Systems Innovation concept map

SI Event limited edition

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1 Introduction

This document describes the System Innovation concept map – shown on the right of this page – which describes our **current** understanding of the complex systems in which contemporary complex problems arise and the pathways to approach those problems. The purpose of this concept map is to illustrate the core concepts around the term *systems innovation* and create clarity about where it comes from (understanding the mess), what it is (changing the mess) and which methods, techniques and tools are used (praxis). We use the term 'mess' instead of 'problem', given its broader meaning of *"a set of conditions that produces dissatisfaction [...] a system of apparently conflicting or contradictory problems or opportunities"* (Ison, 2017, p.23). Before we untangle the conceptual 'spaghetti' of innovation, systems, and complexity, let us first define the concept of systems innovation.

1.1 Systems innovation

Systems Innovation (SI) is a type of innovation that addresses complex societal problems by changing the architecture and the social or technological components of socio-technical systems, aiming to improve those in terms of societal values (Suurs & Roelofs, 2014; OECD, 2015). Possible SI changes to the system often produces new knowledge, skills and technological capabilities, fundamentally different consumer behavior and new markets, or new infrastructures, rules and regulations (OECD, 2015). These changes occur over a (long) period – thus SI takes the shape of a transition or transformation during which existing competences and market structures are disrupted, leading to the creation of new markets (OECD, 2015; Leadbeater & Winhall, 2020).

The socio-technical system may also span multiple domains that are often considered separately. For instance, 'smart cities' where energy, mobility, education, the built environment come together, or the 'healthcare system' which can be viewed in a broader sense to include lifestyle improvement and healthy ageing - where the fields of medicine, agriculture and biology intersect. In line with this definition, we may also refer to SI *as an approach* to tackle complex problem situations, aiming to innovate the functioning of a socio-technical system (Suurs & Roelofs, 2014)[1].

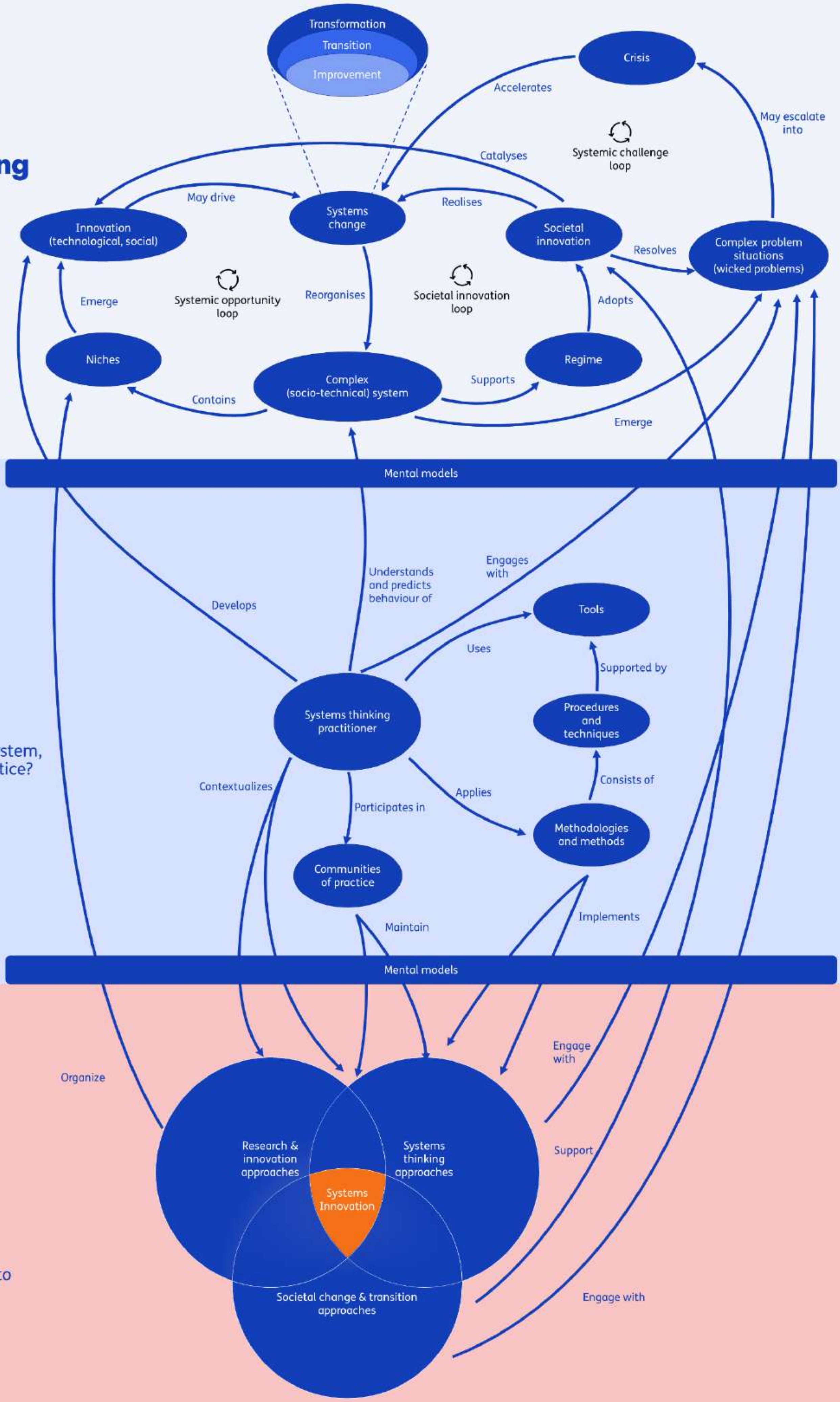
To better conceptualize SI, we look at it through three layers, three approaches, and three loops. The three layers are *understanding the mess, changing the mess and 'praxis',* which are described in the following chapters. In our understanding of the 'mess', we notice three loops – building on Leadbeater & Winhall's (2020) concepts of systemic opportunity and systemic challenge. For our approaches to changing the mess, we focus on three knowledge areas that support Systems Innovation, namely R&I approaches, systems thinking approaches, and societal change approaches. *Praxis* is theory-informed practical action (Ison, 2017), 'sandwiched' between our understanding and our approaches for good reason: it connects the real-world mess to our (theoretical) approach. In other words, we take an approach and put it into practice within a specific context.

This concept map was created through desk research of the current literature on this domain and aims to clarify the relationships between many – seemingly similar – concepts and their definitions. This document describes these three layers in further detail.

[1] This duality of the term 'innovation' (innovation *as a process* and *as an outcome* of that process) is also described in the section on innovation.

Understanding the mess

What is the situation?
How is the system changed?



Praxis

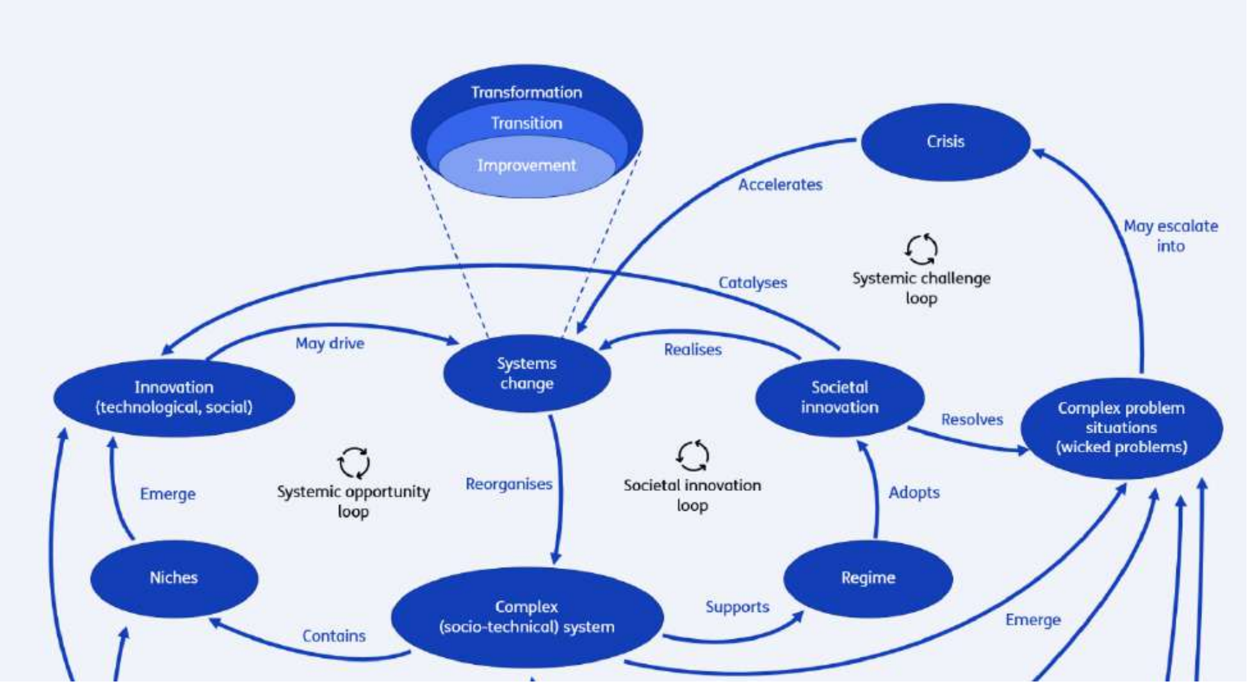
When changing the system, what do we do in practice?

Changing the mess

What is our approach to changing the system?

2 Understanding the mess

Understanding the mess deals with the core concepts of systems innovation: systems, problems, complexity, and change. In our understanding of the mess – a dissatisfaction or contradiction between problems and opportunities – we identify the relevant concepts as part of the loops: systemic opportunity and systemic challenge, and societal innovation loop.



System innovation focuses on *complex socio-technical systems,* such as the energy grid, the internet, or highway system[2]. In such a type of system, complex problem situations (a.k.a. 'wicked problems') emerge, such as net congestion in the energy grid, the spread of disinformation, or traffic accidents. We identify three **loops** through which such systems may change:

1. The *systemic challenge* loop, a (negative) feedback loop in which transitions have the potential to resolve complex problem situations. Complex problems may result in crises that potentially trigger unintentional or unplanned transitions which may resolve that complex problem situation (e.g. the COVID-19 pandemic put digitalization in overdrive). During a transition, the system temporarily destabilizes and reorganizes.

2. The *societal innovation* loop, in which change occurs from innovations in the socio-technical regime itself, through many ways. In this loop systems change is relatively guided and directed by changes in the regime through societal innovations.

3. The *systemic opportunity* loop, which recognizes that transitions can also be driven by innovations that are adopted (specifically general purpose technologies such as the steam engine, the internet, or AI). Innovations are novelties (i.e. inventions, technologies, solutions) which may emerge in the niches of complex socio-technical systems, outside of the mainstream markets. Technological innovations (e.g. jet engine, artificial intelligence) can be an important driver of transitions.

[2] A complex socio-technical system refers to systems where both people and technology interact (Geels, 2004).

2.1 Systems, complexity, and change

A system may be described as an *"interconnected set of elements that is coherently organized in a way that achieves something"* (Meadows, 2008, p.1). Some characteristics of a system are geography, technology, relationships, boundaries, formal and informal aspects, and its goal (OECD, 2015). This section further explores what a complex socio-technical system is, and how systems change relates to this.

2.1.1 Complex socio-technical systems

Socio-technical systems (STS) are systems composed of people and technology interacting (Soliman & Saurin, 2017), hence the term '*socio-technical'* (which is a contraction of *social* and *technical).* STS helps thinking about the role of technology in society not merely as technological systems or social systems (Geels, 2004). Technology is used and applied in human contexts. It can even be challenged that there is such a thing as a divide between the 'technological' world of things and the 'social' world of humans[3].
Complex socio-technical systems are those STS that have characteristics of complexity (Soliman & Saurin, 2017). These characteristics are:

- many elements (employees, equipment, procedures, users, departments)
- interactions that are *dynamic* (mutual information exchange), *rich* (one-to-many relationships), *non-linear* (small variations can cause large disruptions)
- feedback loops
- openness (the system may be subject to external factors)
- instability (the system is ever adjusting its functioning, seeking an equilibrium)
- history (path dependency)
- ignorance of the behavior of the system as a whole (actors that do not recognize the emergent properties of the system)

Moreover, multiple complex socio-technical systems are typically interconnected. For instance, the pension, welfare, work, and income systems – with all their social and technological components – are mutually dependent (Leadbeater & Winhall, 2020).

Complex and complicated

While complexity refers to characteristics of a system that make it unpredictable and interconnected, complicatedness refers to the difficulty of understanding the system or solving problems in it. A complex system is impossible to fully describe and model, and it will show unpredictable behavior.

Meanwhile, a complicated system can have many parts, but these follow predefined rules and have linear interactions. So for a human observer, the system may be too complicated to understand, and they may want to use a computer to model the system and develop their solutions. In essence, if you have a powerful enough brain (or computer), you can solve problems of highly complicated system.

To illustrate complicatedness, let us discuss the cryptographic algorithm RSA, which is a 'system' that can be used for secure data transfer like visiting a website. At the heart of the algorithm lies a pair of prime numbers – the public key and the private key. You need both the public and private keys to read messages that are encrypted through RSA. The only reason RSA is useful is because it is impossible to 'brute force' the calculations to find out the private key. It cannot be solved with the available resources – it is intractable. However, if you have a powerful enough computer, it should be possible to 'crack the code'. Luckily, this is currently not (yet!) the case. But mathematician Peter Shor proved in 1994 already that a quantum computer can efficiently find the private key . Complicatedness may be seen as an aspect of complexity that is dependent of the observer (Soliman & Saurin, 2017).

[3] We refer the reader to *actor-network theory*, which is wonderfully illustrated by Latour (1988) using the simple example of a door.

The dynamics of complex socio-technical systems

The multi-level perspective (Geels, 2004) is a way to describe the dynamics between processes at different levels in the complex socio-technical system, and how innovations can change the socio-technical regime. These dynamics are shown in figure 2.1. These levels are:

1. *Macro* factors: the 'landscape' or wider context that slowly changes, which influences niche and regime dynamics. This may be demographical, ecological, macro-economic, social-cultural, political, or technological patterns.
2. *Meso* factors: the socio-technical system, or regime. Relevant factors at the meso-level are material and technical elements, actors and (social) networks, norms and rules that guide the behavior of actors
3. *Micro* factors: Factors that arise in "secluded margins within the socio-technical system" called *niches* (Geels, 2004, p.3) where niche actors (e.g. entrepreneurs, start-ups, or communities) develop new innovations with the potential to influence the regime at the meso level.

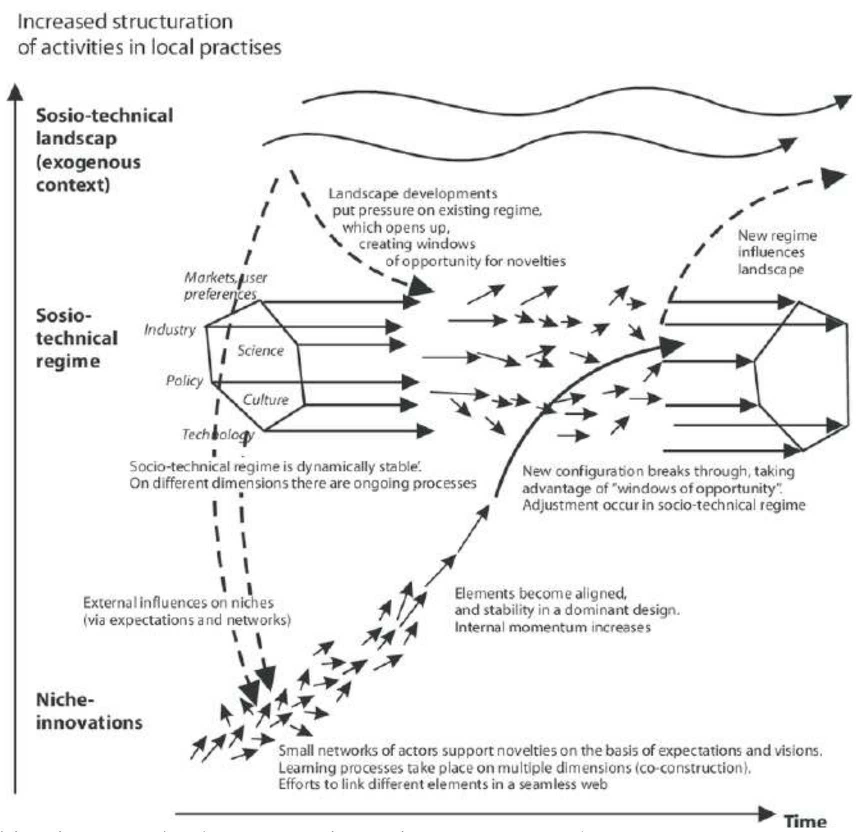


Figure 2.1: The multi-level perspective (source: Geels & Schot, 2007, p. 401)

2.1.2 Systems change, transition and transformation

Terms like change, transition and transformation seem similar and are used interchangeably[4], but they are conceptually different as they stem from different research areas interested in systemic societal change (Hölscher et al., 2018). *Systems* change tends to refer to a modification to the system elements, while *systemic* change refers to a change of the whole system its structure, function, process, context (Gharajedaghi, 2011). Three different orders of change can be identified: improvements, transitions, and transformations (Boonstra, 2004). Improvements tend to be seen as a modification to system elements

[4] This similarity is clear from the dictionary entries. *Change* is defined as "to become […or] to make something different", while *transition* is defined as a "change or shift from one state, subject, place, etc. to another" and *transformation* is defined as "change in composition or structure; […] outward form or appearance; […] character or condition" (www.merriam-webster.com). Transition seems to emphasize the process of change while transformation emphasizes the new state.

(systems change), and transitions and transformations as changes to the whole system – its structure, function, process, context (Gharajedaghi, 2011). The three orders of change can be understood as follows:

1. **Improvements**, first-order changes, might be considered the majority of changes. These are enhancements within the existing context.

2. **Transitions** or second-order changes try to create a different desirable future that can only be accomplished by making significant changes to the current technical, political, and cultural systems. Thoroughly evaluating the assumptions behind these institutionally embedded systems is important to reach the desired future.

3. **Transformation**, third-order change, refers to the emergence of a wholly new state from the ruins of the previous one. In contrast to transitions, transformations do not reveal the new state until it manifests. Transformations are multifaceted, multilevel, and connect to the deepest level of change

It should be emphasized that both transitions and transformations provide complementary perspectives on desirable societal change (Hölscher et al., 2018). Both frameworks differ in:

- scope (changes in subsystems, large-scale change processes)
- dynamics (patterns, emergence)
- normativity (assuming an unsustainable state, or an undesirable state)
- agency & governance (developing interventions, responding to change)

<u>The dynamics of systems change</u>
Both transitions and transformations are temporary destabilizations and reorganizations of a system and may be required to solve a complex problem situation (e.g. energy transition). They are long-term processes of change and generally have 4 phases of diffusion, as seen in the figure below (Rotmans et al., 2001).

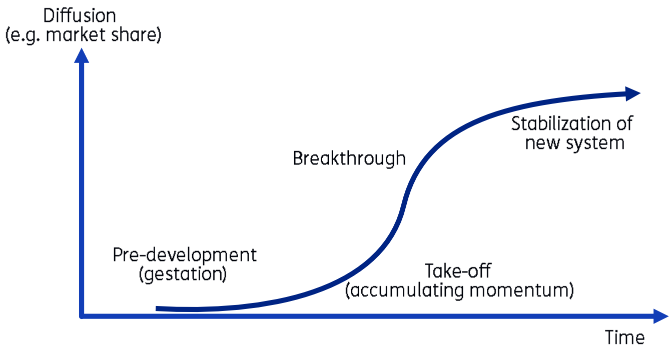


Figure 2.2: The four-staged transition model (Based on: Rotmans et al., 2001)

2.2 Concepts in the systemic challenge loop

The systemic challenge loop describes complex problem situations (or wicked problems) and crises. In this loop, complex problem situations – if not addressed – may evolve into crises, which have the potential to accelerate systems change.

2.2.1 Complex problem situations (wicked problems)

Wicked problems, such as climate change, poverty, health care and social inequality, are problems that are extremely complex and change over time, have stakeholders with different world views, and there are no unambiguous solutions, and these solutions do not solve the problem definitively – potentially leading to unintended consequences (Rittel & Webber, 1973).

Wicked problems are implied by a "VUCA" context, where complexity is merely one dimension. The term, coined by Bennis & Nanus (1985), refers to the factors that make the world chaotic, leading to wicked problems and difficulties in decision-making. VUCA stands for *volatility*, *uncertainty*, *complexity,* and *ambiguity* (see Figure 3).

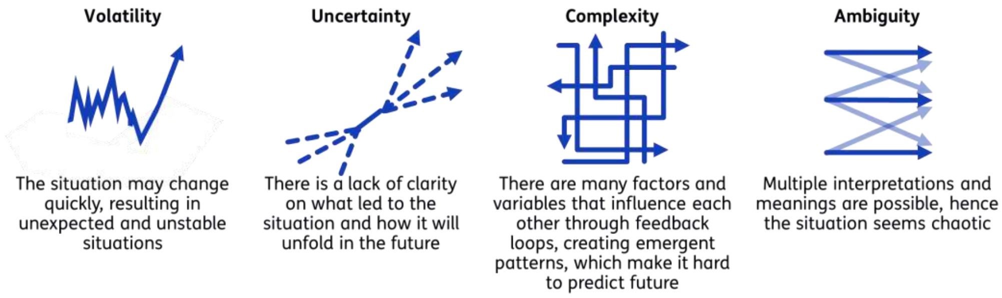


Figure 2.3: Four contextual VUCA-factors of systems that lead to wicked problems

2.2.2 Crises

Crises can be defined as sudden and unpredictable events or situations that threaten to harm individuals, organizations, or entire societies. They often arise from a combination of factors such as natural disasters, economic instability, social unrest, or political upheaval. These problems can lead to crises when they are not addressed effectively, or when they are exacerbated by external factors such as environmental changes or technological disruptions. The extreme setting of crises exposes strains in current systems and accelerates change to new systems (Leadbeater & Winhall, 2020).

Crises can also trigger the need for innovation because they create a sense of urgency and necessity for change. In times of crisis, people and organizations may be forced to think outside the box and develop new solutions to immediate problems. This can lead to the creation of innovative technologies, processes, and systems that address the root causes of the crisis and prevent similar crises from occurring in the future. For example, the COVID-19 pandemic has led to the rapid development of vaccines, new medical treatments, and innovative technologies for remote work and learning (Geurts et al., 2022).

2.3 Concepts in the systemic opportunity loop

The systemic opportunity loop describes the way in which innovations may drive systems change - in particular those innovations that are not yet mainstream (as they are in niches) but have transformative potential.

2.3.1 Niches

Niches are 'protected spaces' where innovations are developed. This can be a (shared) laboratory, a demonstration project, or a small market niche for specific users (Geels, 2011). Niche innovations refer to new products, services, or technologies that are developed to meet the specific needs or demands of a particular market niche or group of consumers. These niches often arise from identifying a gap or unmet need within an existing market and developing a solution to address that need.

Niche innovations are a vital component of creating change at the micro level. These innovations are often driven by individuals who are seeking to develop radical new solutions, habits, and ways of life in response to local needs and opportunities (Leadbeater & Winhall, 2020). Examples of niche innovations include electric cars, plant-based meat alternatives. While initially developed for a specific market niche, these innovations have the potential to expand and disrupt larger markets as they gain broader adoption and acceptance (Christensen, 1997). A prominent example is for instance the development of touch screens, initially designed as a niche innovation as a drawing tool and now widely used in all kinds of technology.

2.3.2 Innovation

To explain innovation, first we must remove the ambiguity of the word as it can refer to innovation *as a process* and innovation *as an outcome* of that process. In the first case, innovation activities are the developmental, financial, and commercial activities that are intended to result in an innovation (OECD/Eurostat, 2018, p.35). An *innovation* is "a new or improved product or process (or combination thereof) that differs significantly from previous products or processes and that has been made available to potential users or brought into use by the unit" (OECD/Eurostat, 2018, p.35). They may emerge in the niches of systems, outside of the mainstream markets (Suurs & Roelofs, 2014).

<u>Types of innovation</u>

To better understand innovation, it is useful to look at different types of innovation (Leadbeater & Winhall, 2020). The following distinctions are often made:

- *Technological or social* – Based on the previously given definition of innovation, we can further define these as follows:
    - *Technological innovation* is the development and implementation of new or improved technologies and/or technology-driven improvement of products, services, or processes (OECD/Eurostat, 2018).
    - *Social innovation* is the development and implementation of new or improved ideas, aimed at changing ideas and attitudes of people and organizations (Lin & Chen, 2016; Satalkina & Steiner, 2022). It is often aimed at social needs and characterized by mid- to small-scale innovations for specific social subgroups of people. These innovations tend to develop through social businesses (e.g. fair-trade coffee) or expanding market interests (e.g. veganism) – creating new ways to offer societal value (Lin and Chen, 2016)[5].
- *Artifact (*e.g. products, services, software, processes)
- *Radicality:* Incremental or radical - Incremental innovations and steps can also lead to radical change (Termeer, 2019).
- *Societal disruptiveness:* Disruptive or sustaining, where disruption refers to niche players like startups successfully challenging established the mainstream businesses (e.g. home delivery supermarket) and sustaining refers to those innovations that improve mainstream business' products to their customers, such as higher definition TV (Christensen, 1997).
- *Novelty*: new-to-firm, new-to-market, or new-to-world (OECD, 2015)

This results in a more fine-grained view of the concept of innovation, where some of these distinctions produce different types (see Figure 4).

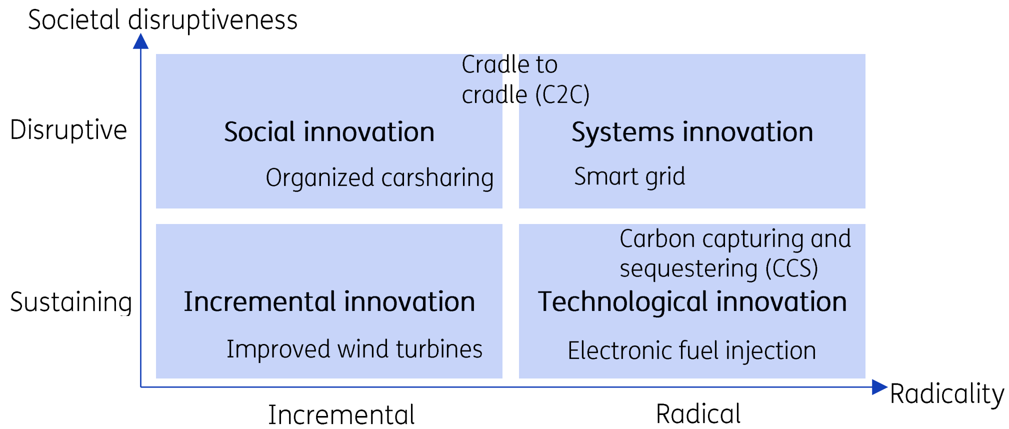


Figure 2.4: Different forms of innovation in terms of their and societal disruptiveness (user practices, markets, institutions) and technological radicality (requiring new knowledge, competences, skills). (Based on: Kemp, 2011).

[5] While the distinction between technological and social innovation is useful, it may be challenged that there is purely technological and purely social innovation, see the section 'Complex socio-technical systems'.

2.4 Concepts in the societal innovation loop

The societal innovation loop refers to those innovations that are often driven by the socio-technical regime, with the potential for systemic, structural change.

2.4.1 Regime

The *socio-technical regime* is a “set of rules that orient and coordinate the activities of social groups in markets, science, policy, culture, and technology (Geels, 2004). These rules can be shared beliefs, competences, lifestyles and user practices, and legal contracts – accounting for the stability of the socio-technical system (Geels, 2004). The rules may be embedded in infrastructure, institutions, and markets (Leadbeater & Winhall, 2020). Unlike niches, regimes tend to maintain the status quo and resist change because they depend on existing systems and structures. A regime can also be seen as a system that provides stability by setting rules and norms for those within it, and it can sometimes be seen as an obstacle to new ideas and change coming from outside. When one regime is replaced by the emergence of the next, system transitions occur. In order to develop a different and improved system, changes at both the macro and micro levels are not sufficient; changes must also occur at the meso-level.

2.4.2 Societal innovation

Societal innovation refers to innovations with the potential to realize desired systemic and structural societal changes and to direct and accelerate transitions and transformations. These innovations may be of different natures: political innovations, institutional innovations, economic innovations, legal innovations, business innovations and spatial planning innovations – which may all contribute to initiating change in how government, businesses and citizens observe, think and act. Widespread adoption of such innovations in existing systems allows for the realization of structural change. *Structural and systemic* change refers to achieving a substantial change through incremental or radical steps (Lin & Chen, 2016).

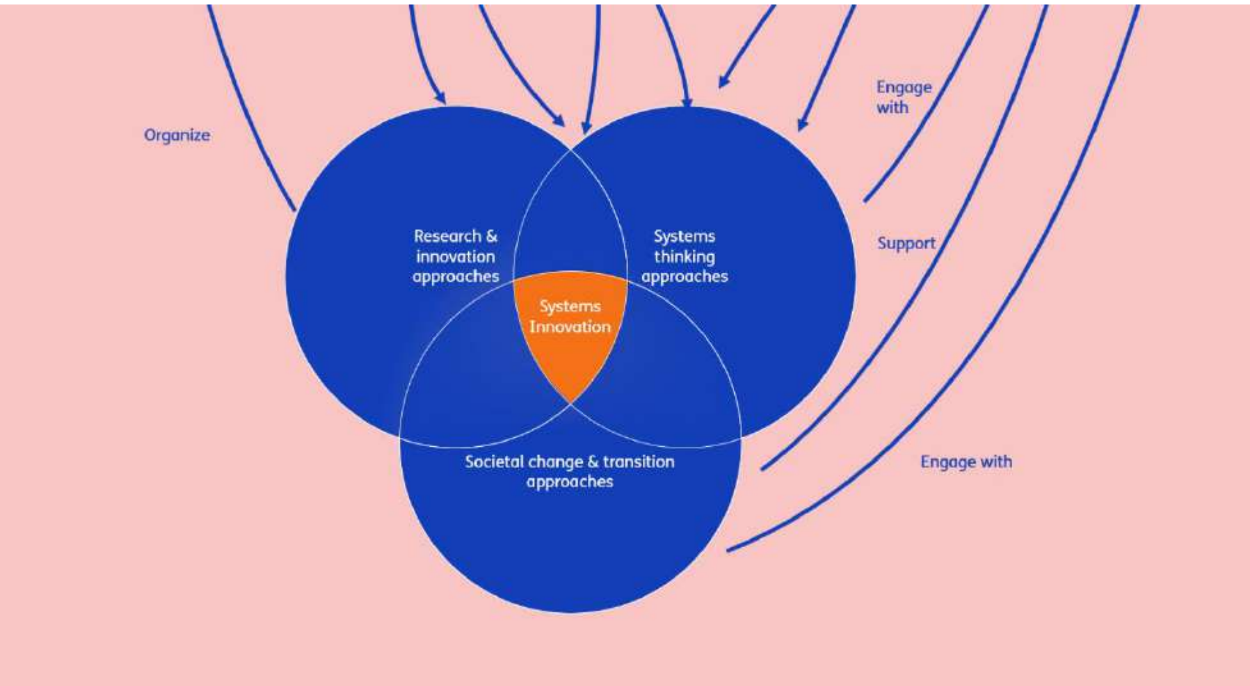
Actors are dependent of each other, thus societal innovation cannot be realized by just one actor, but by a movement of actors that settles in society and realizes increasingly larger change (Lethola & Ståhle, 2014).

These structural and systemic changes make societal innovation a catalyzer for technological innovation and social innovation. Technology may present solutions to societal problems, and the investment, development, and adoption are guided by societal goals. Social innovation creates change based on social needs, through movements and social entrepreneurship, but it does not remain until it is accepted and deployed by both civil society and government – i.e. institutionalized social change (Lin & Chen, 2016). Societal innovation requires the building up of new systems and the breaking down of old systems, changing existing socio-technical regimes (Hebinck et al., 2022).

3 Changing the mess – our approaches

Considering 'the mess', in the past decades many approaches have been developed for changing it and engaging with complex problem situations – either by researching or innovating with societal stakeholders, designing or engineering systems with societal needs in mind, or to make policies that steer transitions in societally desired ways. To realize systems innovation, we focus on approaches at the intersection of these three domains:

1) Research & innovation
2) Systems thinking in practice
3) Societal change & transitions



3.1 Research & innovation approaches

With research and innovation (R&I) approaches we refer specifically to the disciplines involved in R&I activities – ranging from mono-, multi- inter-, and trans-disciplinarity (Groot et al., 2007).

- *Monodisciplinarity* stays within the boundaries of a specific discipline.
- *Multidisciplinarity* draws on knowledge from different disciplines but stays within the boundaries of those fields (Choi & Pak, 2006).
- *Interdisciplinarity* "analyzes, synthesizes, and harmonizes links between disciplines into a coordinated and coherent whole" (Choi & Pak, 2006).
- *Transdisciplinarity* engages with complex problem situations, involves people with diverse disciplines, and has an iterative character in problem-setting and solution-finding (Steen & Sassen, 2021). These terms can be viewed as different degrees of involvement of multiple disciplines, (as shown on the left of figure 3.1), or as different ways to view a complex problem situation (right side of figure 3.1). McPhee et al. (2018) explain it as follows:

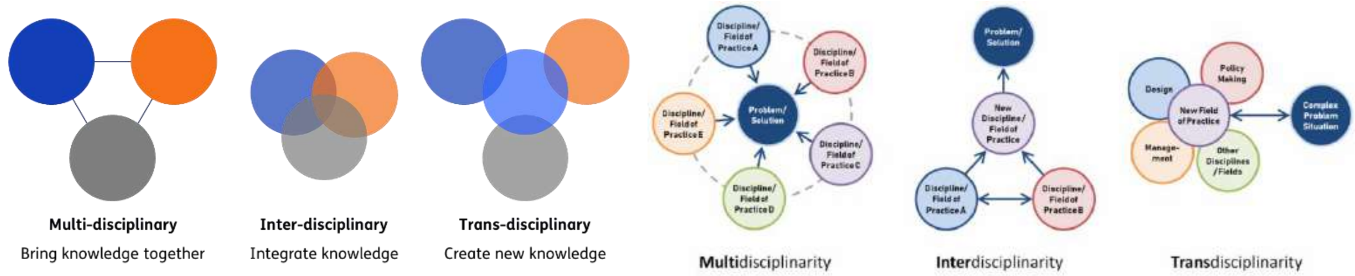


Figure 3.1: Two characterizations of disciplinarity. Right is from Choi & Pak (2006), left is from McPhee et al (2018)

> *"Transdisciplinary innovation differs from multidisciplinary and interdisciplinary approaches in that it is not just about working towards a shared goal or having disciplines interact with and enrich each other. Instead, transdisciplinary innovation is about placing these interactions in an integrated system with a social purpose, resulting in a continuously evolving and adapting practice" (McPhee et al, 2018).*

3.2 Systems thinking approaches

System thinking refers to “thinking and acting using system concepts and designing/using systems-methodological processes to support the systemic thinking and action of others, so they too can innovate” (Midgley & Lindhult, 2021, p.656). **The ‘systems concept’ is a tool for critical thinking**, helping people to not overlook or take for granted “the boundaries, interactions, perspectives and patterns of emergence” (Midgley & Lindhult, 2021, p.656). Systems thinkers investigate how multiple perspectives, values, power, conflict, identity, cocreation and marginalization play out in stakeholder relationships, which often are significant barriers to systems innovation. Systems thinking approaches offer ways to understand barriers to innovation, and methods to address them (Cabrera, Cabrera & Midgley, 2022).

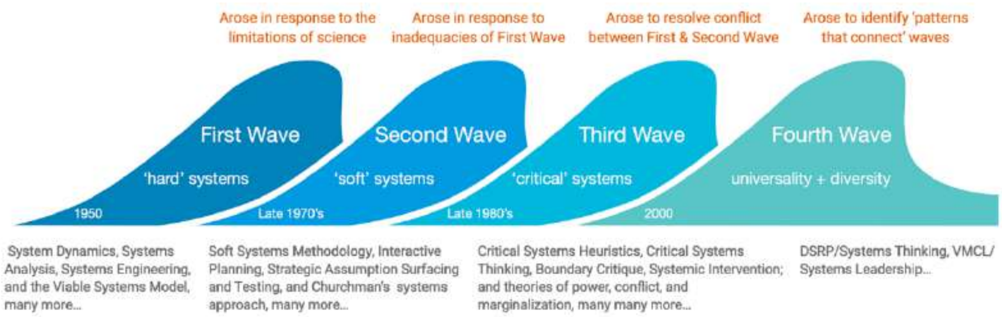


Figure 3.2: The four waves of systems thinking (from Cabrera et al., 2022)

Over time, several systems thinking disciplines have emerged, such as system dynamics and software systems engineering. Where the first three waves of systems thinking approaches first appeared in 1950-2000, it is argued that there is a fourth wave emerging (Cabrera et al., 2022). These earlier waves have not ended, but merely changed. For instance, the field of *Systems Engineering* is constantly updated.

> *“The fourth wave of systems thinking builds the biggest tent: illustrating how systems thinking applies as much to quantum mechanics as it does to the auto mechanic; poets to politicians; sociologists to physicists; and farmers to pharmacists. It has an ability to be coarse or fine grained in its use; that is, it can be a chainsaw or a scalpel, and it has both extremely general applications as well as highly refined ones. It needs to be both welcoming and accessible to any newcomer; any person, interested in anything—which means the field of systems thinking can begin to meet its potential to truly bring about change.” (Cabrera et al., 2022, p.35)*

3.2.1 Leverage points and intervention points

Two core concepts of systems change in systems thinking are leverage points and intervention points. *Leverage points* are those points within a complex socio-technical system where "a small shift in one thing can produce big changes in everything" (Meadows, 2008). These can be of different types, namely physical, feedback mechanisms, system design, or mental models. *Intervention points* are interventions by change makers which make use of a leverage point (Murphy, 2022). The most common typology of leverage points originates from Meadows (2008) and is shown in figure 3.3. An explanation and illustration of the leverage points is given in table 3.1, on the next page.

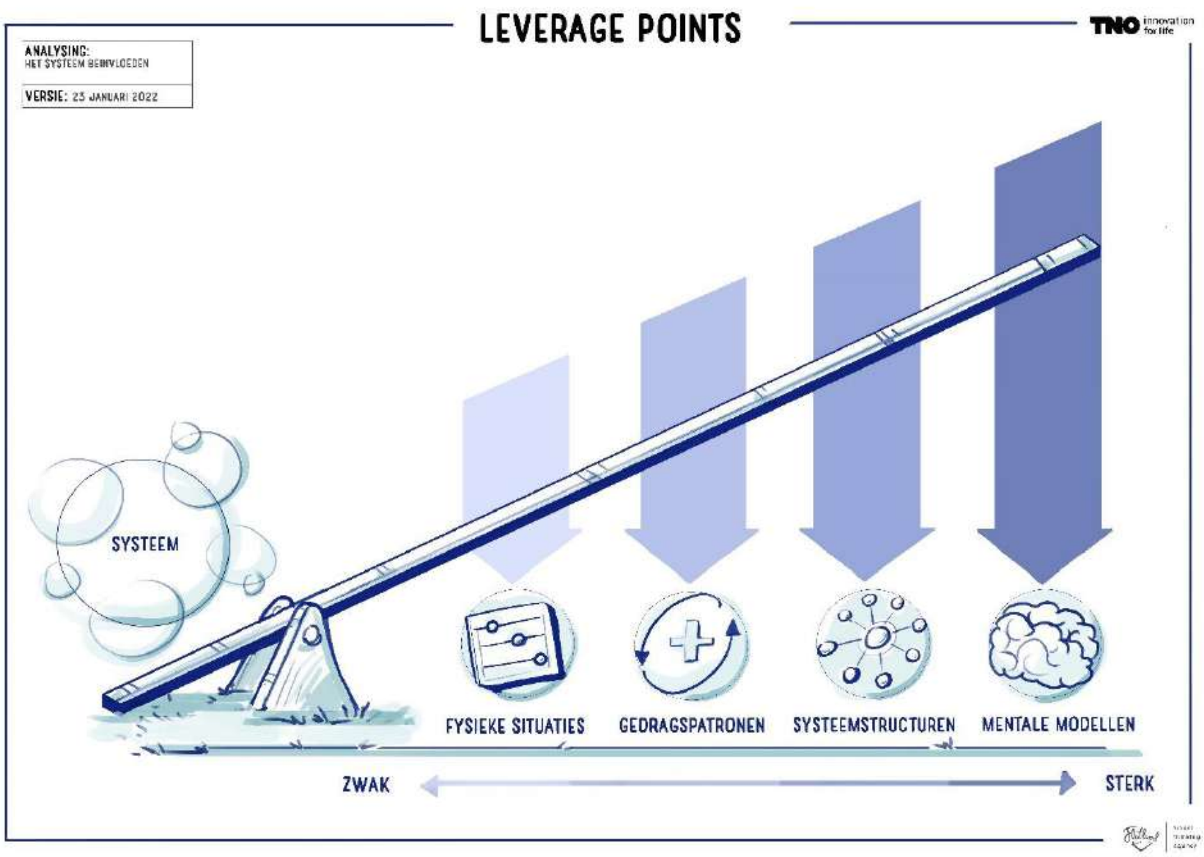


Figure 3.3: The leverage points of complex socio-technical systems. The categories are described in English in table 3.1 (source: Flatland commissioned by TNO)

Table 3.1: Leverage points and examples [based on Meadows (2008) and Murphy (2022)]

Category	Types of leverage points in order of increasing power	Example(s) of leverage points	Example of an intervention related to such a leverage point
Physical *Mechanistic Components of the system*	12. **The constants, parameters & numbers**	Wages, subsidies, interest rates, research investments	City council offering subsidies for 'green roofs'
	11. The **buffer sizes** and other stabilizing stocks relative to their flows	Stocks of goods such as medical masks, antibiotics, or steel.	Lumber yard deciding to cut down a smaller proportion of their logging forest.
	10. The structure of **material stocks and flows**	Transport networks, population, fixed costs, incomes. ** Difficult to change*	Railway company building new high-speed connections between European cities
Feedbacks *The drivers of internal dynamics resulting from interactions between elements of a system.*	9. The lengths of the **delays relative** to the rate of system change	How long it takes to find a higher-paying job ** Difficult to change*	Solar panel manufacturer renting out solar panels, so sunk costs are lower.
	8. The strength of **balancing feedback loops** relative to the impacts they are trying to correct against	Varying prices to balance supply and demand. Another example is democracy.	Company introducing a whistleblower policy, resulting in faster exposure of wrongdoing and faster resolution.
	7. The gain around driving **positive feedback loops**	Recession causing reduced spending	Farmer deciding to switch to biodynamic agriculture, resulting in higher quality products and soil fertility.
System design *The forces in a system that govern feedbacks and parameters.*	6. The structure of **information flows** (who does and does not have access to what kind of information)	How aware you are of impending recession/future rising costs	Household using a smart meter to monitor their energy consumption, resulting in more frugal energy use.
	5. **Rules of the system** (such as incentives, punishments, constraints)	Who suffers because of poorly managed recession	The abolition of Apartheid resulted in equal rights for all citizens of South Africa.
	4. The power to add, change evolve, or self-organize **the structure of the system**	Central banks, Ministries of Finance	Uganda's Ministry of Fisheries releasing a few hundreds of Nile perch (fish) in the Victoria Lake to stimulate the industry.
Mental models and intent *The worldviews, values, and goals of system actors shaping and underpinning the mental models of the system and how it should behave.*	3. **Goals of the system**	GDP growth, survival	Electing a Republican president after eight years of Democratic presidency radically changed the US' goals on health care, immigration, and foreign trade.
	2. The **mindset or context paradigm** out of which the system – its goals, structure, rules, delays, parameters- arise	Growth above all	Women's voting rights and college admission slowly led to women taking place in male-dominated jobs, changing societal sentiment that women are less suitable for political or management positions.
	1. The power to **transcend paradigms**	Choose between paradigms: growth sustainable development, flourishing	National planning agencies changing their idea of 'welfare' to 'broad welfare', resulting in more sustainable national goals.

Systems Engineering and Systems Innovation

Systems Engineering (SE) is an approach to the successful realization, use, and retirement of engineered systems, with the purpose of creating products and services that meet the needs of society or specific stakeholders (INCOSE Fellows, 2019; Aslasken, 2013). It is the 'art' of realizing physical or digital technological systems in a creative way, while considering constraints and limited resources. SE is transdisciplinary and integrative – making use of systems principles and concepts, as well as scientific, technological, and management methods (INCOSE Fellows, 2019). In SE, *engineering* is considered in a broad sense as "the action of working artfully to bring something about" (SEBoK, 2022), and may involve people, human-made objects, and natural elements (INCOSE Fellows, 2019).

The two approaches are complementary – SE is the best way to realize technological innovations in systems, while SI is the best way of enabling technological innovations to address societal problems. Systems Innovation is not necessarily about realizing physical systems but considers societal change through the lens of complex systems with social and technical components. Rather, it uses systems thinking concepts for critical thinking in order to find boundaries, assumptions, barriers, feedback and power dynamics, relevant aspects to socio-technical systems (Midgley & Lindhult, 2021). Engineering, in the sense of 'artfully bringing about technological innovations', is a complementary activity to SI as systemic changes to socio-technical systems may build on technological innovation. For instance, TROPOMI is a satellite instrument that monitors the composition of our atmosphere. It is a system which is engineered for a specific societal relevance, as it helps with finding sources of pollution and helps with monitoring the effect of environmental policies[6]. In this example, SI would for instance relate to how TROPOMI can be used to adapt policies, to find new uses of the TROPOMI system that solve problems in other domains, or to how geopolitical dynamics affect the use of TROPOMI data.

Both SE and SI heavily rely on knowledge but have a different relationship with practical and scientific knowledge. Practical knowledge is gained by a person (a practitioner) through their own experience. Scientific knowledge is knowledge which is verifiable and based on observable phenomena (Popper, 2002). SE developed in the 20th century from practical knowledge of engineering in industry, from a need to build large and complex physical systems (Ramage & Shipp, 2020). Engineering dates to many centuries earlier. For example, the Sainte-Chapelle in Paris is a thirteenth century cathedral that has been designed and built by masons that did not know science or mathematics – instead using rules of thumb. As SE tends to focus on building of physical systems, its more involved in the natural sciences than social sciences and the humanities. For instance, material properties, mechanics, radiation. Moreover, engineering relies heavily on scientific knowledge, but judges that knowledge by usefulness rather than as to whether it represents truth (Aslasken, 2013). For instance, scientific knowledge on the expanding universe is (currently) not useful for engineering, while the first law of thermodynamics is useful for designing more efficient energy conversion processes in engines.

Figure 3.4: The interior of the Sainte-Chapelle, built in the 13th century by masons (source: Wikipedia)

On the contrary, SI historically developed from the sciences like systems theory and innovation management. SI is mainly focused on societal change through the lens of systems that have technological and social components. SI relies on multiple sources of knowledge (and truth) - social sciences and humanities, and practical knowledge. For instance, Innovation systems, an approach to enact societal change by creating a mission-driven ecosystem innovation, draws not from the theories of quantum mechanics or computer science, but theories of knowledge management, technology transfer, and research. Thus, the science of innovation systems literature is more involved in the functioning of those systems and the processes of innovation than the innovations themselves (Hekkert et al., 2007).

[6] http://www.tropomi.eu/

3.3 Societal change, transition & transformation approaches

Theories about how society changes and how that change can be steered. These often look at society as a system-of-systems, where complexity arises from the interaction of social, technological, or ecological systems, namely *socio-technical* (Geels, 2004), *socio-ecological* (Ostrom, 2009), or even *socio-ecological-technical* (Folke et al., 2005; Chaffin et al., 2014). There are multiple approaches to analyzing and steering societal transitions, among which the following have been identified by El Bilali (2020):

1. Multi-level Perspective
2. Transition Management
3. Strategic Niche Management
4. Social Practice Approach
5. Innovation Systems

Different approaches to innovation systems are: R&D systems, (regional) Innovation systems and transformative innovation policy (Schot & Steinmueller, 2018; Haddad et al., 2022).
The gap between societal change approaches and systems thinking approaches can be bridged though systemic innovation, by using processes where innovators and their stakeholders use systems concepts and practices to change thinking, relationships, interactions and actions to co-create new value (Midgley & Lindhult, 2021).

Innovation systems and Systems Innovation

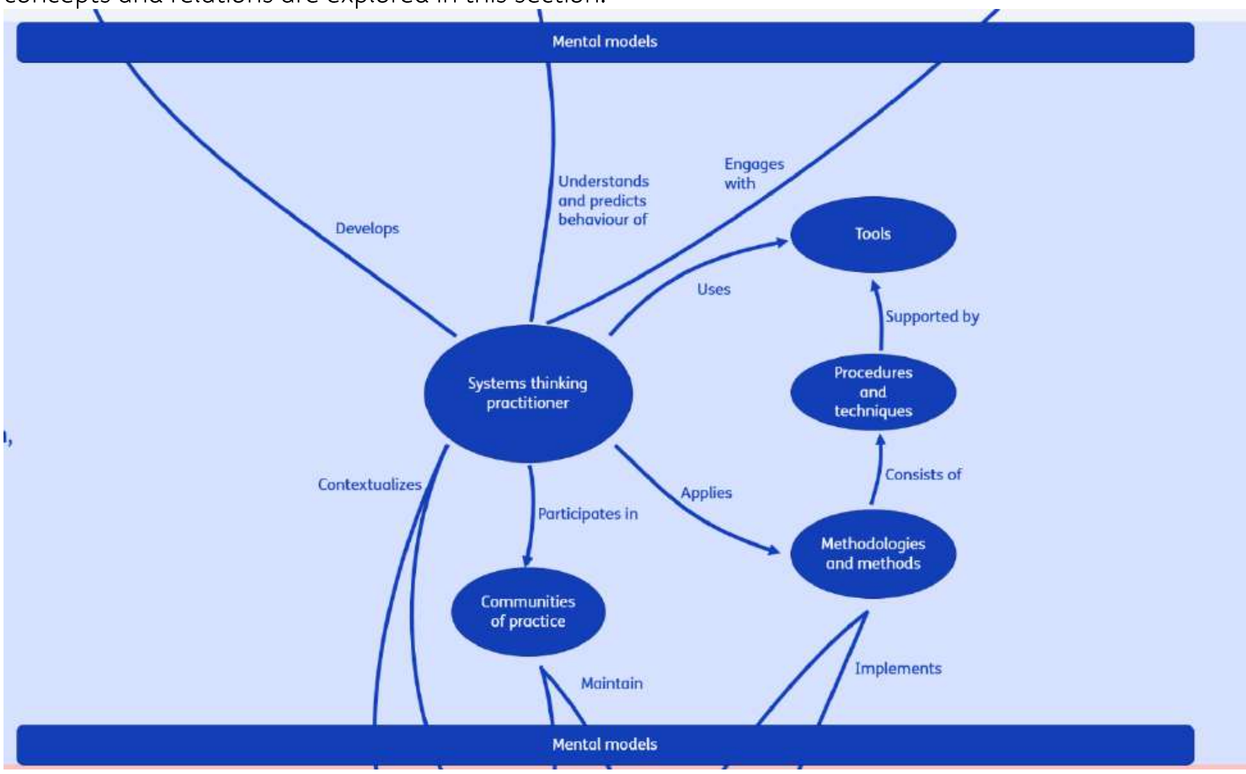
An *innovation system* is a socio-technical system in which a network of actors interacts with each other to realize innovation (Suurs & Roelofs, 2014). The focus of innovation systems is to make the most of an existing or emerging innovation system by supporting system functions (the system itself then changes at most due to the dynamics that technological change entails).

Systems innovation focuses on the transformation of socio-technical systems. The focus in system innovation is on realizing systemic change (not necessarily strengthening existing/emerging innovation systems) and this requires changes in behavior, infrastructure, social, institutional in addition to technology/innovation. This philosophy is supported by the idea that the complex societal challenges cause important societal systems/functions (around energy, mobility, health, and food) to change. To shape this change, a design approach is needed, while the realization of this systemic change requires disciplines to work together (transdisciplinary work).

Recently, we have seen a shift in the view of innovation policy, guiding innovation towards widely supported societal challenges. This is also increasingly focusing on system change of socio-technical systems, getting closer to systems innovation.

4 Praxis

Between the way in which we understand the mess and our approach to changing the mess is our *praxis* – theory-informed practical action (Ison, 2017, p.4). In this case, we think of the *systems thinking practitioner* as someone who puts systems thinking into their practice. They do this by applying certain *methodologies, methods, or procedures* in their approach, using *tools and techniques*. Their practice is shaped and maintained through *Communities of Practice*. The praxis is guided by our *mental models* – which make us 'perceive' the mess and which approach we find suitable to change the mess. These concepts and relations are explored in this section.



4.1 Contextualizing approaches

How the approach is put into practice so that it is effective in a specific real-world context – the thinking that enables practitioners to use relevant methods, tools and techniques (Ison, 2017, p.157). In order to better classify and compare systems innovation solutions, we adapt the conceptual definition from Andiappan & Wan (2020). We expand their concepts of approach, methodology, method, procedure, and technique to also include the concept of a *tool*. This gives us the following hierarchy:

- An **approach** is "the basic philosophy or belief concerning a given subject matter. It is a way or direction used to address a problem based on a set of assumptions." For instance, in process design there are two approaches: hierarchical design or concurrent design.
- A **methodology** "describes the general strategy to solve a problem" and allows the practitioner to make choices within a certain set of rules or boundaries. A methodology is a system of methods used with set rules or criteria. A *framework* is considered a methodology that is less procedural and functions more as guidelines.

- A **method** entails "how an approach will be practically implemented". For instance, a design problem may be tackled by a nondeterministic approach, which is implemented through the method of 'stochastic programming'. Methods are not necessarily part of a methodology.
- A **procedure** is "a sequence of techniques, conducted in a certain order". These may be defined by the practitioner in order to follow a specific method or may follow 'built-in' algorithms.
- A **technique** is a specific, immediate action with immediate result. For example, activities such as collecting data, conducting interviews, setting operating conditions, solving a model.
- A **tool** is a tangible item that can be used in performing a technique. These items can be physical objects (e.g. microscope, gas chromatographs), software (online survey program, simulation program, statistical analysis program), templates (e.g. visual toolbox).

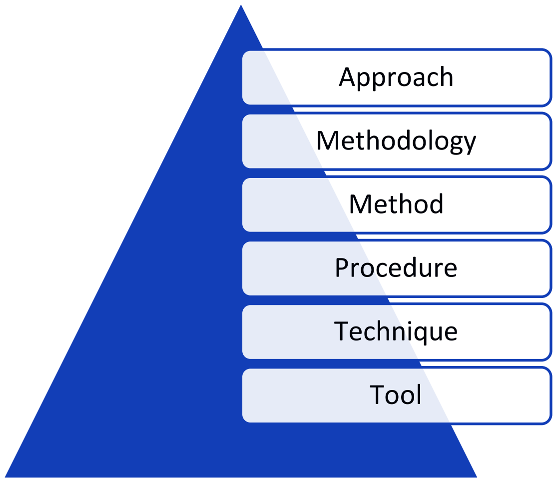


Figure 4.1: The approach pyramid

4.2 Practitioner

What does it mean for a practitioner to be a systems thinking practitioner? Systems thinking researcher Ray Ison (2017) argues that systems practice is best learned experientially, from one's own practice. Ison notices that there are three categories (see figure 4.2):

1. Many people have a *systemic sensibility* or *awareness* and "are able to appreciate the interdependencies between people, events and things and, knowingly or not, reject the idea that simple cause and effect operates everywhere" (p.20). They are not necessarily familiar with systems concepts. They understand concepts such as cycles, counterintuitive effects or unintended consequences.
2. *Systems literacy*: people who are familiar with several concepts from the systems sciences (e.g. through related fields) and have encountered the history of systems scholarship.
3. *Systems thinking in practice* is a set of capabilities that supersedes literacy and awareness. This is shown in an ability to understand, apply and relate systems concepts in multiple contexts – or the ability to integrate into one or more disciplines or situations. Jones et al (2009) distinguish between different sets of capacities, namely: sensemaking; practical mastery; theoretical mastery; praxis mastery (See table 4.1). Another way of assessing these capacities is the systems thinking and metacognition inventory (Cabrera, Sokolow & Cabrera, 2022).

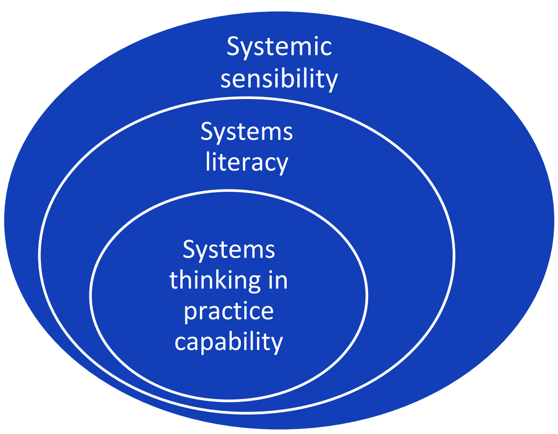


Figure 4.2: Three nested systems capabilities (based on Ison & Shelley, 2016)

Table 4.1: Different sets of capacities and the corresponding learning goals (based on: Ison, 2017)

Main learning outcome	Learning system model	
	Domain specific	Generic
Sensemaking	Able to use the basic systems concepts to make sense of phenomena, objects and processes in the world	Systems student or systemically aware citizen
Practical mastery	Able to competently apply systems concepts for research or practice	Systems practitioner
Theoretical mastery	In a position to add competently to the body of knowledge as well as areas of practical application in specific contexts	Systems facilitator who creates circumstances for systemic ways of knowing
Praxis mastery	Able to combine theory and practice for a specific problem situation	Systemic designer who is an aware systems practitioner (able to be reflexively responsible)

System<u>ic</u> and system<u>atic</u>

One of the capacities at the systemic sensibility and literacy levels is awareness of the distinction between *systemic* and *systematic* approaches (Ison, 2017). Systemic relates to part-whole relationships where properties emerge, systems are characterized by feedback, and boundaries are determined by one's perspective. Systematic thinking is characterized by a focus on linear cause-effect in a fully understandable, concrete system. The system may be understood through a reproducible step-by-step analysis. This distinction means that there is also a difference between systemic practice and systematic practice (see Table 4.2).

> *"Someone who pays particular attention to interconnections is said to be systemic (e.g. a systemic family therapist is someone who considers the interconnections amongst the whole family [...]). On the other hand, to follow a recipe in a step-by step manner is being systematic. Medical students in courses on anatomy often take a systematic approach to their study of the human body – the hand, leg, internal organs, etc. – but at the end of their study they may have very little understanding of the body as a whole because the whole is different to the sum of the parts, i.e. the whole has emergent properties such as 'life'. Effective systems practice to change or improve situations of complexity and uncertainty means being both systemic and systematic when appropriate." (Ison, 2017, p.30)*

Table 4.2: The differences between systemic and systematic actions (based on: Ison, 2017)

Aspect	Systemic action	Systematic action
Decision-maker	The decision-maker is part of the system. How the researcher perceives the situation is critical to the system being studied.	In practice, the decision-maker claims to be objective and thus remains 'outside' of the system being studied
Ethics and values	How a system is perceived is also ethical. What might be good from one perspective might be bad at another. Responsibility replaces objectivity.	Not addressed as a central theme or integrated in the change process. Researchers take an objective stance.
System	The specification of a system of interest and its interaction with its environment is the main focus of exploration	The system being studied is inherently distinct from its environment and explored as a 'closed' system
Perception and action	Based on experience in the world, the experience of patterns	Belief in a 'real world', consisting of discrete entities that have meaning in, and of themselves
Traditions of understanding	There is an attempt to stand back and explore the traditions of understanding in which the practitioner is immersed	Traditions of understanding may not be questioned although the method of analysis may be evaluated

4.2.1 Systems thinking skills

Putting systems thinking in practice requires several skills that – with in an individual, team, or organization – improve the capability to identify, understand, predicting the behavior, and design changes to systems so that desired effects are reached (Arnold & Wade, 2015). These skills are:

1. Recognizing interconnections
2. Identifying and understanding feedback
3. Understanding system structure
4. Differentiating types of stocks, flows, variables
5. Identifying and understanding non-linear relationships
6. Understanding dynamic behavior
7. Reducing complexity by modeling systems conceptually
8. Understanding systems at different scales

4.3 Mental models

People have mental models – ideas, beliefs, concepts, and facts that represent the real world (Forrester, 1971). Through mental models, people make sense of *the mess* (what is the system, what is the problem, what are viable innovations?), and make sense of suitable approaches that may change that mess. This helps in decision-making under uncertainty, but also is susceptible to cognitive biases (Tversky & Kahneman, 1974).

As there is a mismatch between the mental model and the real world, people are constantly updating their mental models (Cabrera & Cabrera, 2018). Learning is essential as it improves our mental models of complex problems, specifically by reflecting on the assumptions upon which an approach is based (double-loop learning). For instance, after a fire in the office the solution might be to place more fire extinguishers (single loop) or to investigate the underlying causes such as old kitchen appliances where the solution to invest in a safer work environment (double loop). Learning networks (such as communities of practice) are a way to build shared mental models.

4.4 Communities of Practice

Communities of Practice (or more broadly called 'Learning networks') are networks in which people within a certain context organize themselves to learn from each other and create involvement and new practical knowledge. They may be intra- or inter-organizational. A community of practice has three basic dimensions: domain, community, and practice (Snyder & Wenger, 2004).

1. *Domain* (or *discipline*) refers to the identity and what the community cares about
2. *Community* refers to the quality of the relationships between members
3. *Practice* refers to the knowledge of practitioners in its domain

Besides communities around specific expertise (e.g. software engineering), CoPs are also useful in many knowledge areas, such as practice-oriented research in the social domain (TNO, 2021).

4.5 Methodologies

While practitioners may take an approach to provide certain principles, rules, or boundaries, they need to select or shape a method or methodology (or framework) as the general strategy to solve a problem (Andiappan & Wan, 2020). Each approach to problem-solving has their own dominant and novel methodologies, and it is easier to compare those within a specific approach than between approaches. In the system dynamics approach (Forrester, 1971), the MARVEL method is one of the many ways to apply system dynamics (Van Zijderveld, 2007) – although it can be argued that MARVEL has grown into a methodology with supporting tools and techniques (Veldhuis, Van Scheepstal, Vink, 2014).

An example of a methodology which has been developed in a TNO niche is *Orchestrating Innovation* (Berkers, Klein Woolthuis, de Boer, 2015), a methodology to realize effective innovation systems. An 'Innovation systems' is considered an approach to "develop, apply and diffuse new technological knowledge" among a network of innovation actors (Hekkert et al., 2007, p. 418). While Orchestrating Innovation can be used for innovation system variants like the *technological* innovation system or *regional* innovation system, it can also be applied to innovation system approaches that are based on different principles, such as mission-oriented or transformative innovation policy (Haddad et al., 2022).

Orchestrating innovation and Systems Innovation

Systems Innovation (SI) is an approach to analyze, understand, and design changes to complex socio-technical systems (such as innovation systems), and can have an enormous impact in the way we organize. This approach is substantially different from the predominant linear and reductionist thinking as it incorporates the concepts of systems thinking, such as complexity or feedback loops. In other words, thinking in systems may contribute to better innovation systems (Midgley & Lindhult, 2021). Thanks to SI we can identify leverage points (Meadows, 2008) allowing us to pursue better and more resilient innovations leading to less unintended consequences and positively contributing to systems change.

Orchestrating innovation (OI) focuses on creating and stimulating collaborations around innovations for complex societal challenges, by creating a shared vision and strategy with relevant stakeholders and connecting relevant by their individual and shared interests. OI produces scalable and sustainable ecosystems that contribute to societal welfare and wellbeing. OI can benefit from a systems approach as orchestrators may be looking for the most promising intervention points, interdependencies and feedback loops, or which stakeholders fit within the boundaries of the innovation ecosystems, which a systems innovation approach might suggest. SI can benefit from orchestrating innovation by mobilizing societal actors, directing and enacting change. SI needs orchestrators because systems interventions are often a lengthy and abstract endeavor, requiring an ecosystems' collaboration, in which mutual benefits and clarity needs to be created and pursued over time.

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Your feedback can help us improve the concept map. If you would like to comment or suggest corrections, please reach out to claudio.lazo@tno.nl (corresponding author).

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