning, economics, and design.

As Mang & Haggard (2016, p. XIX) point out, with this ever-increasing cornucopia of methodologies, we 'must see the relationships among these varied strategies and how they fit together', so that they can be successfully accessed and put into practice. It is also by looking at the relationships between the methodologies, that it becomes possible to see their different roles or *functions*, and their interdependences and synergies within a greater whole. Brought together within an *integrative* model, based on an ecosystem functions and metabolism framework, it is intended that this supports coherence with, and learning from, living systems.

The paper begins with an introduction explaining the goals of the study, some definitions of key concepts and the link between them and the goals. The second section reviews the foundations for the development of the framework and model described in this paper. The third section describes the integrative systems of production (ISP) model. The fourth section uses the foundational ecosystem metabolisms and functions (EMF) model as a lens to look at our predominant forms of production, and hence, underline what the ISP model attempts to transform. The final section ends with a discussion on principles, regeneration, and an integration caveat, followed by the conclusion.

**Key goals**
The key goals of the ISP framework and models presented in this paper are as follows:

- To support the *design of regenerative and integrative systems of production* (the means) with a framework and model based on *EMFs* with the intent of supporting congruence between the two;
- To bring a range of *existing eco-design* concepts with different focus points and strengths, together into one integrative model, potentially greater than the sum of the parts;
- To support a form of *systemic production literacy*, by presenting a wide range of different methodologies, supporting the sharing of knowledge, potential collaborations across disciplines, and ultimately, their appropriate integration by and into design.

**Systems of production**
Hodgson (2001, p. 315), the institutional economist, defines *production* as

> the *intentional* creation of a good or service, by one or more human beings, using appropriate knowledge, skills, organisation, tools, machines and materials. Production may include items that are useful or useless, ceremonial or practical. Production in this sense is universal to all human societies.

Therefore, *systems of production* include all productive activities, from hunting and gathering to agriculture, industry and infrastructure activities (which can be seen as the socialisation of production) that collectively meet the material needs of society.

**Eco-design, regeneration and a living-systems worldview**
Rockström et al. (2009) present an explicit message within the 'planetary boundaries' framework, stating that humanity is already pushing beyond Earth's ability to fully regenerate. Our systems of production are evidently a fundamental way that humanity is doing this. Therefore, a transformation from predominantly (fossil fuel–based) extractive, destructive and wasteful *linear* systems of production to those that are *congruent* with *regenerative* systems of Earth, is an existential challenge of our time.

With this in mind, du Plessis' (2012) regenerative sustainability paradigm proposes a transition from the mechanistic to an ecological or living-systems worldview. Looking to living systems for how this transformation may be achieved makes sense, not only because these systems provide abundant inspiration, but also because congruence necessitates that our systems of production are an 'effective *adaption to* and *integration with* nature's processes (Cowan & Van der Ryn, 1996, p. 34), which is a definition of ecological design. After a long legacy of ecosystem—and community—degradation, it is imperative that our systems of production also regenerate, supporting the 'expansion of natural capital' (Cowan & Van der Ryn, 1996; and social capital), as opposed to purely sustaining impoverished capital.

**Moving from artefact ends to production means—and goals as ends**
Charles Eames defined design as a 'plan for arranging elements in such a way as best to accomplish a particular purpose' (cited in Neuhart & Neuhart, 1998, p. 14). Eames and his wife, Ray, were both industrial designers and highly engaged in a plethora of other activities, including fine art, film, graphic design, exhibition design and architecture, although their work retained a distinct orbit around *artefacts* (Neuhart & Neuhart, 1998).

Some more nascent branches of design have been broadening the design field beyond artefacts—where the *ends* (in this case, the artefact) has been the focus—to a greater focus on the *means* (Sanders & Stappers, 2014). Furthermore, as explained by Luigi Bistagnino (2017, p. 75):

> Born from Design practise as an approach that shifts the attention from the product to the production process behind, [Systemic Design's] main goal is to prevent waste, but not just that. The major result is the creation of relationships, among both production processes and actors involved.

This shifts the design focus upstream (Ryan, 2014) to a form of Systemic Design (SD) in which, through this greater focus on the *means of production*, some of the more positive ends (rather than 'negative externalities') become less 'designed' and potentially more 'emergent'. These include zero waste, community, reciprocity, collaboration and even the business models for sustaining these systems economically. Relatedly, since the early 1990s, some designers have also been working downstream from the artefact, on producer–consumer relationships—this is briefly discussed in the section on design for circularity.

Several economists (see Daly & Farley, 2004/2011; Mazzucato, 2018; Raworth, 2017) and the United Nations Sustainable Development Goals (UN SDSN, 2015) have proposed that we should (re)define the *objective* goals/missions/objectives/ends (or '*Telos*') for our various (or overall) economic activities. This represents a move from goals that predominantly focus, for example, on increasing gross domestic product and growth (on a finite planet), profit maximisation and shareholder value and consumer preferences (subjective values) to ends that give greater priorities to social and ecosystem health. Design also has a role to play in facilitating group collaboration, value conflicts and ambiguity over these types of ends (Ryan, 2014), or viewed a slightly different way, their *potential* (Mang & Haggard, 2016).

**Integrative production literacy and limits to this framework and model**

The ISP model outlines a plethora of different ways designers (and other stakeholders) can transform matter and use energy flows to address the material needs of society, with the intention of creating zero waste and potentially regenerating EMFs. The different possibilities are fundamentally built on physics, (green) chemistry and biology, and then ecology, engineering, agriculture, infrastructure and planning, which spread across these foundations. As a result, designers need to develop a *fundamental literacy* of these practices as the potential connector across these often segmented disciplines.

An important point to underline is the ISP framework and model supports the understanding of what we *can* do, not what we *should* do. Therefore, on its own, it cannot guarantee zero waste or regeneration, for example, as an emergent end. This is almost certainly not possible without appropriate frameworks (e.g. 'regenerative development' by Mang & Haggard, 2016), and integration with (or development of) suitable 'provisioning institutions' – those institutions that societies have developed for the 'production, distribution, acquisition, maintenance and protection of the means of everyday life' (Hodgson, 2001, p. 299); and supported with principles, ethics and forms of feedback that support adaptive responses (to keep a check on the dynamic means and ends).

**Frameworks, models and analogies**

Carol Sanford (2016) asserts that frameworks 'invite the generation of a pattern, in this time and space, rather than follow[ing] a preset pattern'. In this paper, the framework is principally the mental concept of using ecosystems as the underlying way to think about systems of production. This is done with ecosystem concepts and principles, and the use of an analogy between the three metabolic groups found in ecosystems—producers, consumers and decomposers (and mixed groups; Figure 1)—and three principle ways we can optimise the breakdown or build-up of matter using energy, through synergies, circularity and cascading processes (and mixed or hybrid processes), within systems of production (Figure 10). The analogy is also made between ecosystems' nutrient pools (NPs), and regenerative nutrients in systems of production. The EMF model also focusses on functions, which consider how different organisms function *in relation to* other organisms and their environment. This is also used as an analogy in the ISP model, which looks at how different forms of production function in relation to other forms of production and their environment.

Models 'show how to replicate an existing pattern' (Sanford, 2016). The ISP model is a clear attempt to replicate the different metabolic patterns and the relationships between them, as well as their relationships with NPs at the level of an ecosystem (illustrated in Figure 1). It is proposed that the EMF model can be used to explicitly present how life creates the conditions for more life (and new forms of life), regenerates and produces zero waste (with only heat going back out into space) *as a collective whole*. It is proposed (with the support of systems mentioned in the previous section) that, by replicating the EMF model patterns, the ISP model can support the same potential conditions.

## THE FOUNDATIONS FOR THE INTEGRATIVE SYSTEMS OF PRODUCTION MODEL

This section outlines the main foundations for the ISP model, including the EMF framework based on metabolism and the relationship this describes between living and non-living elements; a brief introduction of the EMF model (see Snow, 2020, for a full paper on this topic); a list of ecosystem concepts developed for and during the development of the EMF framework and model (duplicated from Snow, 2020); and finally, outlines of the proposed value adding of the EMF model and the ISP model, both in relation to each other and for design. The broad range of eco-design practices and schools of thought that also formed a fundamental basis for the ISP model are mentioned throughout the next main section, which describes the ISP model in full.

### Integrative forms of metabolisms and the nutrient pools framework

German biologist Wilhelm Pfeffer (1845–1920) is credited as the first to assign names to the different forms of feeding that organisms use to metabolise supplies from their environment (Sahtouris, 2000). Vladimir Ivanovich Vernadsky (1863–1945) is credited as the first to use these different metabolism forms as a way to classify all life (Sahtouris, 2000).

Metabolism is a process of chemical changes in living matter, in which energy is used to take in (e.g. ingest) matter, build and maintain cells and gather together and excrete wastes (Sahtouris, 2000). Metabolism consists of two fundamental processes, which are as follows: anabolism, the building up of more complex substances (which requires energy), and catabolism, the breaking down of complex substances (which can release energy).

In nature, there are principally three different forms of metabolisers, with a fourth, which is a hybrid of the main three. These are *autotrophs* (or producers), which are 'self-feeding'; these organisms can build complex molecules from simple molecules and elements. *Heterotrophs* (or consumers) 'feed off others', as these organisms need to eat ready-made molecules created by others. Moreover, *saprotrophs* (or decomposers) 'feed on the dead'; these organisms also turn large molecules into smaller basic ones that the autotrophs can reuse. Finally, *mixotrophs* can bridge or switch metabolisms as required. There are finer distinctions within each category.

The different forms of metabolism can be thought about functionally in that, collectively, they interact with each other and are essentially *interdependent*, with the different functions collaboratively forming functioning ecosystem wholes. Therefore, metabolism is an 'activity of all Earth's living matter taken together, as well as that of any particular organism' (Sahtouris, 2020, p. 77).

Vernadsky's holistic vision of *The Biosphere* (1926/1997) included the living (the different metabolisms) continuously intwined with Earth's non-living elements, or NPs, which life finds, uses, transforms and recycles (as a whole) through metabolism. In this way, Vernadsky saw *life as principally rock rearranging itself* (Sahtouris, 2000) – a geological force of 'living matter', which he studied 'without preconceived ideas of what was and was not alive' (Margulis & Sagan, 1995, p. 49).

By classifying life through metabolisms and by not distinguishing between non-living and living elements, Vernadsky developed a classification and mental framework that looked at different forms of living matter in relation to each other and their environment and how they were actively affected by and affected their proper (and others') contexts. This collective view of relationships between the living and non-living, in one particular place, describes an *ecosystem*.

The mental frameworks mentioned above were used to create the EMF model described in the following subsection, and they have been used as analogies for the different ways humans 'metabolise' matter and use energy in different types of environments, for different forms of systems of production. This will be discussed further at the end of this main section.

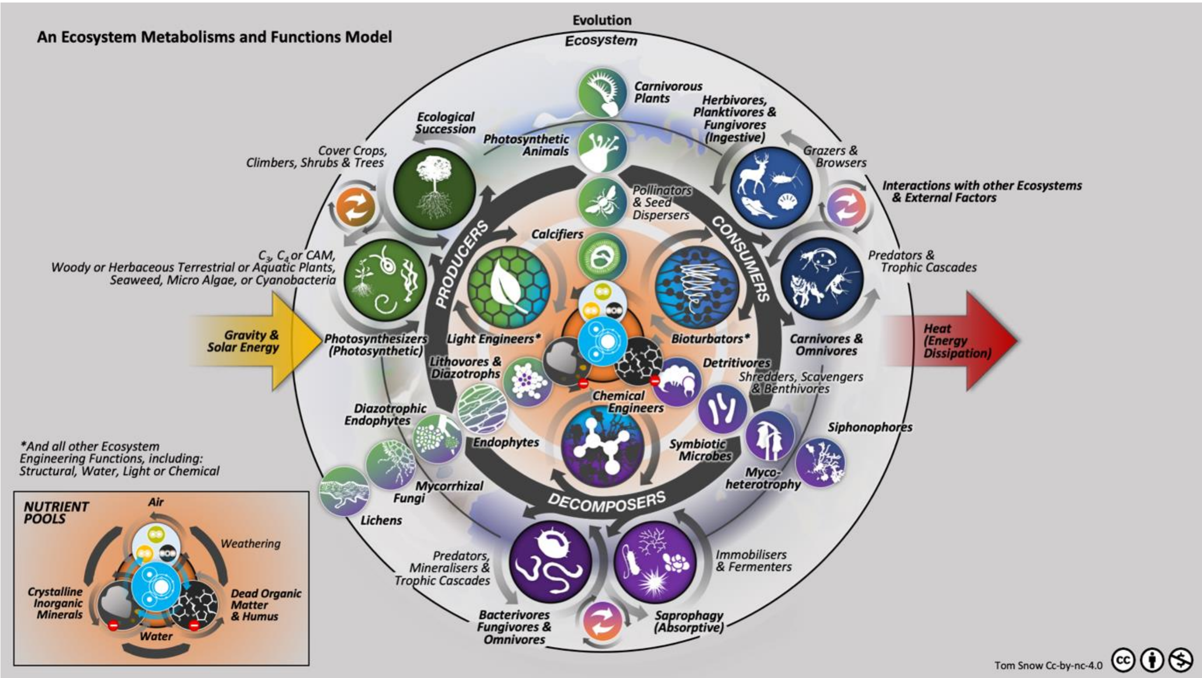


FIGURE 1. Ecosystem metabolisms and functions (EMF) model (Snow, 2020).

**An ecosystem metabolisms and functions model**

Figure 1 illustrates how energy flows into Earth as solar energy and dissipates out as heat. Gravity, the force that brings all the stars and planets together in their orbit and collective wholes, also interacts with matter on Earth 24 hours a day.

At the centre are the NPs, where matter cycles through the different spheres (hydrosphere: water, lithosphere: crystalline inorganic minerals, atmosphere: gases) and as dead organic matter, in different quantities, qualities and rates. This central collective node can be thought about as soil (the pedosphere), with water at the core, as the molecule linking non-living and living elements. The central node interacts with life (the biosphere), making it *living soil* on land, and water and air mixed with sediments in the oceans.

The *producers* can be seen at the top left (in green), the *consumers* at the top right (in blue), the *decomposers* at the bottom (in purple) and the *mixotrophs* as the smaller icons bridging the classification boundaries between all three groups. Plants are an example of producers; they can use energy from the Sun to 'eat' the air and transform $CO_2$ into sugars—the organic building blocks for all life's structures. Animals are an example of consumers, eating plants or other animals (or fungi—decomposers) for food as their source of energy. Decomposers, such as bacteria and fungi, feed on dead organic matter, and through their external digestion process of decomposition, break down complex molecules; through various indirect interactions, these become available to producers as fundamental mineral nutrients. Mixotrophs are important in directly or indirectly making nutrients available for, or sharing nutrients and *information* between, the other metabolisms—particularly as conjunctive symbionts, for example, which are one (temporary or persistent) collective organism and support different reproduction functions. This briefly outlines the principle of metabolisms' integration and interdependence.

Consumers and decomposers have predators, influencing the type of organisms and their numbers in an ecosystem, and this can have effects on other metabolic groups (e.g. carnivores, secondary consumers, feed on herbivores, primary consumers, which can help stabilise the overconsumption of plants by herbivores). Pure 'secondary producers' (predators that are producers) do not exist *per se* (although pathogenic plants do exist; moreover, carnivorous plants exist, but this is an example of a mixotroph). In this model, ecological succession—which describes the process whereby one or more species are *displaced*, not *eaten*, as with predators, by those of greater size and lifespan (for example), which themselves may be further displaced (in a relatively predictable way)—is positioned as the producer predator equivalent.

When one organism eats another, such as an animal eating a plant, this is shown as a direct *trophic* (food and feeding) interaction (large circular arrows). These trophic relationships can be bi-directional; for example, plants feed decomposers sugars (and other organic matter), predominantly within exudates excreted from their roots, in exchange for direct or indirect nutrients. Indirect relationships occur via other organisms or the central NPs (smaller circular arrows). For example, a plant may drop its leaves in the autumn, and these fall to the ground, feeding the decomposers (e.g. fungi) *indirectly* via the NPs during the winter; alternatively, decomposer predators feed on decomposers and produce vast amounts of excrements, which add to the NPs and become the main inorganic mineral nutrients for plants. Many consumers and producers have symbiotic decomposers living inside them (and on them), and in the case of the consumers, this can form bi-directional relationships similar to that described between plants and decomposers.

Placed between the NPs and the three metabolic groups are three icons (the leaf, vortex and chemical molecule), which represent the predominant ecosystem engineering functions. These make explicit some *non-trophic* (non-feeding) interactions that organisms have with other organisms and their environment. For example, the producers are predominantly the 'light engineers', as they not only use light as energy and bring that energy to the rest of the ecosystem, but they also create shade and scatter light, altering its transmission and intensity. Consumers are principally 'bioturbators', as they can burrow, excavate, disturb and mix materials in their surroundings as they move around. Furthermore, decomposers are principally the 'chemical engineers', modifying the chemistry (e.g. pH, structure, composition), for instance, of air and soil and slicing large molecules into available nutrients for themselves and other organisms (Snow, 2020).

**Ecosystem function concepts**

This subsection introduces some concepts that can act as a synthesis of some of the main points raised within the development of the EMF framework and model in Snow (2020). Concepts related to energy are as follows (the last three in this list are not discussed in detail in Snow, 2020, but they are mentioned here because they are considered important within the overall theme):

- *Gravitational energy is primary before solar energy*: Earth is an open system to energy and is powered by direct sunshine around half a day on roughly half of the Earth's surface and gravitationally powered 24 hours a day everywhere (Pauli, 2010b).
- *Energy quality changes as it flows through ecosystems*: Energy flows into Earth as mostly high-quality and powerful light; eventually, all energy is transformed and flows back into space as low quality, dispersed heat (infrared), with virtually no recycling. This relates to the First Law of Thermodynamics and the concept of emergy and transformity.
- *Producers drive energy into the biosphere*: Energy flows into the biosphere via producers (mainly plants on land and algae in our oceans), and it is transferred to other lifeforms in the form of high-energy organic compounds (see Soil and Water Conservation Society [SWCS], 2000).
- *Recycling energy requires energy*: Through each transformation, as one organism eats another, there is an expenditure of energy, which results in a loss of total available (free) energy (Rifkin, 2011). This relates to the Second Law of Thermodynamics.
- *Water cools*: Plants transpire, and particular plants (some with or some without symbiotic bacteria) can support the formation of clouds. Transpiration and cloud formation have a local and planetary cooling effect and can potentially draw water inland from the oceans. Plants

cannot transpire if there is no carbon soil sponge—water held in the soil thanks to a healthy soil food web and organic matter (Schwartz, 2016).

- *Cellular energy is driven by hydrogen batteries and adenosine triphosphate 'currency'*: Many producers extract hydrogen from water using the energy of sunlight to create a hydrogen *differential*. This generates flow, driving a 'turbine' (adenosine triphosphate [ATP] synthase) that produces ATP. ATP is a stable form of energy transport in the cells that can work in various ways. Respiration uses a similar hydrogen differential in the process of producing ATP from high-energy organic compounds (e.g. glucose), while producing water as a by-product.
- *The ecosystem economy is based on sugar*: Producers use ATP (and electron carriers [1]) to power the fixation of $CO_2$ and produce glucose. Glucose is a base fuel in cellular, inter-cellular and inter-organism transport (exchange and use), as well as for making many structural molecules (e.g. cellulose). Glucose can be transformed for transport (e.g. sucrose), sharing with others (e.g. fructose) or storage (e.g. starch).
- *Lipids store large amounts of energy*: Lipids, such as fats and oils, store vast amounts of energy. Lipids also form biological membranes and can be used for communication.

Matter is related to the following concepts:

- *Matter cycles*: Earth is practically a closed system to matter. Ecosystems are open systems to matter and energy (Jørgensen & Mitsch, 2004). Matter (re)cycles many times around the bio-sphere and through the other spheres (biotic and abiotic) at different rates and in different forms. This affects and is affected by life.
- *Matter cycles and is bi-directional*: Matter flows indirectly via NPs and directly through trophic relationships. Matter flowing through trophic relationships predominantly moves from producers to consumers to decomposers; however, matter also flows in both directions, between producers and decomposers and symbiotic decomposers and consumers. Therefore, direct trophic relationships are truly circular (not linear) and bi-directional (see SWCS, 2000).
- *Life creates structures*: All forms of life can build (biosynthesise) different forms of carbohydrates, lipids, proteins and nucleic acids (macromolecules) as building blocks for more complex structures (e.g. polymers, or enzymes) and secondary metabolites. Ecosystems store information in the structures (Jørgensen & Mitsch, 2004).
- *Matter is never truly consumed*: What is consumed comprises the qualities—the concentration, the purity and the structure—of matter and the ability of energy to perform work (Robèrt et al., 2010).

Concepts related to life are as follows:

- *Life is autopoietic—self-making*: The main characteristics of life are that life self-maintains (with a persistent input of energy) through an internal network of chemical systems that reproduces itself continuously, within some form of boundary of its making (Capra & Luisi, 2014/2015).
- *Life is self-organising and self-replicating*: Living systems are self-organising networks; unlike chemical reactions, they can replicate themselves (Pross, 2012).
- *Functions emerged through life*: There are no true functions in the abiotic physical and chemical systems of Earth or any planet. Functions emerged from life at all scales—from rubisco enzyme that fixes $CO_2$ to a heart that pumps blood, an ear that can hear (see Pross, 2012) or a *living* watershed that cleans water.
- *Functions are nested*: As we continue to remove (kill or make extinct) different species from ecosystems, we are not only removing a direct or indirect food source for other organisms, but we are also removing a functioning individual whole within an assemblage whole and greater ecosystem whole.
- *Organisms develop multi-functionality*: Fats keep us warm or plants cool (by reflecting light),

and they are highly efficient in storing energy. Roots hold a plant to the ground and soil macroaggregates together, and they collect, store and share nutrients with living soil.

- *Forms of metabolism can define all forms of life*: Healthy, modern ecosystems usually consist of three foundational functional *biotic* groups or metabolisms, which are as follows: producers, consumers and decomposers. These are all inseparably integrative and interact with their environment, the NPs and each other (Sahtouris, 2000; Vernadsky, 1997).
- *Life interacts directly and indirectly through trophic relationships*: Organisms can be eaten by another directly or indirectly via NPs; they produce secondary metabolites for their use or for direct exchange with other organisms; and they produce by-products or 'wastes', which can be (unintentionally) foods for other organisms.
- *Waste for one is food for another*: Metabolic wastes of one form of metabolism can be food for others in the *same* metabolism group (but not directly between producers, although plants do share nutrients via fungal networks) or other metabolism groups (see simplified version by Margulis & Sagan, 1995). On land, virtually all wastes of producers and consumers are food for decomposers; in the oceans, microscopic aquatic *producers*, such as micro-algae (which are from the Kingdom Protista) and cyanobacteria (Kingdom Monera) can also absorb organic wastes.
- *Functions can be trophic and non-trophic*: Organisms interact directly and indirectly in all directions through different *trophic functions*, including who-eats-whom, eating behaviours, modes of nutrition (photosynthetic, ingestive and absorptive), and *non-trophic functions*, such as ecological engineering (e.g. structural, light, chemical and water engineers and bioturbators).
- *Life collectively creates living soil*: Life both uses what it needs from living soil (as opposed to non-living regolith) and creates and regenerates it. Soil is alive with microbes, plant roots, and many animals and insects, which create its structure and other abiotic properties (Ingham & Rollins, 2011). Soil is the interface between all the abiotic spheres on Earth (e.g. hydrosphere, lithosphere, atmosphere) and life (the biosphere).
- *Consumers are value adding*: Consumers may not be obligatory organisms in all modern ecosystems; however, their presence can support greater cycling rates of nutrients (principally by increasing the bio-availability of nutrients for decomposers), defence, pollination and seed dispersal of plants, provoking change to or maintaining ecosystem communities, changing hydrological flows and reducing loss of biomass into the atmosphere, for example, during annual fires (Butterfield & Savory, 2016; Schwartz, 2016). Therefore, they can be considered obligatory for highly functioning, bio-diverse and healthy ecosystems.
- *Collaboration and division of labour exist in living systems*: Conjunctive symbionts (those that bond together in a physical way) show that many organisms give up individual freedom for the benefits of living with and within a host, either permanently or temporarily. The host creates an appropriate environment (e.g. appropriate pH, water and oxygen levels, food and shelter from the environment or predators), and in return, the symbiont can fully focus on what it does best—producing an important nutrient, such as glucose or nitrogen, or helping break down wastes.
- *Pioneer and foundational species are often conjunctive symbionts*: Conjunctive symbiotic organisms are often structural and/or pioneer species in early ecological succession ecosystems. Some are eventually displaced, while others remain as important foundational organisms.
- *Life is foundationally symbiotic*: At a cellular level, all eukaryotic forms of life are symbiotic (symbiogenesis), and all plants and animals are symbionts of some sort (often with bacteria, fungi and/or protists). What started out as cooperation between separate bacteria in the early evolution of life ended in the creation of one indivisible cell, illustrating a general principle: 'Sometimes, social groups become so functionally integrated that they become higher-level organisms in their own right' (Sloan Wilson, cited in Brown, 2003). Life involves competition, but at the same time, it is highly symbiotic, integrative and interdependent (Margulis & Sagan,

1995).

- *Plants are a fractal of a functional modern ecosystem*: At the cellular level, plants can be seen as one of the most advanced organisms on Earth; they are a fractal of a functioning modern ecosystem. That is to say, they have organelles that function in similar ways to producers, consumers and decomposers at the ecosystem level.
- *Life is one integrative and interdependent metabolism*: There is no such thing as a fully independent metabolism of a single multi-cellular organism (Sahtouris, 2000; Vernadsky, 1997). Perhaps collectively, the three fundamental forms of metabolism (producers, consumers and decomposers) co-create the one emergent NP (therefore, three + one), forming a *fourth dimension* in the ecosystem of collective efficiency. It is proposed that increases in scale, and with them, increased complexity and function, are made possible through internal and external fractal and non-fractal networks between the different forms of metabolism and NPs.
- *Life integrates and separates*: As well as integrating (e.g. biosynthesis or anabolism), organisms also separate substances (see Pauli, n.d.), such as through catabolism—breaking down complex molecules into smaller molecules (usually releasing energy in the process), which can then be used for the anabolism of other complex molecules (requiring energy; Sahtouris, 2000). Decomposers decompose minerals and organic matter into mineral elements using enzymes. Mineralisation is an advanced form of decomposition by organisms into inorganic elements.
- *Evolution can also occur at the ecosystem level*: Life on terrestrial Earth evolved through collaborations between fungi, plants and bacteria, and later, animals (Margulis, 1998). There are potential mechanisms that lead to the evolution of foundational biotic/metabolism groups (producers, consumers, decomposers) with their environment, through ecosystem-level selection of ecosystem properties. In this way, the fitness of the species that make up an assemblage is potentially determined by their collective behaviour, selecting for optimum assemblage performance (see Todd, 2019).

**Proposed added value of the ecosystem function model for design**

Building the EMF model on the principle metabolisms has several benefits, which are as follows:

- Metabolism helps explain how different organisms use energy to find and transform matter and what types of metabolic wastes they produce.
- Understanding the different forms of metabolisms and their wastes explains how different organisms *relate* to each other, in and to a place (an ecosystem).
- It is through these relationships that the different forms of metabolism express their function within ecosystems (e.g. producers *produce* the building blocks of life, consumers *consume* them and decomposers *decompose* them and make them available for producers); this helps explain interdependency.
- Functions can also be *non-trophic*, and making this explicit supports understanding of how organisms affect other organisms and their environment in ways that are not necessarily expressed, for example, in food webs.
- By understanding functions, designers can select different organisms, depending on the functions they provide—and the functions that are needed and for the specific place in which they will function—to build ‘mesocosms’ (e.g. Todd, 2019), compost (e.g. Ingham & Rollins, 2011), holistic grazing plans (e.g. Butterfield & Savory, 2016), a forest garden (e.g. Crawford, 2010) or integrated elements, for example, within passive buildings.

**Proposed added value of the integrative systems of production model for design**

Building the ISP model on analogies from the EMF model has a number of benefits, which are as follows:

- By developing the two models concurrently, a potentially more coherent foundation is provided for designers of systems of production.

- Making the analogy between the three principle metabolisms (and mixed ones) and the three principle methods (and mixed ones) by which humans can transform matter brings these two activities conceptually in line, and they are arguably *both metabolisms*. (One key difference between the two is that the latter involves the intention of design). Therefore, this opens space to think about the design of systems of production that are regenerative and produce zero waste, representing an integrative 'production ecosystem'.
- By linking the two models via metabolisms, the conceptual link seems strong enough that many principles, patterns, and analogies are potentially transferable from one to the other. Through personal experience so far, the deeper the understanding within the EMF model, the greater the possibilities of thinking about the ISP model—and in some cases, vice versa.
- Like the EMF model (at least with plants and ecosystems), the ISP model is also fractal—from 'mesocosm' or 'eco-machines' (micro-) design to a single production site (meso-) design and regional (macro-) design.
- The EMF model does not view life through kingdoms and hierarchies. This is also transferred to the ISP model, where no economic hierarchies, for example, are inferred (explicitly, implicitly or otherwise) between different forms of production.
- By making the main different types of 'regenerative nutrients' explicit in the model, it makes it easier to talk about and discuss, for instance, the interdependent needs for matter and energy in our systems of production, how our activities transform them and where outputs can become inputs for another activity.
- Like the EMF model, the ISP model attempts to look at and understand all forms of life via the different forms of production and eco-design practices. This has the potential—as in living systems—to provoke cross-pollination, synergies, symbiosis, co-evolution and interdependencies; ultimately, as these different activities all support *parts* of the solution, together, they may be able to form truly regenerative and zero-waste systems as an integrative whole.
- The EMF model discusses structure—the different structures organisms make within and with their bodies (autogenic) and in their environment (allogenic)—via 'ecological engineers'; here, in the ISP model, hard infrastructure links the analogy.
- Other than forms of symbiosis, expressed within the EMF model, the ISP model does not explicitly include any discussion about the ways organisms *organise* themselves and their resources, for example, in terms of hierarchies and power structures. The benefit is that the ISP model is pertinent to all forms of collective collaboration (e.g. public, markets, commons and households). Furthermore, different frameworks and models are appropriate for thinking about these forms of social/provisioning institutions.

The broad range of influences from different fields and schools of thought are discussed in the appropriate subsections in the next main section.

## AN INTEGRATIVE SYSTEMS OF PRODUCTION MODEL

This third main section describes the ISP model. Each subsection looks at the model in parts, progressively building up a picture of the whole model, which is presented in its entirety at the end of the section (Figure 10). The first subsection looks at the central regenerative nutrients, followed by three principle processes for designing ISPs (synergistic, circular and cascading); this is followed by three hybrid processes (biomimetics, recycling and bio-fabrication) and infrastructure, which connects them all together at the end. Although the ISP model is described in parts, it should be kept in mind that the ultimate goal is for these potentially different approaches to be brought together at the micro-, meso- and macro-levels (discussed at the end of this section), potentially making the integrative whole greater than the sum of its parts.

### Regenerated nutrient pools: Increased qualities bring higher productivity potential

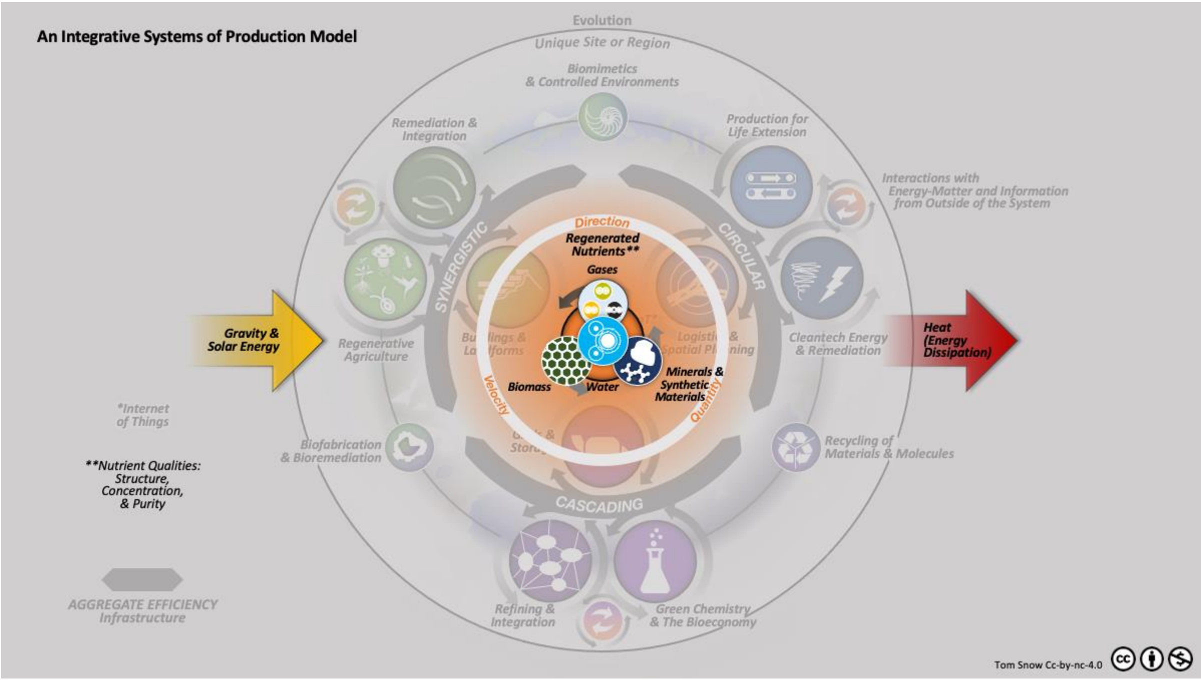


FIGURE 2. Regenerative nutrients (Snow, 2020).

Energy and matter are neither created nor destroyed, and therefore, they are never truly consumed. What are consumed are the *qualities* of matter—the concentration, the purity and the structure of the matter—and the ability of energy-matter to perform work (Robèrt et al., 2010). Through the integration and practice of the three principle design strategies and hybrids and their corresponding forms of production, we should aim at maintaining or even increasing nutrient qualities. In essence, this central node is an analogy of living soil, but in the ISP model, it expresses the dynamic and related resources that we share through our use and transformation processes—and with the ecosystems in which they are embedded.

Regenerated nutrients are made up of the following basic nutrients: water (e.g. warm, cold, fresh, salty, dirty or clean), gases (all types of gases, including those compressed in liquid form), biomass (e.g. terrestrial and aquatic living or dead organic matter, including residuals, which are *not* fossil based) and mineral and synthetic materials (e.g. metals and non-metals, synthetic chemicals and polymers and fossil fuels). Combined with the energy flowing through the system, these are the basic 'nutrients' that we use to produce all material goods.

For designers looking at the *form* of energy supply for a particular system, they can, for instance, consider the forms of energy available and their quality—or exergy—the maximum useful work possible during a process (Dincer & Rosen, 2001), linked with the existing and potential *requirements* for the use of the energy for a particular system. Designers can also consider how different forms of energy transformation can be integrated and how some may require storage and/or further transformation (see more in infrastructure section).

Virtually all systems of production are extremely water intensive; therefore, one of the key activities is designing for the proper use of water and supporting the natural functioning of the hydrological cycle (Hall & Klitgaard, 2018). Water can vary, for example, in its level of salinity, phase or concentration (e.g. as clouds, mists or dew), as well as the way it falls to Earth (e.g. rain, snow, hail), how it deposits on objects, where it is stored and for how long and its form after use (e.g. grey water, black water, white water and heated water).

Gases in systems of production include the often lesser known gas sectors that extract, clean, store and often compress gases for industrial, food, pharmacy and energy applications, among others. Gases including $CO_2$, given off during fermentation, can be captured and used for other processes, such as enriching the atmosphere in greenhouses.

Biomass is a substance composed of organisms that are living or dead (Bos et al., 2019). On Earth, it is estimated that 82% of all biomass is plant-based, and 13% is bacteria, while all other organisms make up just 5% of the biomass—with humans representing less than 0.01% (Carrington, 2018). Living organisms produce an abundance of different forms of biomass (and potential materials), which can be used for a vast number of design applications (see more in the section on circularity and the bioeconomy). Designers can search for, and use, primary products—biomass that has been grown for a specific product, such as trees grown for timber, cork, resins or latex—and secondary products/by-products/residuals, which can often be considered wastes, such as tree foliage, sawdust and bark. Standard ratio figures of the two forms exist; for example, the primary products of a tree can make up 70% of the biomass, while the secondary products can make up 30% of the biomass (Bos et al., 2019); this makes it possible for designers to calculate potential quantities from a single system of production or across regions.

Minerals include clays, salts, limestone, diamonds, sands and gravels, rocks for structures, a plethora of mineral elements that include metal ores and non-metals and combustible fossil fuels (e.g. coal, natural gas petroleum products and uranium). This node also includes synthetic (human-made) materials, such as metals, glass, plastics, non-organic textile fibres, materials in powder and liquid form, chemicals and composite elements—even electronic elements defined under 'WEEE' (Waste Electrical and Electronic Equipment). Our modern lives are made possible by the use of minerals and synthetic materials and through their enabling of new technologies (Graedel et al., 2015). Over time, demand for technologies has increased, augmenting the amount and array of materials required (Barbara et al., 2015). Minerals also have certain concentrations in specific geological locations, and therefore, geo-political repercussions (European Commission, n.d.); they are associated with supply risks (e.g. depletion time), environmental implications (e.g. human and ecosystem health) and vulnerability to supply restrictions (e.g. market importance and substitutability constraints; Graedel et al., 2011). Generally, minerals tend to slowly disperse or form (even microscopic) toxic concentrations.

Principally, where possible, biomass may be able to replace many of the materials (not necessarily the fuels, except perhaps for aviation) that are currently based on fossil fuels (see the 'Bio-economy' section); the use of synergies, circularity, recycling and substitution (where possible) will all support the reduction of mining and the negative effects this has on ecosystems and human health. At the same time, not without controversy, groups including DeepGreen Metals Inc. have proposed bringing a large amount of concentrated and relatively pure metals (and other minerals) from deep-ocean locations, which they suggest could create a large enough foundational mineral 'pool ' to support a global metal recycling system—and for instance, the shift to electric battery cars (DeepGreen, n.d.). Research by McGlade and Ekins (2015) has estimated that, to limit climate change to 2°C (and ideally to below 1.5°C) in the period until the end of this century, one-third of all oil reserves, half of gas reserves and more than 80% of coal reserves must remain unexploited.

**Synergistic systems: beneficial relationships and behaviors stimulate collective functionality**

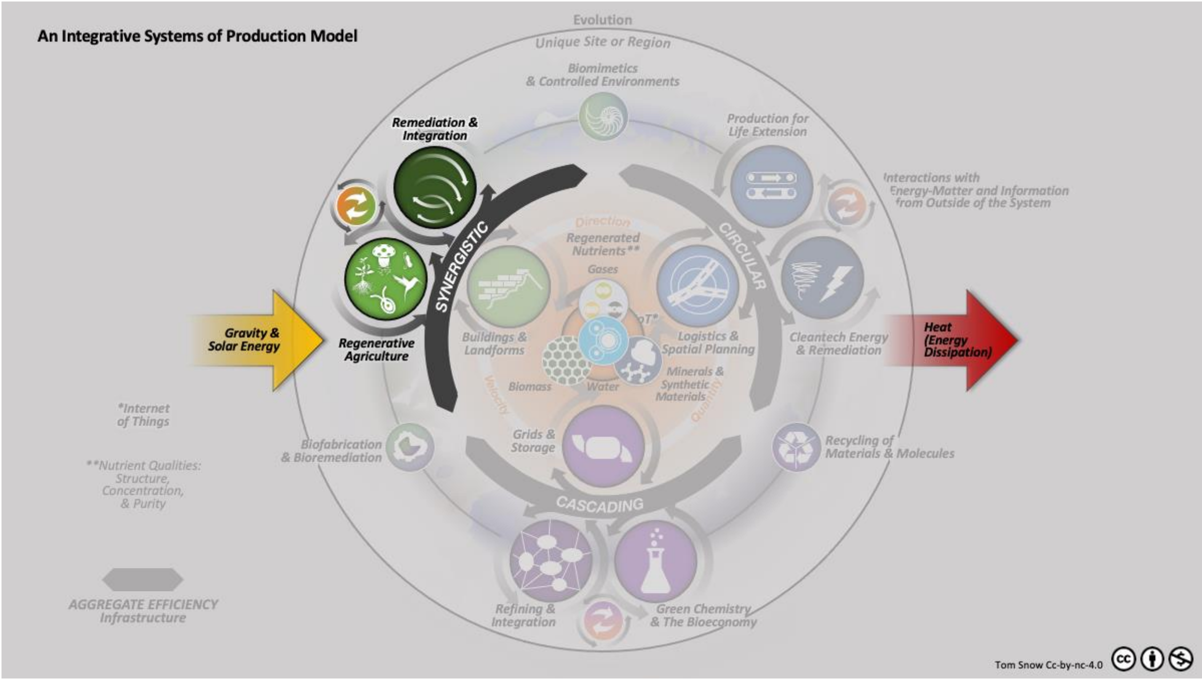


**FIGURE 3.** Synergistic systems (Snow, 2020).

The next group of integrated elements works with, and designs living systems based on, the concept of looking for and developing *synergies* that support *growth, health and reproduction*. The main inspirations for this node come from different branches of regenerative agriculture, used here as an umbrella term for concepts/schools of thought; these include natural farming (Fukuoka, 2009), permaculture (e.g. Hemenway, 2009; Holmgren, 2011; Mollison & Slay, 1998; Whitfield, 1996/2016), agroecology (e.g. Altieri, 1995; Altieri et al., 2005; Gliessman, 2015; Shiva, 2016), holistic management (Butterfield & Savory, 2016), biodynamics, conservation agriculture (e.g. Montgomery, 2017) and agroforestry (Agforward EU, n.d.).

A definition of regenerative agriculture by Terra Genesis International (n.d.) is that it is a

> system of farming principles and practices that increases biodiversity, enriches soils, improves watersheds, and enhances ecosystem services. Regenerative agriculture aims to capture carbon in soil and aboveground biomass, reversing current global trends of atmospheric accumulation. At the same time, it offers increased yields, resilience to climate instability, and higher health and vitality for farming and ranching communities.

There are a range of *practices* that these different, but often overlapping, alternative agricultural design schools discuss and/or promote. These are listed as follows, in subgroups developed for this paper:

- *Polyculture (vs. monoculture)*: This can be established by increasing *vertical diversity* (greater mix of the form of metabolism, e.g. mixing animals, plants and microbes) and horizontal diversity (variety within the same metabolic groups, e.g. most plant species). Diversity can potentially improve collective functions, such as nutrient accessibility and cycling, water storage and resilience; provide shelter and food for beneficial (pest) predators and pollinators over space and time (Altieri et al., 2005); and potentially be more productive—as a whole—over space and time.
- *Thinking in Three Dimensions (vs. yield per m$^2$)*: An idea that is linked to but distinct from polycultures is the concept of developing terrestrial and marine agricultural systems that are

stacked or layered to maximise the horizontal *and* vertical dimension (upwards and downwards; Pauli & Kamp, 2017). This can potentially improve overall collective yields (not only the yield of one species), provide diverse usable and valuable products over different timescales and allow designing for 3D synergies, such as trees being used as structures for climbing plants (e.g. vines). Many of the works around food forests (Crawford, 2010; Jacke & Toensmeier, 2005; Whitfield, 1996/2016), 3D/regenerative ocean farming (GreenWave, n.d.) and agroforestry lay out fundamentals of these strategies.

- *Integrating animals (vs. urbanisation of animals and broken synergies)*: This can be done through the following: *i)* integrating certain animals into specific regenerative systems through strategies that include holistic planned grazing (Butterfield & Savory, 2016); pasture cropping (Butterfield & Savory, 2016); pastured small livestock, such as fowl and rabbits in moveable pens (Pollan, 2006); and silvopasture (mixing trees into animal pastures). These can all be used to diversify incomes (e.g. meat, fibre, milk, eggs or other products) and be part of a regenerative management plan for (re)building living soil. Selective breeding is also an important component of this node; *ii)* integrating pollinators (e.g. bees) into all landscapes for pollination, as three-quarters of crops across the globe that produce seeds or fruits for human consumption depend (at least in part) on pollinators (Food and Agricultural Organization of the United Nations [FAO], 2018); *iii)* shellfish can be integrated into the 3D ocean farming of seaweed, including scallops, mussels, oysters and clams; the bountiful ocean forests can also help regenerate local fish and large mammal ecosystems (by supporting the existence of all the ecological functional groups) and support the process of turning $CO_2$ into limestone (by making *shells*, which fall to the bottom of the ocean as they die)—although as we continue to acidify our oceans, making shells becomes increasingly difficult (Bjornerud, 2018); *iv)* replanting damaged corals, which are (sessile) animals and important structures within coastal marine ecosystems, and finding solutions to bleached coral reefs. Integrated pest management, which is mostly for plant pests, can also be developed for animal farming (which is evolving, e.g. in fisheries).
- *Integrating functional behaviours (vs. division and suppressing natural behaviours)*: In many ways, the 'Permaculture Chicken' (see Figure 1, p. 38, 'Products and Behaviours of a Hen', Mollison, 2012) embodies the basic approach. For example, it includes a review of inputs ('needs'), outputs ('products'; see the cascading section for this) and behaviours (e.g. scratching, foraging) that link to functions and intrinsic characteristics (e.g. breed, colour, climate tolerance) of a chicken (Mollison, 2012). This is then repeated for other elements in the system boundary (ecosystem), which can lead to different elements being brought together, developing a wide range of optimising design solutions and management techniques (Mang & Reed, 2012). For example, by integrating the scratching behaviour of chickens with the need to clear a vegetable patch at the end of the growing season, chickens do what they do best ('plough'), and the farmer can have less work to do. See 'ecosystem engineers' in Figure 1.
- *Integrating regeneration in practice (vs. diminishing the natural capital)*: This is about improving the natural capital of the place through, and integrating with, specific practices. This particularly includes the work of Elaine Ingham and Walter Jehne, who promote activities to support the functioning of living soil—or the 'soil carbon sponge' (Schwartz, 2016), such as with the use of composts, cover-crops (or other 'soil shields'), no- or low-till land management and potentially appropriate use of biochar and Terra preta (Terra Genesis International, n.d.). This also includes reforestation and conservation projects, such as wildlife corridors and national parks. Plants (and cyanobacteria) can also be used for phytoremediation—the use of plants to clean soil, air and water (Gremida et al., 2008). For example, certain plants have the ability to concentrate elements or compounds from the environment and (bio)accumulate, degrade and/or render them harmless; heavy metals are often the major target (e.g. in abandoned mine workings). Riparian woodlands can also be planted, for instance, to protect riverbanks and flood plains from erosion. Decomposers, such as bacteria and fungi, can also be used for remediation, including degrading targeted pollutants. Some examples include myco-remediation (using

fungi), bioventing (cleaning groundwater with bacteria) and bioleaching (using microbes to extract metals from their ores).

- *Integrating perennials and group-level selection (vs. focus on annuals and importing animal or seed stock based on individual yield)*: One of the important shifts that can be made in agricultural systems is the shift from annual to perennial plants. This can be done in a number of ways: *i)* Since 1976, the Land Institute, based in Kansas (USA), has been working on the domestication of wild perennials and crossing annual crops with their perennial relatives, to replace the main staple annual crops (e.g. rice, sorghum, sunflowers and chickpeas; Montgomery, 2017); *ii)* growing (more) perennial vegetables (globe artichokes and rhubarb are the most common), which can reduce work through less need to cultivate the soil, extend the growing season and release fewer carbon emissions (as less cultivation means less nutrient flushes for decomposers; Crawford, 2012); thanks to the healthier living soil, a more mature root system and longer lifecycle, the perennial plants also have a greater ability to build more relationships in the soil, and therefore, absorb more nutrients; *iii)* growing trees for flour (instead of monoculture, annual cereals), such as sweet chestnut nuts (Crawford, 2010); iv) this links (to previous point) to the different strategies under the umbrella of 'agroforestry'—the deliberate integration of trees (and shrubs) into crop or animal systems, benefiting the ecological functions of the system, while also bringing new potential income streams to farms (Agforward EU, n.d.) and potentially non-farm production. This also ties in with the work of people like Vandana Shiva and the *Navdanya Network Seed Project*, as well as global projects, such as the global seed vault in Svalbard, representing the process of saving seeds and genetic variety and genetics that have evolved within certain ecosystems. Local seed saving can lead to the selection of varieties by the farmer that work best in their ecosystem. Theoretical biologist Sloan Wilson (2008) highlights that artificial selection at the *level of groups* (vs. selecting the most productive individual) can also have beneficial effects, such as the greater yield of the group as a whole.

This is a brief introduction to *some* of the many synergy concepts that these different fields have developed. The second of the two nodes, 'Remediation and Integration', is partly covered in this brief introduction. Here, remediation is the conscious restoration of toxic or dilapidated land; generally, it is the first step in bringing the functions back, not necessarily into a highly functioning state. The term 'integration' used in the second node underlines the potential to integrate these productive living systems with the other systems and our urban environments. Mixed with areas of 'rewilding' and protected areas, we can have vast areas of beautiful, diverse and productive landscapes.

## Circular systems design: optimising product life extension slows dissipation

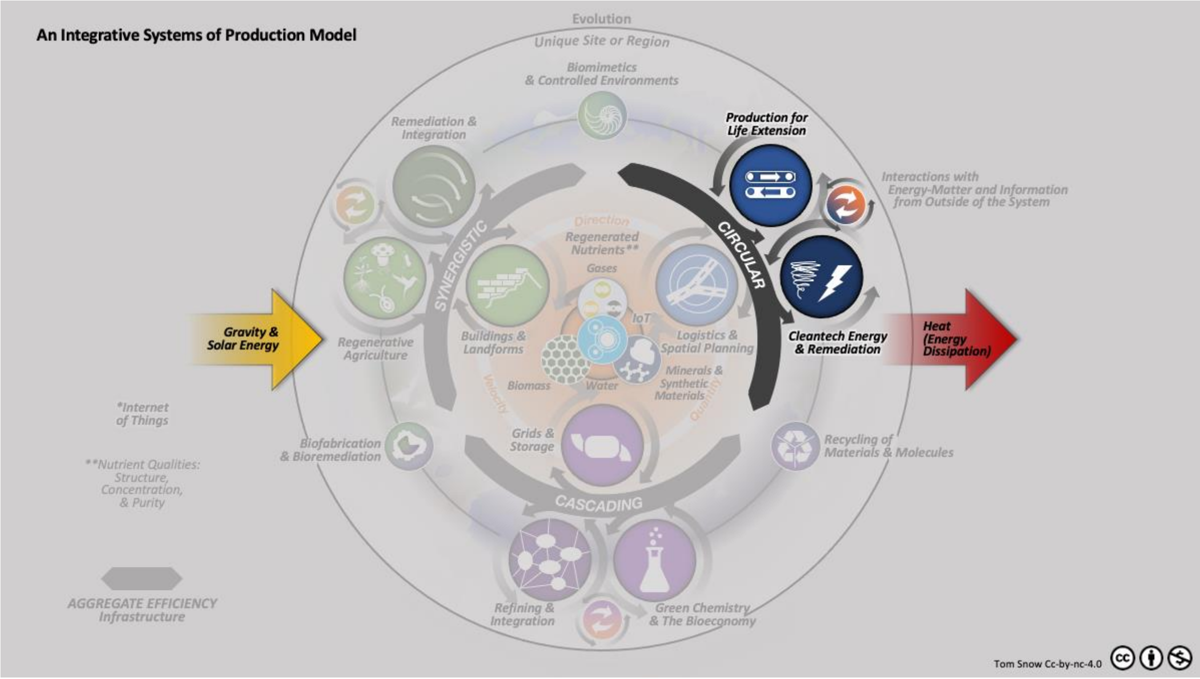


FIGURE 4. Circular systems (Snow, 2020).

This group of interrelated *assembly/disassembly* activities is predominantly inspired by Stahel (Stahel, 2006, 2013, 2019; Stahel & Ready, 1976, 1981), Steinhilper (2000), Sundin (2000), Charter & Tischner (2001), McDonough & Braungart (2012), and relatedly, the Ellen MacArthur Foundation (2012).

This group of interrelated systems focusses on circularity, which attempts to reuse the most appropriate amount of a product and/or its components or sub-components for an optimal amount of time. These are synthetic (or 'technical') products, such as mobile phones, cars and aeroplanes, and for example, they are made out of metals and/or plastics, composites, and to a lesser extent, wood (and potentially some natural fibres); this makes them *entropic goods—they wear* down with time and use. As Daly and Farley (2004/2011, p. 19) explained, 'An entropic flow is simply a flow in which matter and energy become less useful'.


FIGURE 5. 'Intervention spectrum' for circularity. Original photos from left to right: Germanslat (2018), AnnaPannaAnna (2018), Bluebudgie (2018), Sutulo (2017), Barni1 (2015) (diagram: Snow, 2020).

As in nature, animals (the consumer analogy of this part of the ISP model) eat other animals, and so some energy is transferred (recycled) from the prey to the consumer. However, hunting and transforming energy, matter and so on requires energy. In circular systems, the goal is that this energy comes from renewable resources; therefore, this section includes *cleantech* products that have been developed (and defined in this paper) to produce clean energy through physics (and thus, do not include biological or chemical energy production).

The optimal product life extension of technical products can include a number of different strategies to increase (and make possible) maintenance (including repairing, inspection and servicing; Steinhilper, 2000), refurbishing, reconditioning, remanufacturing, cannibalisation and repurposing (Figure 5). In brief, industrial sophistication and the extent of the intervention usually increases from left to right (Figure 5), with maintenance extending from simple, regular inspection protocols to remanufacturing, which can involve disassembly of the entire product (or *core*), cleaning and replacing or even upgrading components so that the reassembled products are as least as good as the original (European Remanufacturing Network, n.d.; for a further introduction, see The All-Party Parliamentary Sustainable Resource Group, 2014). In this paper, *cannibalisation* is the collection of components or cores for storage and later re-sale and/or re-use. The intervention spectrum should follow the basic rules that the 'tighter' the reuse cycle, the 'higher the potential savings on the shares of material, labour, energy, and capital embedded in the product and on the associated rucksack of externalities (such as greenhouse gas (GHG) emissions, water, toxicity)' (Ellen MacArthur Foundation, 2012, p. 7), which is linked to the mandate, 'Don't repair what is not broken, don't remanufacture what can be repaired, don't recycle what can be remanufactured'. The following is a brief overview of some key strategies available for designers:

- *Design for hyper-efficiency or even for 'nothing' (vs. design for greater aggregate consumption)*: This focusses on designing products that are as efficient as possible (e.g. Lovins et al., 1999). This can mean reducing energy requirements for individual products and/or integrating different products to potentially reduce their overall energy requirements. Examples include the light weighting of cars, designing pipes that improve flow and LED (light-emitting diode) lighting. The mandate to 'Substitute Something for Nothing' (Pauli, 2012) also provokes us to not just think about reducing the effect or increasing the performance of an element but also to design a system that does not even require it. An example of this can be, instead of designing new filters for cleaning water, using vortexes powered by gravity that can potentially remove the need for filters altogether.
- *Design for multi-functionality and modularity (vs. design for single function and use)*: This inspired by living systems, where elements of organisms often have multiple functions, such as lipids (see the earlier section on ecosystem concepts). This can reduce the weight, total use of materials, and number of different products required to serve different functions. The classic example is the Swiss army knife; another is the hybrid thermal water heater and photovoltaic system, developed by *Solarus Smart Energy Solutions*, which produces a collective benefit of the solar-heated water travelling through the system taking heat away from the photovoltaic system, making it more efficient. Modularity can also improve personalisation, the potential to replace damaged/obsolete components and the potential for upgradability. Examples include many elements within bicycles, IKEA furniture and the Fairphone mobile phone.
- *Design for product life extension (vs. 'end of pipe solutions')*: Many innovations and innovators have developed solutions 'at the end of the pipe', such as independent shops that fix and re-sell mobile phones. However, if all products are designed for circularity from conception, then clearly, a vast number of issues around qualities—and the related economic viability—could be addressed. In some ways, product life extension acts like the consumer predators in the ecosystem framework: Keeping a check on the growth of new ('virgin') production—and through this, potential competition—can increase the fitness of the new products being developed. This last point underlines that it is not necessarily the objective to have products that last 'forever', as new technologies can become more efficient (e.g. using less water or

energy), while others can be made redundant (hence the use of the word 'optimal'). The following are some potential design subgroups for this section:

- *Design for cleaning*: Cleaning is most often used to remove rust, old paint and grease. The methods used include $CO_2$ spray (such as dry ice), compressed air (Charter & Gray, 2007), ultrasonic baths, sand blasting, steel brushing, washing in cleaning petrol, baking ovens, steam or hot water jet cleaning and chemical detergent spraying or purifying baths (Steinhilper, 2000). Multiple treatments can be applied to the same core in a sequence or even at the same time. Designing the product to be easily cleaned ultimately makes this process cheaper, quicker and more effective.
- *Design for disassembly & reassembly*: This is ultimately designing products/components that can be efficiently disassembled at low cost while preserving their initial properties (high quality)—prior to relevant life-extension processes—and designing products/ components that can be efficiently put back together at low costs while preserving their initial properties (high quality). See Chiodo (2005) for a list of principles, as well as Steinhilper (2000) and Ijomah et al. (2007) for a range of design strategies.
- *Design for inspection, fault detection and sorting*: The inspection and sorting phases are closely related, as the second activity can be viewed as the completion of the first (Gallo et al., 2012). Design can improve the speed of analysis and the quality of intervention options selected (including the option for no intervention) by a potential range of different stakeholders. In other words, the inspection process is used to establish the current status and the history of the products/components to enable applying the appropriate methods for reparation (Charter & Gray, 2007). Easy access to elements within a product and to information—either digital or visual—can help determine the state of the product (e.g. wear level, use rate and what is specifically wrong).
- *Design for new business models and relationships*: Circularity provokes (and in many cases requires) new relationships between manufacturers and their clients and between manufacturers and other actors within the circular ecosystem. By being more actively engaged with the product during use and at end of use, companies often need to engage, for example, with waste collection networks, after-sales services and new regulatory bodies. This also opens up possibilities for developing new forms of exchange and ownership models between manufacturers and their clients. As an umbrella term, *product–service systems* (e.g. Stahel & Giarini, 1989; Jansen et al., 1997; Manzini et al., 2001) include a variety of product–service hybrid solutions. For example, products and services both provide useful functions for consumers (the 'ends' in this case); however, functions usually offered only by products (e.g. washing machines) can also be provided via an integrated mix of products and services—the 'means' in this case (e.g. a laundrette). Through this mix, a function (following this previous example, the functional 'end' is clean clothes) can potentially be supplied with a reduced environmental footprint through dematerialisation and/or efficiency improvements and higher value relationships between consumers and companies (Charter & Tischner, 2001).

Many cleantech energy systems capture energy from geological (abiotic) sources, such as those that take advantage of differentials in temperature, pressure, altitude (and therefore gravitational potential energy), current and flow direction. Others use technologies to transform solar energy into electricity (e.g. photovoltaics, concentrated solar power), sunlight into water heating, thermal mass, solar chimneys, solar cooking, solar air conditioning, solar desalination and solar furnaces, to name but a few.

## Cascading systems design: provoke new relationships before returning to nutrient pools

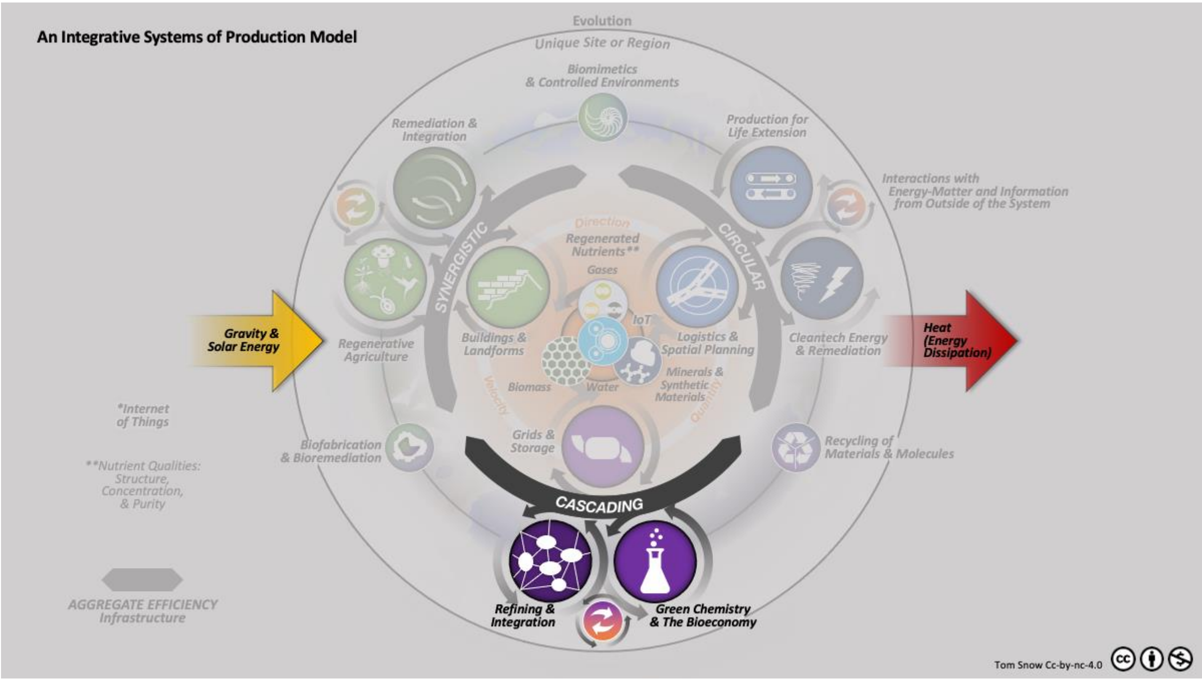


FIGURE 6. Cascading systems (Snow, 2020).

This group of interrelated *transformation* activities is predominantly inspired by the individual and collective works of Odum (e.g. 1969), Gunter Pauli (e.g. Pauli, 1998, 2010a, 2010b; Pauli & Kamp, 2017), Bistagnino (2011, 2014/2016) and the work around organic mushroom farming (e.g. Cotter, 2014; McCoy, 2016; Milenkovic & Mllosavljevic, 2017; Stamets & Chilten, 1983), green chemistry (e.g. Anastas & Warner, 2000), and McDonough & Braungart (2012).

These *cascading* systems, much like the detritus food chains (waste is food, rather than prey is food) within food webs that they often aim to (and do) emulate, have the potential to produce zero waste, while returning biomass, gases and liquids (but less so minerals, other than the mineral nutrients that may be contained in the others) back into the atmosphere, hydrosphere and lithosphere. The minerals and synthetic materials (or 'technical nutrients'), in contrast, are designed—and intended—to remain in the circular systems or be recycled.

Much like the decomposers that this group is analogous to (see the EMF Model, Figure 1), cascading systems can be integrated to manage waste flows that cannot be used (or are not the most appropriate for use) within the other design systems. For example, by-products produced within agricultural systems can be used as inputs to a diverse range of cascading production systems, as can potentially heat, gases and nutrient-rich water, for instance, produced by circular systems. Cascading systems can include life, and therefore can be classed as 'agriculture', while other systems do not include life. The following are some groupings of potential design strategies that can be made within this collective group:

- *Design using green chemistry principles*: Arguably, the basis of these, generally chemical and bio-chemical (involving living) systems, is the understanding and practice of what has been termed 'green chemistry'. Paul Anastas and John Warner (2000) defined green chemistry as 'the design of chemical products and processes that reduce and/or eliminate the use or generation of hazardous substances. This approach requires an open and interdisciplinary view of material and product design, applying the principle that it is better to consider waste and hazard prevention options during the design and development phase, rather than disposing, treating and handling waste and hazardous chemicals after a process or material has been developed'. In the same book, the authors outline '12 Principles of Green Chemistry', which were developed as a framework for learning about and designing green chemical systems. Supporting (and provoking) the transition towards green chemistry, important legislation like REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) in Europe (since 2007) and work like the ChemSec SIN List—a scientific list of hazardous chemicals that are proposed to be removed from use, with alternatives suggested (if they exist). Another practice is the potential substitution of chemical processes with physical/mechanical or bio-chemical ones that can produce no or low by-products.

- *Waste is food (vs. waste is a problem)*: As seen within food webs, organisms do not just eat other organisms (e.g. predators eating prey); organisms also eat organic (e.g. detritus) and non-organic wastes from other organisms. For example, within communities of *anaerobic* decomposers, some produce waste gases and acids, which become sources of food for other species in the community (or 'consortia'). Within these anaerobic consortia, eventually, all the products are converted into methane ($CH_4$) and carbon dioxide ($CO_2$). These same principals within aerobic and anaerobic detritus chains can be applied to organic wastes, such as spent grains or nutrient-rich wastewater from a brewery becoming the input for a host of cascading possibilities, from inputs for bread or growing mushrooms, to wastewater being feed for pigs and organic waste excrements going to biodigesters (for methane) and ponds to grow algae (Bistagnino, 2011). As Odum (1969, p. 268) proposed, by "…tapping the detritus food chain man can also obtain an appreciable harvest from many natural systems without greatly modifying them or destroying their protective and esthetic value."
- *Economies of scope (vs. economies of scale)*: Within these cascading systems, activities can be clustered—activities related by material flows, not sector or market clusters, which may usually constitute business clusters—that can provide a range of *different* cash flows. And since 'several costs of stand-alone businesses are converted into income, the integrated cash flow for the whole cluster is higher than the consolidated cash flow which is simply the sum of all individual operations' (Pauli, 2010b). Clusters can be developed, for example, within and around breweries. The input–output link between activities within a cluster attempts to capture and create value through every transformation process. Many of these processes require a fundamental understanding of chemistry and bio-chemistry, and in some cases, agriculture, as these systems are primarily about producing chemicals, materials and sometimes food.
- *Intermediate technologies (vs. highly complex and high cost machinery)*: Schumacher (1973) outlines the benefits of low-cost and relatively simple machinery, that supports workers in their production process, whilst being affordable and easy to maintain. Whether it is simple self-assembled tools, sophisticated 3D printers and drones, or the 'open-source' maker movements (Rifkin, 2014) for example, the benefit is that intermediate technologies can help cascading systems be integrated within synergistic and circular systems at the micro and meso scale.

The 'bioeconomy' (Figure 7) can be defined as 'the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy. It includes agriculture, forestry, fisheries, food, and pulp and paper production, as well as parts of the chemical, biotechnological and energy industries' (European Commission, 2012). One principal goal of the bioeconomy is to substitute the use of fossil-based materials with bio-based materials (Bos et al., 2019). The bioeconomy is interdisciplinary, including the chemical, energy, construction and material industries.

The bioeconomy activities can use green chemistry processes (or not), and green chemistry activities can be bio-based (or not). Although there can be strong partnerships, both are *not* generally engaged in the growing of organisms or their harvest: This work is primarily done in synergistic systems. To underline this point, in this framework, the bioeconomy predominantly (if not totally) begins *after* harvest or once a waste residual has been collected from the other systems.

Unlike fossil-based resources, these natural living systems have different dynamics and factors to consider, such as the variabilities in dates of harvest (which depend on the changeable climate), harvest yields, harvesting methods (which can affect the quantities and qualities of the product(s) harvested), post-harvest treatments, extraction and purification methods applied to the product(s), standardisation requirements of the product(s), storage techniques (as organic substances can quickly degrade) and packaging and distribution of the product(s).


**FIGURE 7.** Bioeconomy: the oldest, foundational economy (original photo by Konevi, 2019) (diagram: Snow, 2020).

The different forms of biomass inputs into the bioeconomy can be classed into the three following groups: *first generation*, which generally includes plants (crops or 'primary products') that are grown explicitly for an intended purpose, such as maize for biofuels; *second generation*, which is the use of residuals (or 'secondary products') from agriculture primary products, agribusiness processing operations (e.g. husks, nut shells and shellfish shells, fish skins and bones), restaurant or domestic household food wastes and prunings and cuttings from parks and gardens, for example; and *third generation*, which generally includes systems based on macro- or micro-algae, often transforming human or other excrement wastes into algae biomass, which can potentially be used for high-value products, such as fuels or chemicals. This group can also include working with microbes to build certain materials; however, in this framework, this is *bio-fabrication*.

As a whole, the three generations describe the timeline of their development, with the third generation being the least developed. However, all have a role to play in the bioeconomy. Although there can be huge concerns with the first generation—for example, crops being grown on prime land—which may be better used for growing food, and the real cases of deforestation to plant these crops; elephant grass (*Miscanthus x giganteus*), turkey foot (*Andropogon gerardi*), switchgrass (*Panicum virgatum*), willow (*Salix*) and hemp (*Cannabis sativa*) are all examples of plants that can be grown on marginal land with little additional water or nutrient inputs. These types of crops can be classed within the second generation; however, in this model, the first generation seems more appropriate.

The bioeconomy is highly linked with the concept of *integrated biorefineries.* These are spatially clustered (networked) biorefineries that process different types of matter, producing different products, whereby the output of one activity cascades as an input for another (often via some form of use/consumption). For example, terrestrial crops, such as cereals, are harvested; these are then refined in a raw material biorefinery, extracting several (intermediate) goods, such as starches, oils and flour. Residuals from this production process can go to another biorefinery specialised in composting, for example, or to animals (as feed). Other biorefineries, such as thermal conversion sites, can transform harvested and residual biomass for *combustion* (producing heat and electricity), *gasification* (producing syngas, synthetic natural gas, heat and electricity), *pyrolysis* (biochar and pyrolysis oil) and *torrefaction* (producing pellets for subsequent combustion). Finally, further biorefineries can extract chemicals, materials, fuels and energy from biomass (virgin or residual). Cascading can also be integrated into bioremediation.

## Hybrid systems: bridging systems can create new opportunities

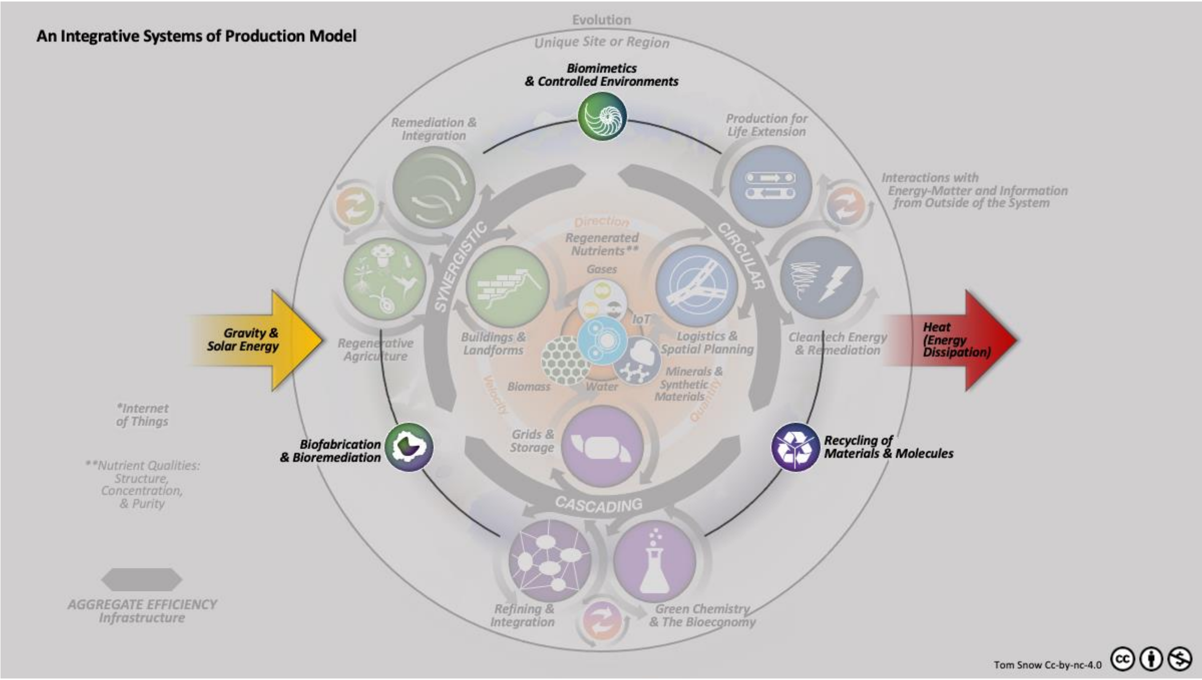


FIGURE 8. Hybrid systems: Biomimetics, Recycling and Biofabrication (Snow, 2020).

### *Biomimetics and controlled environments*

Benyus (1997/2002) developed the biomimicry framework, which looks at nature as model—imitating and taking inspiration from nature; nature as measure—nature has learned what works over the course of 3.8 billion years of evolution; and nature as mentor—this is a new way to value nature, and learn from it, instead of extracting from it. Biomimicry can look at how termites, for example, maintain a stable temperature in their mounds to inspire passive architecture. It is less focussed on the level of ecosystems compared with the other frameworks, and instead, it is more focussed on how individual organisms or populations function (physically, chemically and biologically). Biomimicry is a practice that learns from, and mimics, strategies found in nature to solve human design problems and find hope along the way (Benyus, 1997/2002). The emphasis is often on product design and materials.

Eco-mimetics, a branch of biomimetics, is concerned with transferring knowledge from ecosystems to engineering and design. In architecture, 'the use of an ecomimetic approach has considerable potential in addressing environmental issues such as climate change and resource use' (Garcia-Holguera et al., 2014). Eco-mimetics extends the field of biomimicry into EMFs and processes, including abiotic and biotic relationships and interactions. This link with buildings connects with the section on hard infrastructure (Figure 9).

Ecological engineering uses ecology and engineering to predict, design, build or restore and manage ecosystems that integrate human society with its natural environment for the benefit of both (Jørgensen & Mitsch, 1989). Therefore, it has a broader focus, but it often includes the creation or restoration of ecosystems and waste-/polluted water treatment systems.

This sub-group also includes *controlled environments*—those environments we design to control the environments for specific organisms. This includes indoor agriculture—such as greenhouses, vertical farming, rooftop systems, microgreens, aquaponics, hydroponics, aeroponics and fungi farms. It also includes bioreactors, which are technical systems often designed to support the growth of microbes, protozoa or small plants, such as 'photobioreactors' to grow cyanobacteria, micro-algae and moss (e.g. *gametophores*). These are grouped together and placed in this position in the model, as they often cross over the boundaries between biology in synergistic systems and physics in circular systems.

***Recycling of materials and molecules***
Recycling is a process for treating (industrial or household) waste materials and molecules within products, components or sub-components that have reached the end of their lifecycle, allowing some of the materials/molecules to be reintroduced into the production of new products or as a last resort used as sources for energy recovery (Stahel, 2006). This includes three main forms, which are as follows:

- *Functional recycling,* the reuse of waste material for the same or similar purpose (Ellen McArthur Foundation, 2012), such as recycling glass into glass or HDPE (High Density Poly Ethylene) plastic into HDPE plastic. This can have limits, as long-chain polymers can degrade over time, for instance.
- *Downcycling*, the reuse of materials for a function requiring lower qualities (Ellen McArthur Foundation, 2012) and/or as a cheaper way to 'get rid' of waste rather than via traditional disposal (Pauli, 1998); this can include using waste materials as low-cost 'fillers' within a composite material or 'waste-to-energy' processes.
- *Upcycling*, (in this model) the *conversion* of used materials into new materials of *higher* and increased functionality (Ellen McArthur Foundation, 2013), such as mixing used glass with $CO_2$ (and heat) to create a foamed glass insulation and building product or using mineral waste from mining as a raw material for 'stone paper'.

Predominantly, recycling focusses on used *manmade* (technical) materials (e.g. minerals, metals and fossil-based polymers and chemicals); however, it can also include certain biomaterials, particularly those with *long fibres*, such as wood or certain textile cloths, as these materials can be resilient enough to also be recycled (at least a few times); and recycling can also include (waste) water, different gases (e.g. $CO_2$) and heat (once).

***Bio-fabrication and bioremediation***
Bio-fabrication is making materials *with* living organisms: Instead of transforming plants, animals or oil into consumer materials, materials are grown directly with living organisms. As a still relatively nascent field, one definition from Groll et al. (2016) states that it is the 'automated generation of biologically functional products with structural organisation from living cells, bioactive molecules, biomaterials, cell aggregates such as micro-tissues, or hybrid cell-material constructs through bioprinting or bioassembly and subsequent tissue maturation processes'.

Traditional examples include the transformation of primary products, such as milk, grapes or apples, and through the process of *fermentation* (with specific living yeasts and/or bacteria), producing cheese and yoghurt, wine and cider. Alcohols produced during fermentation can also be sent as feedstock to (green) chemical systems as a base for bioethanol. These examples can take surplus or damaged primary products and transform them into potentially high-value products that can also have a longer shelf life.

More modern examples include working with fungi mycelium to develop fungus-based textiles (e.g. Mycoworks, Mogu, MycoTex); growing microbes for their enzymes, which can be extracted for other uses; or bacterial-based polymers, such as *polyhydroxyalkanoate* (PHA), which can be produced directly as a polymer via *fermentation* (with a 50-year history) and (unlike other bio-based polymers) are made up of bio-based monomers. Some materials produced within these fields can also be used, for instance, as bio-based filters linked with remediation.

This node also includes the production of biogas, which works with a range of different *living microorganisms to* break down organic matter into (bio)methane and $CO_2$. Another example is growing insects (e.g. worms, maggots, and crickets) through the conversion of certain agricultural residues, such as left-over animal carcases (fed to maggots), which turn these residuals into (animal) proteins, and through further extraction processes, particular substances, such as chitin from their skins or fertilisers from their excrements (frass). This is linked with green chemistry and cascading. This node (Figure 8) also includes bioremediation, which can be used for the decontamination of a range of pollutants, actively breaking them down with living organisms.

**Aggregate efficiency design: optimise infrastructure to optimise the entire system**

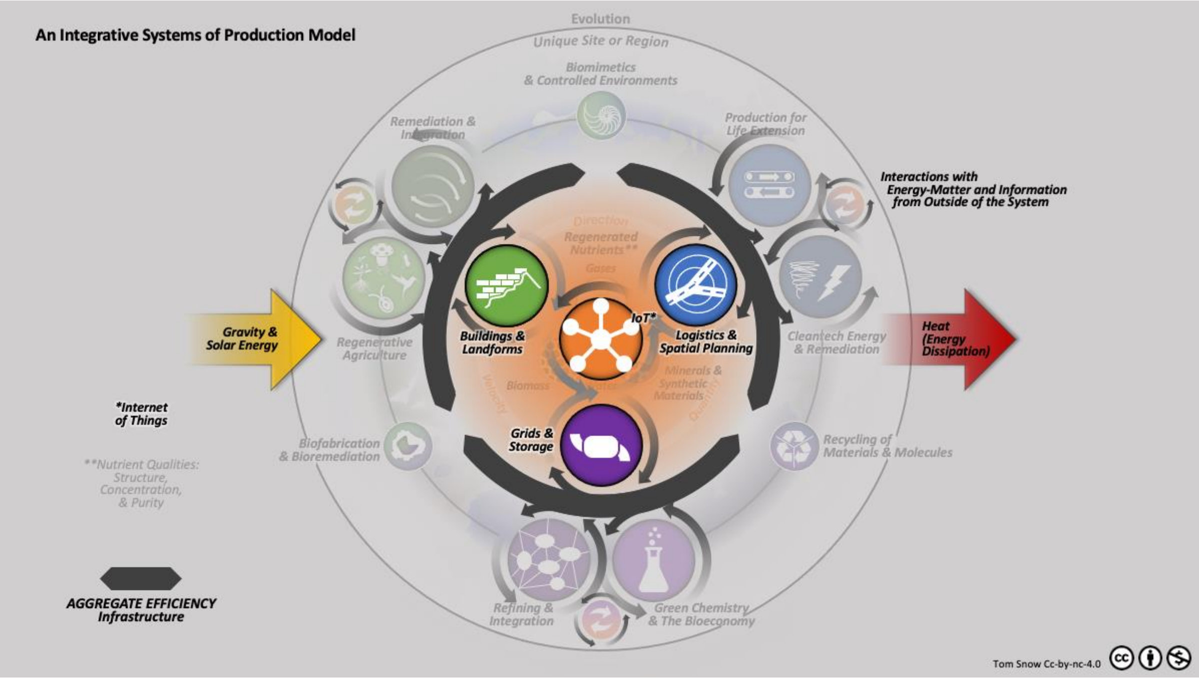


FIGURE 9. Aggregate efficiency design: hard infrastructure (Snow, 2020).

Rifkin (2011) underlines that all forms of human-made infrastructure are not simply a static physical assortment of building blocks (i.e. buildings, earth formations, bridges, airports, sewage systems and telephone cables); instead, they are dynamic elements that support the management of flow and storage of matter-energy and information and energy across our systems of production. This section is highly inspired by Rifkin's (2011) work, particularly his proposed 'Five Pillars of the Third Industrial Revolution' (TIR), and his concept of three interrelated 'internets'—the 'Communication Internet', 'Energy Internet' and 'Logistics Internet'; it also draws on the work of the Rocky Mountain Institute and its co-founder A. Lovins including the work in *Reinventing Fire* (2011). All underline the importance of infrastructure as a key element within the transition of our systems of production. Although with different systemic approaches, there are clear overlaps in their inclusion of transport, energy (including storage and the grids to distribute it), buildings and key infrastructure technologies, such as communications, monitoring and internet technologies.

Lovins et al. (2011) and Rifkin (2011) highlight the importance of infrastructure in increasing the *productivity* and *aggregate efficiency* of the systems of production in reducing energy inputs and waste for a required output. Productivity is 'a measure . . . calculated as the ratio of what is produced to what is required to produce it' (Rifkin, 2014, p. 70). In this case, the cost of producing an additional good or service is virtually zero, and this would be optimum productivity (Rifkin, 2014). Rifkin (2014, p.72) defines *aggregate efficiency* as 'the ratio of useful to potential physical work that can be extracted from materials'. According to this author, a shift to a TIR infrastructure could conceivably 'increase aggregate energy efficiency to 40 percent or more in the next 40 years' (2014, pp. 72-73). Therefore, in this model, the design focus of infrastructure is on increasing *aggregate efficiency*.

In the ISP model, the four core, interdependent hard infrastructure elements do not include energy production (and are dealt with in other nodes), as these are forms of production rather than distribution. Hard infrastructure takes the analogical place of the *ecological engineer* functions in the

EMF model, as hard infrastructure is also not a form of production metabolism; rather, it comprises relationships between metabolic activities and nutrients and the greater environment. It is the *structural* ecological engineers in particular that create allogenic and autogenic structures, which are the key analogical link; these include passive housing inspiration from termites and their mounds (Pauli, 2010a) and transport networks inspired by slime-mould growth patterns (Parr, 2014).

Stamets (2004) makes analogies between the internet and fungal networks; however, information, and with it, communication and feedback, is made and travels through the collective of living and non-living systems, such as chemical elements and energy travelling through the air and water (for example), and it is also written, for instance, in the rocks, ice cores (e.g. historic $CO_2$ levels) and sediments at the bottom of lakes (e.g. historic pollen counts), for those who can read it. Our human-made internet is enabled by a range of different technologies, such as sensors, embedded devices, computational power (e.g. in chip), and increasingly, algorithms and artificial intelligence. This Internet of Things can link the other infrastructural elements and particularly products within circular systems and with the support of the structural services that these systems rely on, such as cloud services, big data and analytics, digital payments, digital logbooks (e.g. blockchain) and mobile devices and apps, can potentially bring the increased productivity gains that Rifkin, for instance, promotes.

The *Buildings and Landforms* node includes all forms of physical structures, such as buildings, dykes, bridges and fences, that we build to live and work within and to protect us. Practices in this node include energy-efficient landscaping, as promoted through land-forming practices in permaculture (e.g. '*Earthworks*') and Keyline Design™, for example, with catchment dams, orientation and wind flows (Yeomans, 1958). Within these design concepts, the production site is optimised, for example, for the following: hydrological catchment, use and storage; the local climate (e.g. winds, frosts, solar cycles and rainfall); zoning of functional areas; and placement of access routes and boundaries. This then integrates with green architecture, passive housing and even *living* architectural structures, such as those promoted by architectural group Terreform ONE, whereby living trees, for instance, make up part of the building's structure. The association between buildings and landforms is the link between the building and the direct surrounding environment. This can include catchment dams, green roofs and walls, and strategic positioning of trees and shrubs for shade from the Sun or wind (changing the micro-climate) or as shelters for beneficial predators.

The *Transport and Spatial Planning* node includes all the forms of physical structures, such as vehicles, logistics and spatial planning systems we use to design our larger urban environments. Transport includes the greening of our currently predominantly combustion-energy-based cars, buses and trucks, and to some extent, the use of different forms of drones, while focussing on walkability and biking integrated with public transport. Transport also includes those logistical systems we design and use to move goods around, which include 'reverse-logistic' systems, required for many circular, and perhaps to a lesser extent, *cascading* systems. Logistics also includes systems that allow governance and transparency of value chains (e.g. 'Provenance') and 'material passports' that store and make material ingredient information available for end-of-life/use (e.g. 'CircularID™' or 'Madaster'). Spatial planning includes the work of Speck (2019) and concepts promoted by Thackara (2006; 2015), such as 'closer not faster'. If we want to make cities walkable, then work and other services need to be within walkable distances. This underlines that the spatial position of nodes is as important as the links between them.

'*Grids & Storage*' includes the pipes, cables and other interlinked and bi-directional conduit networks (e.g. 'Smart Intergrids') that we use to move input and output (including waste), solid materials, liquids, gases, heat, and particularly, electricity around. Many renewable energy sources (including solar and wind) produce variable power. Storage systems can compensate for the resulting imbalances between supply and demand. Heat-storage also allows storage and use of surplus thermal energy hours, days and months later, at scales ranging from individual processes to buildings, districts, cities and regions.

## Integrative for zero waste and regeneration

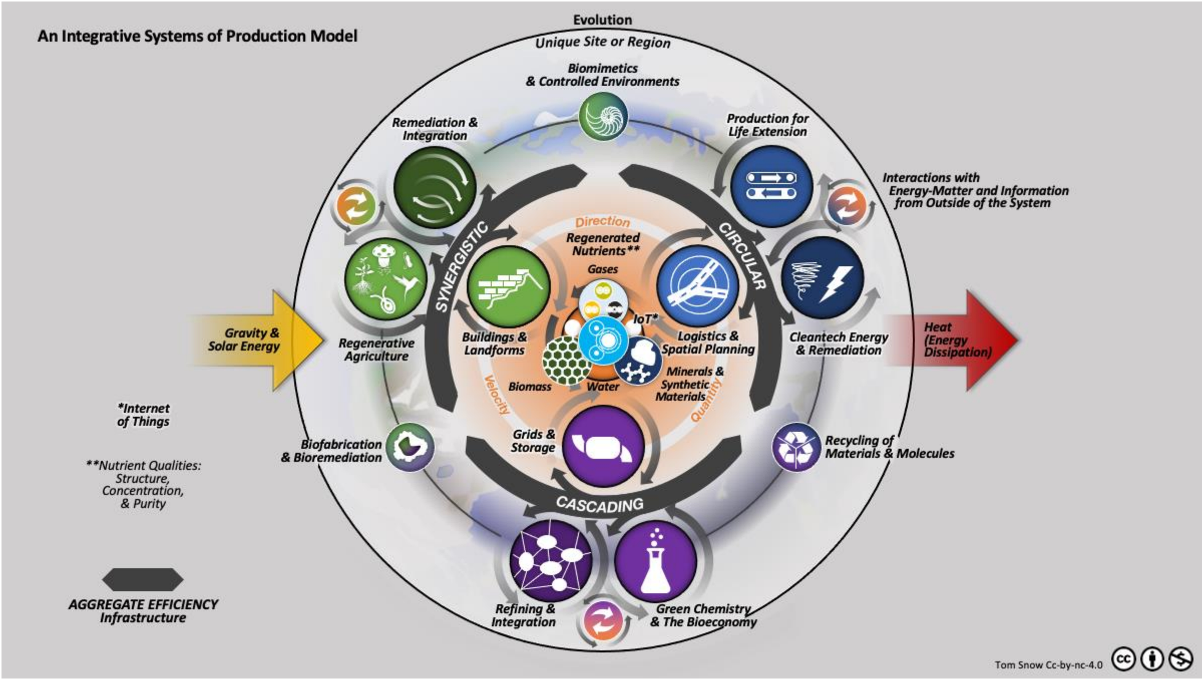


FIGURE 10. Integrative systems of production (ISP) model (Snow, 2020).

Figure 10 shows the ISP model in its entirety. It is after this overview of the diverse (but interdependent) elements that the integrative potential of the model at different scales can now be discussed.

Circular systems can be most effective when applied to durable technical goods and materials. These systems need to optimise life-cycles, and quantities and qualities of components and structures held in accessible stocks (vs. unavailable to use). Developing viable business models and transforming business cultures, for designing and managing circular products, rather than continuously selling new products, can be an ongoing challenge.

Cascading systems can be most effective when applied to organic wastes within/between organic (living and non-living) production systems. These systems need to optimise energy, transportation and transformation costs/complexity, and need to be adaptable to variations in qualities and quantities (and timing) of input flows. As Daly and Farley (2004/2011, p.32) point out, 'no economy can function by directly reusing only its own waste products as raw [input] materials', therefore, these systems have their limits *on their own*.

Synergistic systems can be most effective when applied to growing or harvesting new biomass. These systems need to maximise diverse outputs vs. matter-energy inputs, make regeneration part of the process, and produce healthy food and materials–whilst supporting functional ecosystems. As functional wholes within ecosystems, these systems can also supply a wide range of ecosystem services. As Reinert (2007, p. 108) highlights, agriculture (and fisheries, forestry—and mining) tend to suffer from *diminishing returns*, which basically means that 'at a certain point adding more capital and/or more labour will yield a smaller return for every unit of capital or labour added'—and as Pollan (2007, p. 54) adds, 'demand for food isn't elastic; people don't eat more just because food is cheap.' Therefore (in brief) these systems *can* face certain economic constraints *on their own*.

Aggregate efficiency systems can be most effective when applied to hard infrastructure. These systems need to improve overall efficiency in terms of energy and waste, within and between the other systems. These systems need to take into account flows of matter and energy, integration with natural energy systems and landscapes, and spatial planning and life-styles (and culture) specific to the place. As Daly (2019, p.19) underlines, we need to make sure that greater efficiency does not lead to *increased* extraction and use of matter and energy—known as the 'Jevons effect.' One relatively simple proposition by Daly (2019) for reducing this potential negative effect, is to focus on *frugality first* (and efficiency second). Furthermore, it should be kept in mind that infrastructure is often a means, rather than an ends in itself, hence its interdependence on the other systems.

The ISP model proposes that, if we can collectively integrate, where and when appropriate—we can increase the functionality, regenerate natural capital and produce zero waste—and one or more system can increase the positive potential, and/or reduce the potential limits of another, when used together. This can be thought about at three different scales; if practicing at all scales, the system will potentially further increase its functionality.

At the micro-scale, we can think about *mesocosms*, those systems ecological engineers (in particular) design, based on ecological concepts, that often provide a specific function, such as cleaning wastewater (see Todd, 2019). If we want to design a wastewater system, for instance, we can use the model to think about the different forms and elements within the system. For example, the system will include *synergistic* living elements, such as phytoremediation plants, different types of aerobic or anaerobic fungi or bacteria, potentially protozoa (e.g. algae) and perhaps some fish (producers, consumers and decomposers). The system may also require a physical structure, which could be designed following the circularity principles, and it will probably require some form of aeration or pumping system or vortex to support the functioning and provide energy (if direct sunlight and the producers are not enough). We can then consider potential cascading systems that develop food-web style cascades to support the enhanced cleaning of the water and even produce some high-value by-products (collecting a 'yield'), which may be able to finance the initial investment and/or its running costs. Examples can include wicker from coppiced willow, which may be one of the functional plants in the system; this can also be harvested annually to make baskets that can then be sold (Abrahams et al., 2017). The hybrids, such as biomimetics, can help inform us how to integrate the system with or like, for example, a natural river or bog system; bio-fabrication can also open possibilities for the development of advanced material products from the system. Moreover, recycling will help us recycle any synthetic or mineral based materials within the system that can no longer be used.

At the meso-scale, we can think about industrial manufacturers. They can look at their industrial plant through the model—or 'lens'—and integrate the building within their landscape, while integrating synergistic living systems into the environment, such as by incorporating a wastewater system, as mentioned above (see Ford River Rouge Complex for a large-scale example of this). For the production, all the circularity elements can clearly be implanted into the products and the building itself (buildings can also be circular—designed, e.g. for cleaning and disassembly); and all wastes and by-products can be cascaded on site for a diverse flow of new incomes—or lower charges for external treatment (see, e.g. the previous brewery cluster). Outputs from cascades can go into the synergistic systems as compost and potentially $CO_2$ and nutrient-rich water and perhaps heat. Production systems can also create micro-climates for diverse and rare local species.

As an alternative at the meso-scale, we can think this through on a farm, and in the end, both examples, if taken to their full extent, may look quite similar—although there are doubtlessly differences in the scale and density of each element due to the key differences in priorities. Therefore, these ISPs can potentially become so *individually* integrated that it may be difficult to distinguish a 'farm' from a 'factory' (or even an office) if designed in these ways.

At the macro-level, we can think about the synergistic systems as the entirety of living systems in a region (e.g. agricultural, wilderness, green private, public and common spaces), with the circular systems representing the entirety of the industrial production systems in a region and the cascading systems all the chemical and waste-management systems in a region. Through this approach, it can be possible to link up and integrate matter and energy flows at regional and inter-regional levels. In this way, it can be possible not only to produce more efficient individual systems, or even more efficient collective systems, but also to produce new possibilities for new productive activities, increasing diversity and productivity and resilience of the dynamic system (e.g. Bistagnino, 2011).

## DIVISIONS IN MODERN SYSTEMS OF PRODUCTION—A COUNTER VIEW

This fourth main section uses the ISP model to explore the existing predominant paradigm in production systems in general and specifically in agriculture. The intention is to present the counter direction to which integrative systems of production are aiming to go and can serve as way to think about and explain some existing issues we are grappling with.

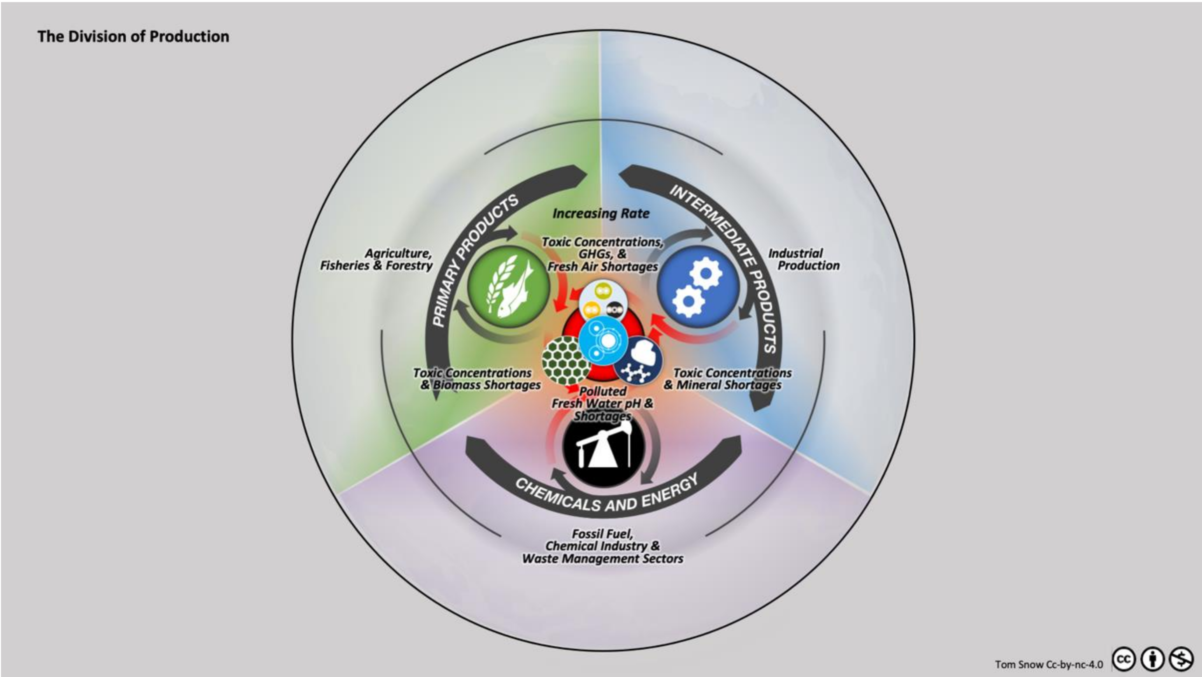


FIGURE 11. Division of production (Snow, 2020).

### Contemporary production: the division of production into industrial sectors

Figure 11 illustrates a simple view of some divisions that exist within the predominant way in which different sectors of production operate. Here, the 'primary products' are *grown and harvested* within the agricultural, fisheries and forestry sectors. The trend continues towards ever increasing economies of scale, increased specialisation and focus on a single yield (for example), and at the same time, shifting many of the transformation activities off-farm (for example) to focus on primary production. This has occurred in parallel with the growth of the agri-food sector, *dissembling and assembling* primary products into the vast array, for instance, of processed foods, food additives, feeds and chemicals that we find in our supermarkets and far beyond. Industrial production also includes the production of goods, such as the farm machinery that farms use—particularly designed for economies of scale and reduction in labour strategies; moreover, it includes the rest of the technical goods society requires. These goods are generally designed to be sold, with some repairs (some forms of circularity) existing within warranty periods (if products are not simply replaced) and for larger products (where the cost can be justified), such as cars, outside the warranty. Since the 1990s, industrial production has progressively focussed on exporting, off-shoring and outsourcing (Milberg & Winkler, 2013); at the same time, it has focussed more heavily on economies of scale and specialisation. The result has been a 'splintering' of large integrated industrial firms into so-called vertically specialised producers within vast, hierarchical global value chains (Argyrous, 2011); with the vast majority producing 'intermediate products', and often a small number controlling and extracting the majority of the financial gains (Milberg & Winkler, 2013).

The third production sector, at the bottom of the model, mainly consists of the energy and chemical sectors, predominantly *extracting and transforming* fossil fuels and minerals, and the waste-management sector, primarily based on recycling, land fill and waste-to-energy (burning).

Within these productive activities, 'nature' is essentially external and externalised (even within agriculture). Interactions between the different sectors can be direct, through the transfer of certain goods (market transactions), but they all interact indirectly through the extraction, and ultimately, the *discharge* of wastes back into what becomes a competitive nutrient pool—as the rate of extraction and discharge continues to increase. This progressively intensifies shortages and increases toxification—and in short, reduces the quality of our natural capital and its carrying capacity, which puts pressure on our social capital and our economies.

**Contemporary industrial agriculture: the division of nature**

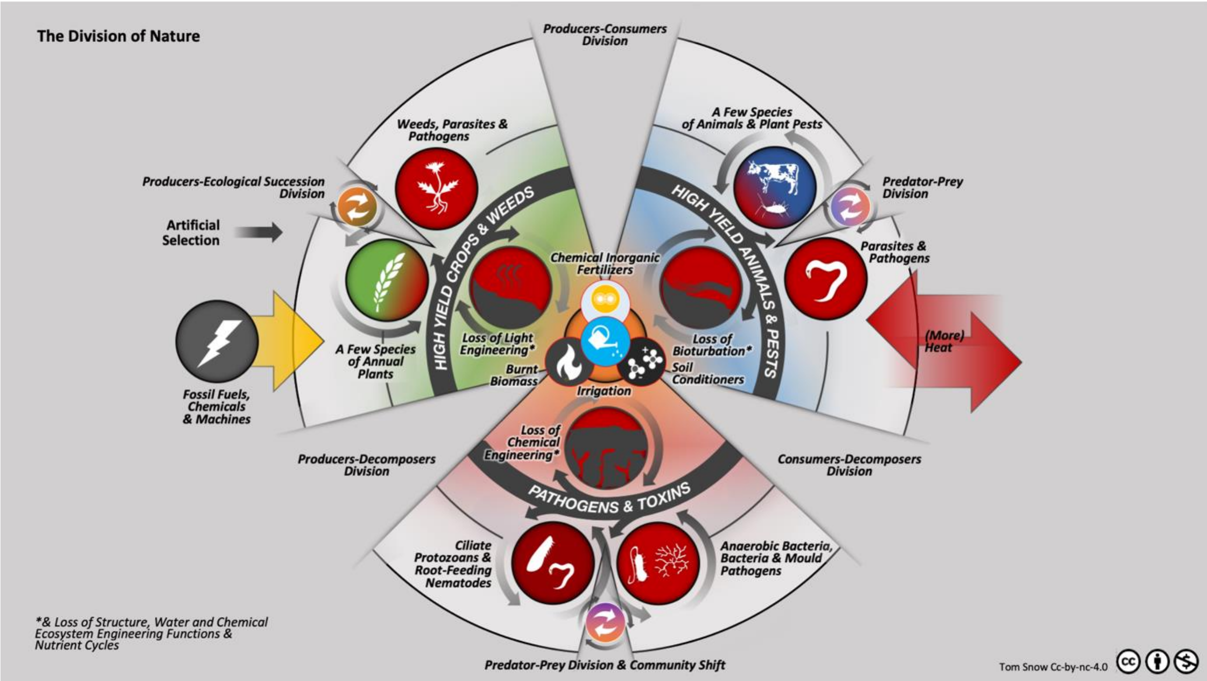


FIGURE 12. Division of nature (Snow, 2020).

Viewing contemporary industrial agriculture through the ISP model, it is possible to describe how the system is actually one of continual divisions rather than integration (Figure 12). Divisional agricultural practices have, little by little, and now more recently *accelerated* (particularly since World War II) the division of different forms of metabolisms, severely affecting the health, functioning and services of ecosystems. In many cases, the wiping out of beneficial decomposers, especially saprophytic fungi and mycorrhizal fungi, has created greater opportunities for microbial pests and human pathogens to develop; this has hampered, if not completely blocked, the emergence of *living soil*, and it has decreased the health, pest resistance and micro-nutrient density of agricultural plants and animals (Biklé & Montgomery, 2016).

The typical responses have focussed on curing the *effects*, not the *causes*, often through physical or chemical practices that attempt to replace (temporarily, if at all) some of the lost attributes of a fully functioning system. Today, the vast majority of *solutions to effects* are made by specialised companies, which require an economic return for their solutions, creating both an incentive for the suppliers to focus on solutions to effects, not causes, and the need for solutions to generate *them* a sustainable income. These solutions are not necessarily the most appropriate for the farmer or the environment (or consumers), and they often become (high cost) inputs, where the intellectual property and other knowledge are maintained outside the boundary of the farm.

The method that has been applied in industrial production to separate activities into discrete units, which can then be individually focussed on to increase efficiency (which often means less labour and lower *unit* cost), has been applied to many of the activities on farms. By also doing this with living systems, the integrative and emergent functionality of the whole has been lost (or at least heavily degraded). This is *division by design*. Some examples of this are illustrated in Figure 12, and they include the following:

- *Dividing consumer predators from their prey*: 'Trophic downgrading' is the overhunting (often to extinction) of large apex predators from their particular ecosystem(s), provoking a negative 'top-down' (anti-clockwise in Figure 12) trophic effect on the levels below (Estes & Terborgh, 2010). Humanity has progressively removed the apex consumers from a broad range of ecosystems across the planet, and in certain cases, it has introduced new apex predators.
- *Dividing producers from ecological succession*: In the process of selecting for annual monocrops, deforestation and constant ploughing, we are in effect dragging ecosystems backwards into earlier ecological succession states, where there can be lower bio-diversity, inter-relationships and carbon and nutrient cycling.
- *Dividing producers from decomposers*: Ploughing can provide benefits in the short term; however, in the long term, constant ploughing can lead to compaction, oxidation of nutrients into the atmosphere and the breaking apart from fungi hyphae—particularly the mycorrhizae—and thus, their important connections with plants are lost (Montgomery, 2017). As plants are removed from the ecosystem through ploughing, so one of the principle foods for the decomposers—the plant *exudates* (sugary foods that plants mainly release from their roots to feed their external 'microbiome')—disappears (Montgomery, 2017). This can all lead to unhealthy plants, which are open (and attractive) to pests, and cause farmers to resort to using chemical inorganic fertilisers to boost growth rates and biocides to kill pests.
- *Dividing decomposer predators from their prey, and community shift:* Through an array of interconnected reasons—including ploughing, compaction, biocides and the loss of the food source for beneficial decomposer predators (decomposers)—the beneficial functions of decomposer predators, such as regulating decomposer populations and the nutrient-rich (micro-) manure they supply to plants, are lost from soils (Lewis & Lowenfels, 2010). Remaining decomposer predators (e.g. ciliate protozoa) also eat plant roots, and along with root-feeding nematodes, for example, decomposer predator communities shift from beneficial organisms to pests (Lewis & Lowenfels, 2010). At the same time, the remaining decomposers shift in population composition from mixes of fungi and bacteria (SWCS, 2000) to predominantly bacterial, and if highly compacted, anaerobic bacteria and some fungi (Lowenfels, 2013). A high concentration of anaerobic microbes produces metabolic by-products that are detrimental to most plants, including acids (e.g. acetic acid, butyric acid and valeric acid), and a range of alcohols. In addition, when oxygen is limiting, some microbes can use other elements instead, such as iron, sulphur, manganese and nitrogen (Lowenfels, 2013) for metabolism, which can render them temporarily unavailable to plants or oxidise them into the atmosphere (i.e. they are lost from the soil).
- *Dividing producers from consumers:* Since World War II, there has been an increased 'urbanisation' of farm animals from open land into buildings (Pollan, 2006). The change has meant that more land has been made available on farms for growing crops—particularly maize (in the United States), and at the same time, the urbanised animals have increasingly begun to be fed on maize (instead of grasses, on grazing pastures). For animal welfare, the separation of animals from their families, environments and natural behaviours, and locking them up in small, confined spaces and fed on unnatural foods (for them), may be one of the cruellest divisions of nature of all. At the same time, with the simplification of landscapes, combined with the application of insecticides and rodenticides, many insects and rodents have been killed and/or have lost their shelters and foods (Carrington, 2019). This leads to the loss of benefits, such as pollination and seed dispersal by animals, the treading-in of seeds and the pulling and tugging (which provokes grasses to release more soil exudates into the soil for decomposers) and eating

the grasses, which provokes more green growth (rather than old dying grass covering new growth; Butterfield & Savory, 2016; Schwartz, 2013).

- *Dividing consumers from decomposers*: This is really a discussion around the microbiome—and the microbes, such as bacteria, fungi and some protozoa—and viruses—that develop beneficial communities within or around organisms that support digestion, immune systems and the production of certain critical nutrients, such as some vitamins (Biklé & Montgomery, 2016). Through the divisions previously mentioned, and through the increased use of antibiotics—and with cattle, for instance, pH buffers and erythromycin (Biklé & Montgomery, 2016; Pollan, 2006), not to mention separating nesting animals from their nests, which can be an important part of their microbiome, and that of their young, we are potentially increasing the negative effects of viruses. As Pollan (2006) shows, in cattle, it may result in ulcers, diarrhoea, bloat, rumenitis, weakened immune systems and liver disease (see also the discussion on mites and bees in Stamets, 2004).
- *Dividing the ecological engineering functions of producers, consumers and decomposers in regenerating nutrient pools:* By dividing and severely hampering the ecological engineering functions, such as bacteria and fungi (decomposers) with their glues, worms (consumers) with their ploughing, and plants (producers) with their roots, collectively building soil structure and voids to support air, water and organism flow, the central NPs—the collective living soil—has been eroded away in many cases, or reduced to 'dirt'—a low nutrient accessible 'substrate'. The predominant response has been to attempt to prop up or replace the NPs and the ecological engineering functions with mechanical (physics) or chemical solutions. Such attempts include the extended use of irrigation, which can increase salts in soils, and compaction (Schwartz, 2016), as well as the application of chemical inorganic fertilisers—which attempt to 'force-feed' crops with basic macro-nutrients (which also leaches, causes eutrophication and enters, e.g. drinking and bathing waters); the burning of plant biomass, often in attempts to release nutrients held above ground in mineral form (see Butterfield & Savory, 2016; Schwartz, 2016); and 'soil conditioners' to *temporarily* supplement/replace, particularly, the *structural* aspects and pH buffering usually found within healthy living soils.

These brief reviews of contemporary production and agricultural systems using the EMF model are at the ecosystem scale, and thus, they do not look into the larger issues that these activities significantly add to at the global scale, such as global warming and ocean acidification. These can be reviewed within the planetary boundary framework developed by Rockström et al. (2009).

## DISCUSSION ON EQUILIBRIUM, INTEGRATION CAVEATS AND FIRST PRINCIPLES

This fifth section is a brief discussion on equilibrium, followed by an integration caveat and a first attempt at some overall 'first principles'.

### Regeneration and dynamic equilibrium

Regeneration ultimately means that, at the level of ecosystems and at the planetary level, we are extracting materials (mineral or organic) from ecosystems at a rate that is lower than the Earth can absorb and regenerate them. This requires that we both increase our rates of regeneration and decrease our rates of extraction. The logic then follows that, through this process, we will eventually create systems that are in some form of *equilibrium*.

Over the last 50 years (at least), economists like Frederick Soddy, Nicolas Georgescu-Roegen, Herman Daly and Jeremy Rifkin—and more recently (women) economists like Ann Pettifor—have been proposing a shift to a *steady-state economy*—one that intends to stay within Earth's safe threshold limits. In summary "In steady-state equilibrium, growth and accumulation would be zero, and input flow would equal output flow" (Daly & Farley, 2004/2011, p.31).

As the planetary boundary framework expresses the decreasing limits of Earth's carrying capacity and the ecological footprint of our ever-increasing demand for carrying capacity (Wackernagel et al., 2019), it is (scientifically) clear that growth—which is both increasing in quantities and rate—is not only impossible on a finite planet, but is, in many cases, already surpassing certain boundaries.

Living systems are, however, *dynamic* and tend to be far from equilibrium—and do not exist in steady states (Mang & Haggard, 2016). As, within ecosystems 'certain parts of organisms, or ecosystems, grow, others decline, releasing and recycling their components which become resources for new growth' (Capra, 2017, p. XV), and individuals, communities and their environments evolve and change overtime. Therefore, although clearly in the right direction, it is quite probable that we need to go further into developing integrative systems that are in *dynamic equilibrium*.

**The integration caveat**

*Integrative* can be defined as 'serving to integrate or favoring integration: directed toward integration' (Merriam-Webster, n.d.); which is different to *integrated*, which can suggest something more static or rigid. Living systems teach us a lot about the importance of being integrative—in metabolic terms, this can be anabolism, the building of new materials; and can be seen through the interdependent functions of organelles in cells, organs within organisms, or the different metabolisms within ecosystems, and symbiosis for instance (the integration of wholes within wholes). One of the principles of permaculture is to 'integrate rather than segregate' (Holmgren, 2011, p155).

Metabolism, however, also teaches us about the importance of catabolism—the breaking down of materials, for example, for mineralisation, detoxification, use for another purpose or extracting energy. Living systems therefore, 'integrate *and separate*' (inspired by Pauli, 2010b). Ecosystems also express how different organisms dynamically dance with being self-assertive and integrative (Capra, 1996).

Neither separative and self-assertive, or integrative is intrinsically good or bad—they are *both* (separative and self-assertive are grouped here as one related phenomena) 'essential aspects of all living systems' (Capra, 1996, p. 6). As Capra (1996, p. 6) goes onto explain, what 'is good, or healthy, is a dynamic balance; what is bad, or unhealthy, is imbalance—overemphasis of one tendency and neglect of the other.'

For example, one major constraint for a *circular economy* is that we 'immobilise' (statically integrate) vast amounts of materials in long-lasting structures, such as buildings, which can act as bottlenecks to material flows. Some solutions have been discussed, such as designing long-life products for *disassembly*, so that parts can be re-used or remanufactured; designing fast-moving goods that quickly biodegrade (in soils, air and water) into constituents for living compost; or designing goods and structures that are highly adaptable/upgradable.

Relatedly, as economic historian Landes (2003, p. 334) highlights, there are 'burdens imposed by interrelatedness, that is, the technical linkage between the component parts of the industrial plant of an enterprise or economy'. That is to say, no factory, farm or chemical plant sits in a vacuum, and it is rare that the removal or addition of machines or processes can be considered in isolation—as they are often influenced (or obliged) by outside factors (e.g. clients, supply chain partners, input types, or regulators). From fossil fuel combustion engines to large factory machines and input materials, there can be huge legacy constraints and inflexibility, particularly in traditional large-scale production systems.

**First/basic principles**

In the 'Trunk and Branches Metaphor' (Robèrt et al., 2010, p25), the trunk and branches of a tree can represent the system's *principles*, while the leaves represent the system's tangible *details*. Within this metaphor, the principles remain relatively unchanged (like the trunk and branches), while the details can and do constantly change depending on the context (like the leaves on a tree). Robèrt et al. (2010, p. 23) further define a basic principle as 'a condition that must be met for a system to continue in a certain state'. Principles can also be rules that help frame the way in which a framework and/or model are used.

The points below list some criteria for creating principles, specifically for sustainability (Robèrt et al., 2010). The use of the term 'sustainability' has been replaced with 'regeneration' to fit this paper's goal. Robèrt et al. (2010, p. 38) advise that the principles should be as follows:

a) 'Based on a *scientifically agreed upon view of the world*';
b) '*Necessary* to achieve [regeneration]';
c) '*Sufficient* to achieve [regeneration]';
d) '*General* enough to structure all of society's activities that are relevant to [regeneration]';
e) '*Concrete* enough to guide action and serve as directional aids in problem analysis and solutions'; and
f) '*Non-overlapping*, or mutually exclusive, in order to enable comprehension and structured analysis of the issues'.

With these points in mind and expressing that this is a 'first pass' at some first/basic principles, learned from developing the EMF and ISP framework, models, concepts and other principles are mentioned at the end of this section. In relation to point (d) above, these principles intend to be general enough for all activities within 'systems of production', not all society's activities, which can include care, relationships, education, and carnival—to name just a few social activities that come to mind, that can also arguably benefit from different forms of 'regeneration' but are outside of the scope of this paper, framework and model (thus far …). Therefore, the four basic integrative systems of production principles state the following:

ISP activities should provide for society's material needs in the following ways:

- Producing *zero waste*, with the only 'waste' being heat going into space—principally through cycling technical products, and cascading residuals as new inputs;
- *Regenerating* the living and non-living systems from which any nutrients are extracted and returned—particularly their synergistic relationships and functioning as integrated wholes;
- Dynamically adapting for *congruence* with living and non-living systems—particularly concerning matter, energy and the rate by which they are extracted, transformed, stored, and reabsorbed; and
- *Functioning* as one *interdependent* and highly *integrative* and *self-assertive* system (dynamically and appropriately, integrating synergistic, circular, cascading systems with aggregating infrastructure) at the micro-, meso- and macro-levels—and embedded in the unique place.

For further reading on the topic of sustainability principles, one can look at the '19 Principles Applied in Ecological Engineering' (Jørgensen & Mitsch, 2004); the 'Hannover Principles' (McDonough & Braungart, 1992); 'Principles of Ecological Design' (Todd & Todd, 1994); 'Principles of Ecological Design' (Cowan & Van der Ryn, 1996); 'Principles of Sustainable Design' (McLennan, 2004); 'Biomimicry Principles' (Benyus, 1997/2002); 'The 12 Principles of the Blue Economy' (Pauli, 2010b); and relatedly, '10 Ecosystem Properties' (Nielsen, 2007; Nielsen & Mueller, 2009)

## CONCLUSIONS

A production systems framework and model based on ecological systems is only as good as the designer's understanding of the ecological systems and the interpretations of what is and what is not important to highlight and build around. The ISP framework, model and first principles do not provide any solutions; they attempt to create a way to structure the myriad of existing frameworks and facilitate their sharing between often-dispersed disciplines and stakeholders. The hope is that by presenting some of the main ways that activities can be approached, coherent with EMFs, designers can see that they have a wide array of potential strategies and methods at their disposal to work with, to support the regeneration of our planet. This requires a greater understanding and literacy of many fields; in short, to 'shift upstream' requires learning some of the different languages of these new environments. Thus, although some subjects may initially seem complex—such as synergistic or cascading phenomena—it is hoped that this perspective will provoke a deeper look and practice.

The ISP model shows more possibilities for design than most (if not all) other models, and this can create some initial complexity for understanding and selection. Therefore, diverse skillsets and teams are a prerequisite for regenerative living-system design—the knowledge, skills and experience will be in the *aggregate* of all those involved.

It is also important to underline that systems of production are not *only* about cycling of matter and flows of energy. As David W. Orr (1992, p. 20) underlines, ecological design also includes the 'careful meshing of human purposes with the larger patterns and flows of the natural world'. At the socio-economic level, we also need our *institutions*, such as governing, financial, educational and health systems, to be congruent with living systems—including the 'rules', such as how value is distributed (including equity and justice), how we organise ownership and ourselves into collaborative groups and how we practice 'ecocentric' (earth-centred) values (Capra, 1996) and systems of power.

It was initially hoped that these socio-economic issues could be integrated, in some way, into the ISP framework and model (e.g. as Lemille, n.d., attempts to do with *The Circular Humansphere*). This will be looked at through a complementary framework/model to come, as it is as rich and diverse (and complex) as the systems described thus far. Still, it should be borne in mind that the creation of separate (although linked) frameworks does risk that these systems will remain mentally divided or go unread.

According to Orr (1992, p. 29), 'The standard for ecological design is neither efficiency nor productivity but health, beginning with that of the soil and extending upward through plants, animals, and people'. If we can work on the means to support the emergence of healthy and prosperous ends, with ISP, which I have argued is the opposite of the predominant division paradigm, then production may be truly regenerative and support all forms of life to thrive now and into the future.

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[1] Electron carriers (also known as electron shuttles) are small organic molecules that are also key in photosynthesis and cellular respiration. Their function is to take electrons from one molecule and transfer them to another. $NADP^+$ (Nicotinamide adenine dinucleotide phosphate) is an example within certain forms of photosynthesis.