

Concept Paper

Integrated Innovation: Applying Systems Thinking to Sustainable Innovation and Transformation

Wayne Visser

Sustainable Transformation Lab, Antwerp Management School, Boogkeers 5, 2000 Antwerpen, Belgium;
wayne.visser@ams.ac.be

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Abstract: Despite allusions to systemic elements in the conception of innovation more generally, and sustainable innovation in particular, the literature generally fails to capture many of the insights that systems science can bring to our understanding of these subjects. This concept paper elaborates five principles of integrated innovation—diversity, aspiration, networks, convergence and emergence—and describes five stages of integrated innovation: intention, ideation, invention, synovation and transformation.

Keywords: innovation; sustainability; transformation; sustainable development; systems thinking; systemic

1. Introduction

Integrated innovation is my term for the creation and implementation of scalable, breakthrough solutions in areas of systemic breakdown, resulting in multi-level, multi-functional improvements across our interconnected economic, social, ecological, technological and human systems. More simply put, integrated innovation means finding market-based solutions to the problems of sustainable development.

This framing of integrated innovation uses a systems science perspective—‘thinking in terms of relationships, patterns, and context’ [1]. Systems thinking ‘is aimed at understanding relationships between components and their overall impact on system outcomes (i.e., intended and unintended) and how a system of interest similarly fits in the broader context of its environment’ [2].

Following a review of the literature, Taylor developed a composite definition of innovation as: ‘the creative process whereby new or improved ideas are successfully developed and applied to produce outcomes that are practical and of value’ [3]. For those wanting a more comprehensive view on the literature on systems thinking and on innovation, I recommend *A Systems View of Life* [1] and *The Innovator’s Dilemma* [4].

My focus for this paper is on how innovation functions as a catalyst or enabler of systems change. This perspective is often implicit in the literature on innovation, but the connection to systems thinking remains largely unacknowledged or superficially addressed. For example, Everett Rogers’ [5] diffusion of innovation model, which is about spreading an innovation in the marketplace, shows the same sigmoid (S-shaped) growth curve as the COVID-19 virus, or the replication of cells in the human body, or the increase in animal or plant populations in balanced ecosystems.

These similarities exist because organisations, industries, economies, societies and ecosystems are all complex, self-regulating systems which exhibit similar behaviour patterns. This is especially true for dealing with change in organisations, which operations theorist Russell Ackoff describes as ‘managing messes’—responding to dynamic situations, where systems thinking helps us ‘manage, adapt, and see the wide range of choices we have before us’ [6]. It is a way of thinking that gives us the freedom to identify root causes of problems and see new opportunities’ [7].

Another example of how systems thinking applies to innovation is the typical distinction between incremental and radical innovation [8]. This is often simply a way of differentiating between innovations that affect only a small part of the system, such as minor improvements to a single product category, versus those that catalyse widespread change in the nested systems of which the product is a part, such as an industry, economy or culture. Such rippling effects are also typical of social and natural systems, such as the trophic cascades in ecosystems [9].

On the topic of sustainable innovation, systems thinking is also in evidence. For example, Nidumolu et al.'s [10] four stages of sustainable innovation—viewing compliance as an opportunity, making value chains sustainable, designing sustainable products and services and developing new business models—describe variations on innovation that require different levels of effort or change and have different levels of impact in the systems in which the business operates as an active agent.

More recently, John Elkington [11] introduced the notion of 'green swans', which riffs off of Nassim Nicholas Taleb's [12] 'black swans' (highly improbable, hard-to-predict, often catastrophic events). This concept is entirely based on the behaviour of complex, non-linear systems. Green swans are profound market shifts driven by 'good' exponentials, which Elkington describes as 'exponential progress in the form of economic, social and environmental wealth creation . . . [with] integrated breakthrough in all three dimensions.'

Despite these allusions to systemic elements in the conception of innovation more generally, and sustainable innovation in particular, they generally fail to capture many of the insights that systems science can bring to our understanding of these subjects. In this paper, therefore, I elaborate five principles of integrated innovation—diversity, aspiration, networks, convergence and emergence—followed by five stages of integrated innovation: intention, ideation, invention, synovation and transformation.

The purpose of discussing integrated innovation is to propose a more effective way to understand and apply innovation to the challenges of sustainable development. The principles are derived by the author from the underlying conditions in complex living systems that enable innovation. However, by applying them to social institutions—most notably business—and global societal challenges, they become normative guidelines to increase the chances of successful innovation for sustainability.

The stages are typical stages of innovation through which most innovations pass *en route* to success or impact at scale. There are two reasons for elaborating them in this paper: first, to show how they can be applied to finding solutions to complex social and environmental problems; and second, to emphasise the importance of synergies (Stage 4) and transformation (Stage 5), which often get less emphasis in both the literature on commercial innovation and sustainable innovation.

It is not necessary to apply all five principles or to pass through all five stages for the innovation to be 'integrated'. Rather, the emphasis on integration is a reference to innovation being integrated within the societal and ecological context. The scientific contribution is twofold: one, adding a normative framework to the understanding of sustainable innovation (or more correctly, innovation for sustainable development); and two, deriving the elements of the framework from an understanding of the science of living systems, i.e., systems theory.

2. The Five Principles of Integrated Innovation

2.1. Principle 1: Diversity

Integrated innovation begins by embracing the principle of diversity. The idea that diverse perspectives and cross-disciplinary collaboration encourages creative thinking is so well known and widely accepted that we regard it as a truism. However, there is also strong evidence from systems science that diversity is crucial for creative adaptation and evolutionary processes. Most fundamentally, Darwinian evolution relies on diversity at all levels of life, which allows for chance variations of organisms that adapt better to new or changing conditions, a process reframed in systems science terms by Jan Smuts' theory of holism [13].

For innovation in social systems, the implication is that diversity increases the chances of cross-disciplinary or multi-perspective collaboration and makes the organisation less dependent on narrow bands of capability or homogenous perspectives. This in turn leads to creative idea generation and problem solving [14]. Task- and competence-related diversity is particularly important in this context, because it has been shown to correlate with employee creativity and innovativeness [15,16].

The existence of multiple forms and behaviours is also strongly associated with resilience [14]. In fact, according to the Stockholm Resilience Centre, diversity and redundancy is one of the seven principles for building resilience in socio-ecological systems [17]. The link to redundancy is not coincidental and is highly relevant for innovation. By redundant, we do not mean irrelevant, but rather an element in a system that may have a similar function but also has key differences.

For example, there are over 40,000 species of rice, but the 3.5 billion people who depend on rice as a staple food rely on the cultivation of only a few types, like long-grain or Basmati rice. If a disease were to wipe out these few species, the ability to innovate new disease-resistant food sources would be highly dependent on the 90,000 samples of cultivated rice and wild species that are stored at the International Rice Gene Bank. This ability to creatively adapt also occurs naturally when diversity exists in ecosystems.

The same is true of social systems. If smallholder farmers in particular countries or regions do not have diversified crops, they cannot innovate when a drought or flood or drop in global commodity prices threatens their livelihood. Or if fisherfolk build up their capacity to also offer eco-tourism services, they will be able to pivot when one sector or the other suffers a setback. The same principle applies to models of governance, styles of leadership or ways to make and deliver products or services.

Many universities were able to rapidly transition to online teaching during the Coronavirus lockdown because they had already invested in and tested blended learning options at a smaller scale. A factory using robots that can multitask will be able to adapt and innovate more quickly in response to shifting customer preferences, and a town or city that has installed a variety of decentralised renewable energy technologies, like wind and solar, combined with batteries, is less likely to be paralysed by energy shocks or climate damage.

2.2. Principle 2: Aspiration

Donella Meadows [7] defines a system as ‘an interconnected set of elements that is coherently organised in a way that achieves something’. Hence, a system must have three things: parts, relationships between the parts and a purpose or function. In biological systems, the function may be implicit, encoded (for example, through DNA), unknown or emergent (spontaneously created through interactions of the parts). In human systems, purpose is often conscious and intentional, by design, although it can also be emergent.

In an innovation context, the element of purpose means answering the question ‘Why?’ Put another way, who or what is the innovation for? And how will the benefits and costs of the innovation be distributed throughout the system? To frame this in terms of systems science, we need to critically reflect on which parts and levels of the nested systems in which the innovation is embedded will be affected. Hence, an innovation that generates opportunities or benefits for one part of the system, such as an individual business or targeted set of customers, but imposes risks or costs on another part, such as a community or ecosystem, cannot be considered as integrated innovation.

There is a nested hierarchy principle at play here. If an innovation benefits one system, such as its own organisation or a local economy, but compromises the functioning of the larger system of which it is a part, such as the society or ecosystem, this is by definition not fully integrated. Similarly, if it creates value at one level, such as for the organisation, but destroys value for a sub-system, such as a group of employees, this is creating system fragmentation as well.

To demonstrate the practical application of this integrated innovation principle, consider the Meaningful Innovation Index, which is premised on the belief that ‘there is an appetite for future innovations to go beyond creating technology for technology’s sake, instead aiming to make

a difference in people's everyday lives'. The Index is a 5000-person, multi-country survey that was conducted by Philips in 2013 in China, The Netherlands, the United States, the Kingdom of Saudi Arabia and Russia, looking at people's needs, attitudes and expectations regarding innovation.

Overall, only 54% of people were found to be satisfied with existing innovations in the areas they considered to be the most important to their lives. In particular, an 'innovation gap' (where companies are not fulfilling needs or expectations) was found in ten key areas of life: protecting the environment, saving money, stress relief, living independently as one ages, education, preventative health (preventing disease and illness), medical treatment, medical diagnosis, workplace efficiency and saving time. The most important areas for meaningful innovation were found to be innovations that contribute to:

- Being happy—selected as the top priority by 94% across all five countries;
- Being an active part of the local community—a top priority for 82% in America;
- Medical treatment—a top priority for 91% in China;
- Living independently as we age—a top priority for 88% in the Netherlands;
- The health of our family—a top priority for 95% in Russia.

A concrete business example is 3M, known and respected for its innovation culture and longstanding interest in sustainability (its Pollution Prevention Pays program was launched in 1975), which announced that, from 2019, all of its new products would have to include at least one sustainability benefit [18]. Considering that 3M spends 6% of revenue on research and development, launches around 1000 new products every year, and generates roughly one-third of its revenue from products released in the past five years, this is no small commitment. Examples of 3M's Sustainability Value Commitment for new products include reusability; recyclability; energy, waste and water savings; responsible sourcing and renewable materials.

2.3. Principle 3: Networks

According to Jan Smuts [13], the evolutionary thrust of life is towards greater and more complex wholes (or systems), and behind this drive are the overlapping 'fields' (or edges) between wholes that allow for new combinations of system elements to be tested or new relationships between organisms to develop. System scientists are at pains to point out that living systems require porous borders (or membranes) to ensure constant interaction and exchange of energy and materials with the surrounding environment [1].

This basic principle underlying evolution is also a fundamental mechanism for ensuring innovation. It is the relationships between the parts of a system that seeds creativity. The more connections there are (i.e., the greater the complexity of the system), the more likely that we will see non-linear effects. Non-linearity is a mathematical concept that underlies complexity theory and chaos theory. There are several lessons we can take from this science of interdependent networks.

The first lesson is that small actions can have big effects. The more tightly networked a system is, the more sensitive it is to what the mathematicians call 'initial conditions'. These trigger variables are what lead to the so-called 'butterfly effect', discovered by the meteorologist Edward Lorenz in the 1960s when he was using non-linear equations to model simple weather systems. The idea of a butterfly flapping its wings in one part of the world and causing a hurricane in another part is now a popular metaphor to describe the phenomenon.

This leads to the second insight, which is that the biggest effects are often non-local. Hence, innovators need to be looking out for changes in the market or technosphere in different industries, disciplines or geographies from where trigger events or inventions take place. For example, the chance discovery by microbiologists of a plastic-eating bacteria near a bottle recycling plant in Japan and a polluted site in Houston, Texas may end up revolutionising the plastics and recycling industries. Likewise, a bacteria that lives in Yellowstone's geothermal hot springs is being used by start-up

Nature's Fynd in the production of alternative protein, backed by \$80 million in seed capital from Bill Gates and Al Gore's Generation Investment.

A third lesson is that change in complex systems is unpredictable and rapid. We see exponential growth effects, where whole new industries and multinational giants can bloom in the space of a few years, while others can collapse within an equally short period. This implies that innovators should spend less time on making predictions, forecasts and strategic plans and more time on building their agility, so that they can respond quickly when those exponential opportunities emerge.

An integrated innovator will try to tap into as many networks as possible, preferably in fields outside of his/her own area of speciality. They will seek out new ways of thinking more than new products or services. For example, they might use biomimicry—inspiration from the genius of nature's design—to come up with breakthrough solutions, such as the vertical wind turbines that mimic the energy efficiencies of fish moving in shoals or self-adhesive floor tiles that mimic the suckers on geckos' feet [19].

2.4. Principle 4: Convergence

Between 1900 and 1913, New York City went from a horse-and-carriage dominated city to an automotive vehicle dominated city. The reason, as Tony Seba points out, was not because we ran out of horses or carriages, but because they were replaced by a superior transportation solution; the car [20]. The car in turn was enabled by a combination of technologies that reached market-readiness at the same time, including the internal combustion engine, which required cheap fossil fuel production, combined with Henry Ford's model of mass production that made cars affordable.

This combination of trends or technologies or markets is also known as convergence. In popular idiom, it is the 'perfect storm'—a confluence of ideal conditions for something to flourish or scale rapidly. It was the lack of insight into converging technologies that allowed the global consultancy McKinsey to provide AT&T with a wildly inaccurate 15-year forecast of the growth potential of mobile phones in 1985, which they estimated would reach 900,000. The actual market size in 2000 was 109 million, so they were out by a factor of 120 [21].

Another good example of technology convergence is the case of the computer, the Internet and the mobile phone. They all started out as different products serving different needs in different markets. However, with improvements in microprocessors, graphic processors, data storage and connectivity, a symbiotic relationship began to emerge and eventually the products themselves merged, leading to a transformed market for mobile computing—everything from smart mobile phones and tablets to cloud computing and content streaming.

One important feature of convergence is that the technologies complement and accelerate each another's adoption in the marketplace [20]. This is a classic case of positive reinforcing feedback loops in action. Put another way, convergence causes these systems to 'go exponential', i.e., to transform extremely rapidly. For example, it took 12 years to reach 50 million laptop sales, seven years to sell 50 million mobile phones and only two years to sell 50 million tablets [22]. If we do not take convergence into account, we will repeatedly underestimate the speed and scale of change in the world.

Innovation for sustainability is evident in the convergence of solar energy, electric vehicles and autonomous vehicles. In 2019, Los Angeles struck a 25-year deal for solar and battery power at a price that, according to *Forbes*, 'crushes fossil fuels [and] buries nuclear' [23]. At 1.997 c/kwh for solar and 1.3 c/kwh for batteries, it is half the cost of power from a new natural gas plant. The LA deal demonstrates Swanson's Law for solar, named after the founder of SunPower Corporation, who observed that the price of solar drops 20% for every doubling of cumulative shipped volume. Currently, costs go down 75% every 10 years.

This is convergence in action: Battery costs are falling rapidly on a similar cost curve to solar panels, due to the scaling of lithium ion battery production, which in turn enables renewables to be linked to battery storage, making them a viable alternative to fossil fuels, even at a power plant or electric grid scale. EV batteries, in turn, are being linked to the grid as an additional source of storage.

Meanwhile, advances in the use of Lidar three-dimensional visualisation technology for autonomous vehicles are increasingly being used to improve solar technology design and efficiency, as well as electric vehicle performance.

2.5. Principle 5: Emergence

Complexity increases the chance of innovation, and if these manage to change the overall system, the effects are widespread. This is related to the principle of emergence, which is the ability of a system to produce behaviours or phenomena that are not evident at the level of its individual parts. In layman's terms, this is often paraphrased as synergy: The whole is greater than the sum of the parts. In effect, emergence is the process of spontaneous innovation in a complex (highly interconnected) system. We see examples of emergence in nature and in society, from slime mould and ant colonies to cities and social movements.

Emergence links to another key feature of systems, which is the principle of self-organisation. This is highly relevant for innovation, because we often assume that innovation is a response to top-down goals. For example, a company would typically direct its R&D departments to come up with new ideas, products or improvements that are in line with its corporate mission. While this approach is certainly common, many systems—including networks of innovators—can also spontaneously self-organise.

An ant colony or a beehive is not being directed or organised by the queen. Rather, they use a few simple genetically programmed rules combined with micro-interactions between individuals to self-organise. Stanford University biologist Deborah Gordon has studied the self-organisation abilities of ants for many years [24]. She has discovered five principles, which are relevant to innovation as an emergent phenomenon.

1. *More is different.* There is a critical mass of ants and interactions needed in order to generate self-organisation of a colony. Hence, the smaller the group (whether it be ants or humans) and the more dispersed its members, the less likely that it will self-organise.
2. *Ignorance is useful.* Ants have a very simple 'language'; Gordon has identified around ten signals that are encoded in the pheromone trails they leave. Hence, if the 'rules' are too complicated, the system will descend into chaos.
3. *Encourage random encounters.* Ants are free to roam around the colony, which increases the chance of discovering new sources of food or danger. Hence, allowing individuals to explore beyond defined boundaries increases innovation potential.
4. *Look for patterns in the signs.* Ants build up a pattern from their individual interactions with others, based not only on the messages, but also their frequency on the trail. Hence, innovators are often pattern-spotters rather than lone inventors.
5. *Pay attention to your neighbours.* An ant colony is created entirely from the sharing of local information; no single ant has the 'big picture overview'. Hence, detecting signals from peers may be more important for innovation than grand strategic insights.

These principles are insightful because innovation, like the self-organising behaviour of ant colonies, is the result of emergence. We can draw more insights on self-organisation from the collective behaviour of birds and fishes. When we apply the natural phenomenon of murmuration (flocks of birds moving together) to social systems, research experiments from the University of Leeds [25] and the University of Pennsylvania [26] suggest that a purpose-aligned minority (anything from 5–25%) can move a random crowd towards a common goal, even without coordination. This is sometimes also referred to as the tipping point phenomenon [27].

3. The Five Stages of Integrated Innovation

3.1. Stage 1: Intention

In human systems like companies, although innovation can begin spontaneously through ideation (Stage 2), this is often preceded by the articulation of a clear sustainable intention based on the principle of aspiration. This means creating a shared understanding of the goal of the intended change that will benefit the larger system, which may include society or the environment. Recall that ‘integrated’ in the term ‘integrated innovation’ is referring to innovation that is responding to the wider societal and environmental system in which it is embedded by addressing sustainable development challenges.

Sustainable intention sounds simple but can be difficult in practice. Sustainability is a meta-level concept that acts as a proxy for the healthy functioning of society, the environment and the economy. However, when we try to apply sustainability as an aspirational goal, it raises a number of questions. For example:

1. *Timescale*: Over what period of time should this goal be applied? Do we mean healthy systems over the next five years, the next generation or the next millennium?
2. *Level*: What is the scale of change we are trying to affect? Is it for the village, the city, the country, the region or the world? Or does it apply to particular companies, industries, cultures or biomes that cut across political or economic borders?
3. *Focus*: Are we talking about social *and* environmental issues? If so, is it all the issues, or particular issues like gender equality and climate change?
4. *Trade-offs*: What happens if there is a conflict between sub-goals, like decreasing poverty and protecting biodiversity, or a tension between equally laudable aspirations, like providing decent work conditions and taking action on climate change?

At a global level, we have made progress on some (but not all) of these questions. The UN Sustainable Development Goals set global targets (to be applied nationally) for 2030, covering 17 aspirational areas across a range of economic, social and environmental topics. They do not really acknowledge the potential trade-offs, but it is a good start. In fact, they have become a beacon guiding the actions not only of governments, but of business and civil society organisations as well.

At the industry or product level, we have seen a proliferation of codes and standards, with the International Institute for Sustainable Development (IISD) [28] estimating that there are over 400 voluntary sustainability standards. Many of these are overlapping or competing initiatives. For example, in the forestry sector, there is the Forest Stewardship Council (FSC), Rainforest Alliance and the Programme for the Endorsement of Forest Certification (PEFC) standards, while in the food sector, there is organic, fairtrade, GMO-free, Red Tractor certified and a host of other sustainability labels.

At the company level, organisations add their own interpretation of sustainability and the priority areas they want to focus on. Examples include Tesla, with its mission to accelerate the world’s transition to sustainable energy, and Unilever, with its three big sustainable living plan goals: to improve health and wellbeing for 1 billion, reduce environmental impact by half and enhance livelihoods for millions. Almost every large company has its own version of sustainability goals now.

All of these multi-level sustainable intentions provide a North Star for innovators to follow, and recalling our earlier discussion on emergence and self-organisation, it is not important that they do not all fully agree or completely align. What matters is the general direction. In effect, innovators are joining an emergent flock and adding their voice—or, more powerfully, their actions. As a result, they amplify the movement; and movements, representing shifting social norms, are what ultimately change complex systems.

3.2. Stage 2: Ideation

Ideation—the generation of novel ideas—is widely recognised as one of the critical early phases of innovation [29]. It can range from simple brainstorming sessions and focus groups to more sophisticated

collaborative ideation processes like collective design thinking and hackathons [30]. But what does it look like for sustainable development, and are there insights from systems thinking we can apply?

First, I think it is helpful to distinguish between different levels of ideation: micro-level, which are ideas to improve products and services; meso-level, which focuses on new organisational processes, business models, or value networks; macro-level, which tries to reimagine whole industries or sectors and meta-level, which works at the level of new paradigms or concepts. These are illustrated for sustainable development in Table 1.

Table 1. Levels of sustainable ideation.

Level	Target	Examples *	Reference
Micro	Products and services	<ul style="list-style-type: none"> • Nonpla’s bio-based, edible packaging • How Do I? app for people with dementia 	<ul style="list-style-type: none"> • Peters, 2020 [31] • Alzheimer’s Society, 2019 [32]
Meso	Organisational processes, business models	<ul style="list-style-type: none"> • Mud Jeans’ Lease A Jeans system • Econyl’s swimwear from old fishing nets 	<ul style="list-style-type: none"> • Cocozza, 2019 [33]
Macro	Industries, sectors, value networks	<ul style="list-style-type: none"> • Terracycle’s Loop platform for reusable packaging • Uber’s self-driving car fleet 	<ul style="list-style-type: none"> • Makower, 2019 [34] • O’Kane, 2019 [35]
Meta	Concepts, paradigms	<ul style="list-style-type: none"> • Doughnut economy • Green swans 	<ul style="list-style-type: none"> • Raworth, 2017 [36] • Elkington, 2020 [11]

* In the table, for illustration, I have used examples representing ideas that have already been introduced or implemented. In practice, sustainable ideation would generate new, untested ideas.

A systems thinking approach to sustainable ideation applies the principles of emergence and self-organisation. Hence, it emphasises a bottom-up perspective that maximises possible interconnections and potential random encounters. An increasingly popular approach which is consistent with these principles is open innovation. This can take two forms: open-sourcing formerly proprietary or confidential information; and crowdsourcing innovation ideas or solutions.

The open innovation paradigm was artfully described in *Wikinomics: How Mass Collaboration Changes Everything* [37], based on the principles of openness, peering, sharing and acting globally. The concept was given a sustainability spin in *Macrowikinomics: Rebooting Business and the World* [38], showing how mass collaboration can revolutionize areas like healthcare, education, energy and environmental management.

In practice, we have seen open-sourcing cases like Glaxosmithkline (GSK) [39] working with the World Intellectual Property Organization (WIPO) Re:Search platform to share its research on neglected tropical diseases that affect a billion people worldwide, or Tesla announcing in 2014 that they would not initiate patent lawsuits against anyone who tries to copy their electric vehicle technologies. The reason, according to CEO Elon Musk, was that ‘it is impossible for Tesla to build electric cars fast enough to address the carbon crisis’ [40].

More recently, Amazon chose to share its cashless checkout system with rivals, and fashion retailer H&M introduced Treadler, a new supply-chain sharing service that will allow smaller brands to utilize its infrastructure from development to delivery [41]. All of these examples lower the barriers

to sustainable innovation and increase the chances of collaborative breakthroughs. A more focused approach is to use open-entry prizes to call for innovation on particular issues.

One champion of this crowdsourced innovation approach is The X-Prize Foundation. For example, their \$10 million Rainforest XPRIZE calls for the development of new, more effective biodiversity assessment technologies; their \$20 million NRG COSIA Carbon XPRIZE is for breakthrough technologies to convert CO₂ emissions into usable products (similar to the \$25 million Virgin Earth Prize); and their \$5 million IBM Watson AI XPRIZE challenges teams to demonstrate how humans can work with AI to tackle global challenges.

3.3. Stage 3: Invention

Invention takes ideas and turns them into products, services or processes. The important distinction between invention and innovations is that they have not yet demonstrated commercial viability in the market. The iconic industrial genius Thomas Edison is the archetype of an inventor. Besides the ubiquitous light bulb, Edison devised inventions for motion pictures, mass communication, sound recording and many other industries. In fact, he filed an incredible 1093 patents covering everything from film and sound to light and materials. His philosophy and approach to invention is encapsulated by his quote: 'I have not failed; I've just found 10,000 ways that won't work.' In practice, he tested more than 6000 potential filaments before settling on carbonized bamboo.

We can find sustainable inventions throughout history. For example, French inventor Gustave Trouvé tested what was arguably the first electric vehicle (a kind of tricycle) in Paris in April 1881, while the first electric car in the United States was developed around 1890 by William Morrison; it was a six-passenger wagon capable of reaching speeds of 23 kilometres per hour. Similarly, in 1878, French mathematician Augustin Mouchot invented a parabolic solar collector, which was exhibited at the Paris Expo that year, while the first patent for a solar cell was granted to English-American chemist Edward Weston in 1888.

Inventors are problem solvers. This is nicely illustrated by Shawn Frayne and Alex Hornstein, two young inventors who say that they 'fell in love with the dream of clean energy, everywhere, for everyone.' The problem they saw (back in 2012) was that solar panels were expensive, broke after a few years and were not very well made, so they joined forces and asked themselves the question: could we make it better? 'This simple question,' they explained, 'led us on a voyage of investigation and discovery through the world of small, low-cost solar; through rotting solar factories in Southern China to shivering, soaked motorcycle trips across unelectrified tropical islands in the Philippines and countless late nights working on prototypes in an industrial building in Hong Kong.'

The result was the Kickstarter funded Solar Pocket Factory, which prototyped a three-dimensional printing machine small enough to fit on a desktop and efficient enough to eventually produce up to one million microsolar panels (0.2W to 10W) per year; one every 15 s [42]. Comparing their design aspirations with traditional microsolar solutions (Table 2) gives an insight into how sustainable inventors use ambition to fuel their creativity [43]. The final part of their story is also not unusual for inventors: Their invention appears to have never achieved commercial viability. As a result, the inventors dropped off the media radar after 2014. This is the key difference between invention and innovation.

There are thousands of other sustainable inventions, some of which make it to market and some of which do not; sometimes, this is a question of still being in the early stage of development, testing and marketing. To give an example, researchers at Japan's National Institute of Advanced Industrial Science and Technology have created a robotic, bee-like drone in response to the rapid decline in global bee populations. The pollinator bee-bot is manually operated and is still far from becoming a market-viable product.

Table 2. Solar Pocket Factory design criteria.

	Traditional Microsolar	Solar Pocket Factory
Materials	Made with low-cost epoxy	Made with long-lasting solar polyurethane or laminated glass
Lifetime	Two years	A minimum of ten years
Cost per panel	\$1.50–\$1.75/W	\$1.00/W
Production	Outsourced to India, China or Bangladesh	Produced in the country where the panels will be used
How it is made	Completely by hand; slow, inaccurate, expensive	Fully automated; fast, accurate, cheap, versatile

Source: Sterling, 2012 [43].

3.4. Stage 4: Synovation

Innovations are inventions that cross the ‘chasm’ in Rogers’ [5] technology adoption lifecycle between the early adopters and the early majority. In practice this means that they find a viable market. Sustainable innovations that have successfully leaped over the chasm include Wello Water’s Hippo Water Roller, which allows water to be rolled in a barrel rather than carried in buckets by hand or on the head in low-income communities, or Freeplay’s off-grid technologies that use hand-powered wind-up battery charging for radios, solar flashlights and lanterns, mobile phone chargers, foot-powered generators and even foetal heart-rate monitors.

These examples are fairly focused on solving single issues, but it is immediately evident that they have multiple benefits, which is often the case with sustainability solutions. Hippo Water Roller helps to alleviate poverty by reducing unproductive time spent fetching water, while also lowering the risk of injury from carrying heavy loads. Freeplay’s devices enable low-income families to work, study and have better health, while simultaneously lowering carbon impacts by using grid-free power and renewable energy sources. Hence, sustainable innovation is, by its nature, what I have called ‘synovation’, meaning synergistic innovation [44].

One useful characterisation of this synergy-driven approach to sustainable innovation is Stuart Hart and Mark Milstein’s sustainable value framework, which looks for the synergies between sustainability vision (by which they mean addressing the unmet needs at the base of the economic pyramid), pollution prevention, product stewardship and clean technology [45]. In their book of the same title, this approach is described as ‘the green leap to an inclusive economy’ [46], which uses innovation to simultaneously tackle the two biggest issues facing humanity and the planet today—inequality and environmental degradation.

My integrated value framework (Figure 1) provides a five-dimensional view of synovation, where innovation occurs in response to the five triggers for transformation, and is at the heart of what I call the nexus economy, where the resilience, access, circular, digital and wellbeing economies meet [47]. Each zone of systemic breakdown (disruption, disparity, degradation, disconnection and discontent) can catalyse innovations, which respectively make our lives more secure, shared, sustainable, smart and satisfying. For example, Boyan Slat’s Ocean Cleanup solution for ridding the ocean of waste plastic is a single-focused sustainable innovation, but when solutions bring benefits across two or more of these breakthrough areas, they create integrated value.

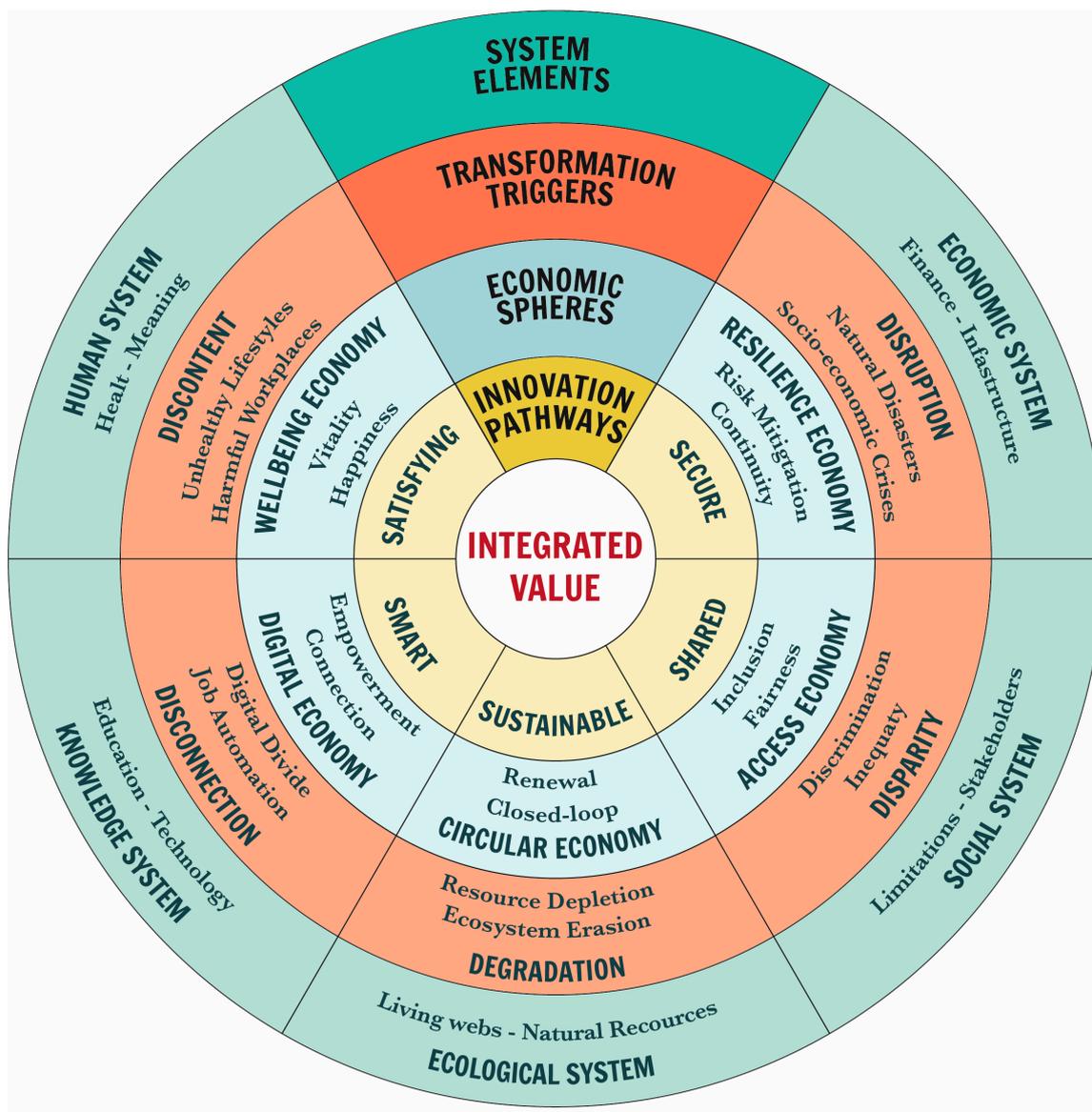


Figure 1. The integrated value framework. Adapted from Visser, 2017 [47]; Copyright 2019 Wayne Visser.

Zipline, voted by FastCompany as one of the world's most innovative companies in 2020, is a good example to illustrate synovation that creates integrated value [48]. The San-Francisco based company uses autonomous drones to deliver medical supplies to hard-to-reach rural areas in Africa and will soon launch in India and the USA. It already transports 75% of Rwanda's blood supply outside its capital city, Kigali, and has connected 2000 hospitals, covering 12 million people, in Ghana. This is a 3-S integrated value solution: smart (using connected technologies), satisfying (providing healthcare services) and shared (including previously excluded segments of the population; the rural poor).

3.5. Stage 5: Transformation

When innovation is elevated from the level of individual product or process innovations to changing whole industries or business models, the possibility for transformation arises. As with synovation, the more dimensions of integrated value that can be joined together, the higher the likelihood of systemic change. Another way the phenomenon of multi-dimensional innovation synergies leading to transformation has been framed is in terms of convergence, most notably in the technology sector.

We see sustainable convergence happening in different sectors, but nowhere more clearly than in the increasing synergies between renewable energy, electric vehicles and autonomous vehicles, as previously noted. Each technology has evolved along separate tracks, benefiting from innovations and declining cost curves for solar cells, batteries, cloud computing, the Internet of Things and artificial intelligence, but now their convergence is ushering in a new mega-market in clean transportation. Tesla is probably the best placed to take advantage of this convergence, as Table 3 shows.

Table 3. The 5-Ss of integrated value (IV) leading to sustainable transformation.

IV Dimension	Description of Value Created
Secure	Grid-scale battery farms combined with renewables increase resilience. In the wake of Hurricane Maria in 2017, Tesla rapidly restored power to hard-hit Puerto Rico.
Shared	Tesla's Model 3 has made electric vehicles more affordable, and it is planning an autonomous fleet that will make electric vehicle (EV) ride-sharing more accessible.
Sustainable	EVs have a lower life cycle carbon footprint and their renewable energy and battery businesses are scaling low-carbon energy solutions for households, companies and governments.
Smart	Tesla's autopilot EV technology uses the Internet of Things (IoT) and artificial intelligence to improve the performance and safety of its vehicles.
Satisfying	Renewables, batteries and EVs have lower health-damaging emissions than alternatives, and Tesla's autopilot (a precursor of full autonomy) is already multiple times safer than human-only driving.

Sustainable transformation is not only about technology convergence. It also relies on disruptive business models. For example, Tesla's future-fitness—and one of the reasons for its \$100 billion valuation—is built on transformational business models, such as the sharing economy. Its car-battery-solar combinations are set to take advantage of distributed energy, while its car leasing scheme and future autonomous fleet may rapidly eclipse Uber, Lyft and other car-sharing service companies. Tesla also has the potential to fully embrace the circular economy in its vehicle and battery design, recovery and recycling.

Hence, sustainable transformation occurs when solutions tap into multiple economic spheres of the integrated value web: the resilience economy, the access economy, the circular economy, the digital economy and the wellbeing economy. The food system is an example of a sector ripe for disruption and transformation to make it more sustainable. Regenerative agriculture, vertical farming and precision farming are just a few of the emerging approaches that could ensure that our agricultural practices simultaneously deliver a future that is more secure, shared, sustainable, smart and satisfying.

Undoubtedly, in order to succeed, we need government policies that support and incentivise transformative practices. A good example is the EU Green Deal, which the President of the European Commission calls 'Europe's man on the moon moment'—an ambitious, world-changing plan. The 2030 goals include: 50% reductions in carbon (up from 40% previously), 32% renewable energy and 32.5% energy efficiency improvement. To get there, Eurocrats will use policy reforms on circular economy, mobility, building and renovation, pollution, ecosystems and biodiversity and food. The EU Emissions Trading Scheme will also be extended and will help to fund the economic transition.

4. Conclusions

In this paper, I have shown how the principles and practices of systems thinking can add insights and nuances to our current understanding of innovation in general and sustainable innovation in particular. I have called this approach integrated innovation and illustrated its value by applying five systems thinking principles—diversity, aspiration, networks, convergence and emergence—to five typical stages of innovation: intention, ideation, invention, synovation and transformation, summarised in Tables 4 and 5.

Table 4. The principles of integrated innovation.

Principle	Description	Example
Diversity	Increasing variance or heterogeneity of perspectives within the system to fuel creative problem-solving	The X-company's Moonshot Factory of diverse inventors and entrepreneurs
Aspiration	Using a larger purpose to inspire and guide innovation to deliver societal and environmental benefits	IKEA's People and Planet Positive and Danone's One Planet One Health strategies
Networks	Tapping into collective ideation and spotting butterfly effects through relationship webs	The Global Sustainable Technology and Innovation Community (G-STIC)
Convergence	Riding the wave of combinations of technologies or trends that complement and accelerate each other	Plant-based diets in response to health, climate and environmental trends
Emergence	Supporting leaderless self-organisation of large groups to bring about novel solutions to complex problems	Zappos' Holacracy approach to self-management and self-organisation

Table 5. The stages of integrated innovation.

Stage.	Description	Example
Intention	Distilling and articulating the non-market function of the innovation system in terms of its societal benefit	Interface's 2020 Mission Zero and 2030 Climate Takeback strategies
Ideation	Using crowdsourcing and open innovation to surface the best ideas for tackling 'wicked' problems	X-Prize Foundation (Rainforest, Carbon, AI) and Virgin's Earth Challenge
Invention	Prototyping specific design, product or process solutions for specific problems that are aligned to societal needs	Yuima Nakazato's biosmocking technology for biofabricated clothes
Synovation	Finding a market for innovations that synergise secure, shared, smart, sustainable and satisfying benefits	GE's Vscan Extend pocket-size ultrasound scanning device
Transformation	Combining convergent technologies or business models and progressive government policies to reinvent industries	Sustainable packaging change to bio-based, biodegradable and circular

There are a number of conclusions that we can draw from this conceptual analysis. First, systems thinking is already implicit in much of the work on innovation, and especially on sustainable innovation. However, it is applied rather loosely, superficially and in an ad-hoc fashion. Therefore, there is value in making it explicit. As our awareness of the relevance of systems thinking for innovation rises and our understanding of how its principles can be applied improves, innovation processes will benefit.

Second, integrated innovation adds to the literature on innovation by giving an intellectual framing for bringing together various concepts that deal with the potential of innovation to bring societal benefits. These include, for example, social innovation, frugal innovation, inclusive innovation, eco-innovation and sustainable innovation. Integrated innovation does not try to replace these concepts and practices, but rather shows how they are part of a broader agenda that is seeking to turn systemic breakdowns into breakthroughs.

Finally, many of the most successful examples of innovative companies, or innovative products and services, apply the principles of integrated innovation and have moved through the stages from intention to transformation. This suggests that applying the systems science lens to innovation is not merely an intellectual exercise, but rather that it describes a more effective innovation practice. By

positioning innovation in service to society and by pointing its creative solutions towards tackling global challenges, the opportunities to make a market impact are also greater.

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