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PSE prospective: paradigm transition towards Complex Thought in a global world under pressure

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Abstract

Many people confront and acknowledge irreversible anthropogenic changes as many global world limits are exceeded. As contributors, process system engineering research activities must undergo a transition within a novel paradigm more fit for addressing the general complexity of all impacted systems. This paper explores three shifts, covering methodological, epistemological and metaphysical intertwined aspects. About methodologies, we discuss energy savings, process intensification and sustainable growth issues, and suggest simultaneously keeping systemic and multiscale approaches and dropping Cartesian reductionism for producing knowledge and engineering expertise that will enable attenuation and adaptation solutions to better address the current challenges. But for that, underlying epistemological and metaphysical aspects must also be revisited. A participative PSE process is proposed to investigate systems in transition, in the spirit of the complex thought paradigm and constructivism, and to head towards not only sustainable but also desirable solutions for people.

Keywords: complex thought; process system engineering; epistemology; anthropocene; participative process

1 Introduction

As our world is getting aware of the extent of the transitions needed to address global issues related to climate, biodiversity, energy, environment, water, food and others, one ought to question the place of PSE activities. Some would object that it might shatter the science neutrality, but I shall reply that this claim is a non-neutral posture and choice itself. Actually, philosophers have elaborated for years that the process of producing knowledge can be neutral but the choice of topics and methods is not (Longino, 1990). Hence, in this contribution, I will explore how PSE can contribute to study global transitions. I shall express personal feelings and opinions that are debatable, sometimes exaggerated in describing PSE postures and advocating for alternatives, but I invite you to examine them with kindness.

PSE activity has thrived for decades in solving problems, at first in the chemical engineering domain but in many other areas as well. It has developed a strong corpus of methods and theories under so-called systemic and multiscale approaches. Over the years, multiobjective optimisation and multicriteria analysis have been implemented to account for energy, environmental, health, safety and social aspects in the solutions. However, the final decision often ends up to be an economic criterion triggered by financial and management stakeholders.

But world climate, energy, social, water, food, etc... crises are growing and are felt everywhere and at all scales. World institutions, agencies and government have taken seriously these crises sometimes with some delay. Prospective scenarios ranging from techno-solutionism to degrowth, with significant carbon emitting energy reduction, have been issued both at the world level and at a country scale. They recommend drastic changes in society; issuing mitigating and adaptation measures, asking for more with less and that affects everyone. On a personal level, these crises also fragment societal and personal values by questioning the meaning of one's activities. Regarding the PSE community, its achievements supported the development of small to large scale industries for the good of people's prosperity but also for the bad with impacts on health, environment and safety. So, academics and industry members of the PSE community are concerned, as citizens as well as workers.

I explore in this paper how PSE engineering practices are affected by these transitions, whether they are fitted for addressing the global challenges at stake and what does it implies to get them ready.

A quick answer is that PSE does already contribute to these challenges: saving energy, increasing process efficiency, developing carbon capture techniques, improving water, food, energy nexus, etc. PSE does so, thanks to its valued system and multiscale approach that echoes the systemic thinking and broader viewpoints advocated for tackling global issues. But is that enough? Is accounting for the social aspect by monetizing job creations enough? Are local energy savings meaningful on a grand scale? Isn't that too much heading towards a techno-solutionist scenario? Aren't there any other low-tech, more participative etc. scenarios worth a PSE contribution as well? Are PSE members legitimate to investigate these issues? More than a decade ago, Klatt and Marquardt (2009) emphasised the need to support system thinking by multiscale approach and a sustainability strategy (cit.) '*not anymore restricted to PSE experts*' and that will include (cit.) '*a recalibration of the interfaces of PSE to the other sciences... the interfaces to the natural sciences and to the core disciplines of chemical engineering*'.

I will show in this paper that for addressing these questions, there are three levels of questioning, about methods, epistemological postures and emotions. First revisiting methods and tools is important, but not only. What is needed in parallel is to explore the philosophical postures underlying PSE practice. On one hand, one has to discuss the way knowledge is acquired and projects are run to find solutions, the so-called paradigm. On the other hand, one has to identify the underlying epistemology that concerns the meaning and the credit we give to knowledge in general (see section 2). The philosophical exploration might seem too much unreal but it does translate into practical recommendations (see sections 3 and 4) that are operative for PSE engineering for addressing global challenges but also in its traditional activities. For that, section 4 presents a novel participative PSE approach to be used for any project. Finally, enforcing a transition in its own activity will make everyone feel different

emotional states. My personal feeling is that they have to be recognized for the transition to be effective. For example, the novel participative PSE approach in section 4 insists about the sharing of emotions along other hidden elements like intentions, backgrounds, hidden strategies) for gaining efficiency and relevance in project running.

As an outline, section 2 asks where do we stand in front of the crises. It provides background elements in three aspects: about planetary limits affecting use, about paradigms and epistemologies underlying PSE activity now and in transition, and about the individual and social determinants that drive a transition in oneself activity, namely individual emotions and social mechanisms of change. Section 3 discusses selected PSE activities confronted to global change issues. It shows successful and operative solutions about energy savings, intensified processes, environmental and social indicators. But it also raises critics on one hand, when a planet wide viewpoint is taken, and on the other hand, about the overuse of Descartes' cartesian reductionism for addressing complex environmental, economic and social issues. Section 4 draws a prospective about PSE activities for addressing global challenges. Both the epistemological posture and its operational instantiation are discussed. First how to explore economics, social and environmental issues within a shift into the so-called general complexity paradigm, embedded in a constructivist epistemology. Second how to enforce in practice this novel perspective via a participative PSE approach.

2 Where do we stand?

2.1 Planetary limits

Global world changes are nowadays indisputably due partly to human activities and they reach further than climate change.

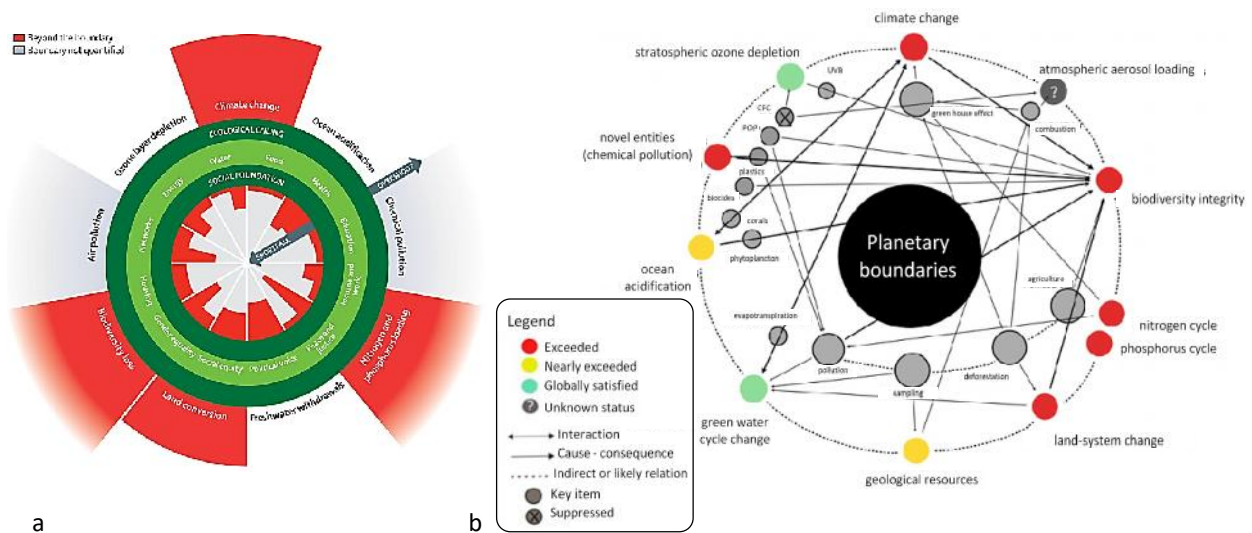


Figure 1. Planetary boundaries Shortfalls and overshoot in the Doughnut. CC-BY a) from Raworth (2017), b) Planet boundaries interrelations translated from Exnaturae.org (2020)

Raworth's doughnut picture (Figure 1a) shows that "the safe and just homeostatic space for humanity" is precarious and is threatened not only its natural aspects but also in its social foundations (Raworth, 2017). Climate change, biodiversity loss, land use, chemical pollution, nitrogen and phosphorus cycles, green water: 6 out of 9 planetary limits have been overshoot (Wang-Erlandsson et al., 2022).. Figure 1a also shows that the social consequences (water & energy access, health, social equity, gender equality, political voice, ...), assessed based on minimum social standards, as identified by the world's governments in the Sustainable Development Goals (UN, 2015), are also in a critical state and they affect our lives both as individuals and in society. What has become a dominant topic for headlines in media and in politics is nowadays becoming a daily and painful experience for many. Expert panels have documented specific issues like green water (Wang-Erlandsson et al., 2022), climate change facts (IPCC, 2021), impacts, adaptation and vulnerability (IPCC, 2022a) and mitigation of climate change (IPCC, 2022b), biodiversity (IPBES, 2019). Recently, panel joint reports have been released; recalling that issues are always intertwined (Pörtner et al., 2021). Indeed, Figure 1b shows the strong interrelation between natural limits and some key processes, entities or substances (Boutaud and Gondran, 2020). For example, climate change is related to atmospheric CO₂ concentration increase. Hence, the oceans, the major CO₂ sink, dissolve more CO₂. The ocean's acidity increases in return, which reduces phytoplankton photosynthesis and threatens corals reefs, reducing marine biodiversity (Exnaturae, 2020).

Acknowledging the fragility of planet boundaries and their social consequences draws a gloomy perspective for future living and raises challenges that necessarily require a combination of sciences of nature and of social sciences. It calls for a shift in human activities, including what concerns PSE, to build a common future for humans and non-humans on the finite planet that one calls Earth.

2.2 *Epistemologies and paradigms for addressing world's complexity*

As the world in which engineering has thrived so far is changing drastically, it is worth recalling that engineering practice is rooted in paradigms and epistemologies that often get unnoticed. For example, the PSE approach to problems is often solution-driven, based on modelling and simulation and it brings satisfaction in many situations. But from a broader viewpoint, solutions are also problems for others, like chemical plant waste management or local social acceptance of large-scale biogas production plants. Furthermore, the art of modelling praised by PSE practitioners is strong and well-founded when dealing with physico-chemical issues. But for including the local aspects of economics, society and environment, it often comes at the expense of reductionist formulations, like the assessment of social impact by the economic value of jobs created (Miret et al., 2016) (more in section 3). Morin (2014b) wrote lucidly that [Cit.] *'the "objects" studied by science, and treated by science simply as objects in fact are all systems'*. PSE would protest that it also practices system thinking but we shall discuss further that it can still be rooted in reductionism if one [Cit.] *'does not take account of the systemic context of the object.'* (Morin 2014b). The systemic context can manifest by accounting for multiple socio-economic-environmental aspects of each problem. The traditional PSE way of mathematizing them into equations or indicators is one way but section 3 will show how it is limited to address global challenges more suitably. Why should one fall into the drawback of thinking solution at all cost to any problem, when the problem statement is possible the problem? There exist other paradigms and epistemologies and the issues related to global planetary changes urge us to reconsider them because these mainstream paradigms have supported the anthropogenic origins of these changes.

What is a paradigm and what is an epistemology? A paradigm is an ensemble of concepts, schemes of thinking, including theories, approaches and methods, postulates and standards that comprise legitimate contributions to a domain; for example, Descartes' cartesianism and Comte's positivism. PSE current practice, with its art of modelling, multiple theories, frameworks, has also reached the status of defining a paradigm but it also builds upon Cartesian and positivist thinking. According to Piaget (1970), epistemology is the branch of philosophy that he calls the theory of knowledge and that aims at studying the building of what constitutes valid knowledge, including scientific knowledge but not only. Examples of epistemologies are empiricism, constructivism, rationalism where one finds Descartes' cartesianism and Comte's positivism paradigms, and many others. In a caricatural way, PSE paradigm belongs mostly to rationalism but it also considers empirical knowledge as valid and sometimes explores solutions in a nonlinear way that refers to constructivist approaches. The term 'building' in Piaget's definition covers both the process involved in getting access to knowledge and the circumstances under which this process occurs. For example, a valid knowledge acquisition can be done by carrying experiments, modelling, analysing data, simulating, etc. Probing reality by using intuition was depreciated in Descartes' rationalism but is accepted in constructivism that also welcomes non-expert viewpoints for acquiring valid

knowledge as in participatory sciences. Regarding circumstances, a rationalist way of conducting a project is to assess constraints and to devise means and planning to reach target objectives. A constructivist-led project might also focus on how to reach a solution that would be satisfactory for all stakeholders (see section 4). Circumstances of acquiring knowledge are important to debate in epistemology and Piaget refines that it includes formal or experimental validation methods but also inputs from both the learner and from the object under investigation. In rationalism, the learner is distinct from its object of investigation, not so in constructivism and one would agree that the way we probe reality influences the knowledge we acquire. Epistemologies are also situated in time and in societies and are therefore associated to a vision of the world, so-called metaphysics. For example, assigning a value to non-human entities as stakeholders equivalent to humans (Latour, 2005, Descola, 2009) is a metaphysical posture that connects with constructivist epistemologies developments in social sciences that we discuss in section 4. It also questions humanity's undisputed right to use planetary resources that is related to the global challenge about resources exhaustion.

Choosing one epistemology does not preclude for using tools and methods that concern paradigms rooted in another epistemology. For example, Descartes' so-called Cartesian paradigm is a representative of the rationalist epistemology, along with Comte's positivism. But it also exists in constructivist epistemology where rational action is one (but not the only one) of the valid ways of finding solutions: always use a hammer to knock a nail.

Building upon the arguments above, I postulate that investigating PSE paradigm transition in a global world under pressure requires primarily shifting from the Cartesian paradigm, at work in engineering and more generally in the sciences of nature, to another paradigm more prone to support changes in the methodological, the epistemological and possibly the metaphysical planes. There exist many alternatives to the paradigms anchored in rationalist epistemology. Since Descartes' time in the 17th century, rationalism itself has evolved and given rise to Comte's positivism, to post-positivism etc... One explores in this paper another branch of epistemology, namely the epistemological attitude of pragmatic and radical constructivism (Glaserfeld, 2001, Le Moigne, 2009, Avenier, 2009, 2011). It is connected to Morin's Complex Thought paradigm (La Pensée Complexe in French) formally initiated by Morin in the 70's (Montuori, 2008; Morin, 1992a, 1992b, 2005, 2014a, 2014b).

Let's examine what are the foundations of Descartes' and Comte's rationalist epistemology. Rationalism states that reason is main source of knowledge and that it helps grasping the truth. Indeed, like Descartes' writing "I think, therefore I am" in 1637 in his treaty "Discourse on the Method", Cartesian, positivist and rational concepts believe in an objective truth and support a logic of disciplinary approaches overlooking objects of investigation in an expert manner with help of a deductive logic only. Comte published in 1830 a so-called 'tableau synoptique du cours de philosophie positive' that describes a hierarchy of sciences, from mathematics to (cit.) 'physique sociale ou sociologie'. It was later revisited by many authors, incl. H. Simon in its

book about the Sciences of the artificial (Simon, 1969), but it is still in use in many higher education universities even today.

Rationalism and related Cartesian and positivist paradigms relies upon principles of objectivity, reductionism, causality, exhaustiveness among others. Over the modern science era, rationalism has proven worthy and is effective in many situations often related to closed systems with defined constraints. As it seeks to explore all the elements of a system to explain their functioning, it can even be associated with some kind of systemic approach that Morin assigned to restricted complexity in his transcribed conference "Restricted complexity, general complexity" (Morin, 2005). Within rationalism, traditional engineering projects are usually operated within a cartesianism top-down viewpoint as they often aim at reaching a pre-targeted goal with great effort within a quite rigid work plan. As such, this engineering process is caricatured merely as an act of translating knowledge into artefacts. But one concedes that in practice, engineers claim some intelligent action in the course of a design process and many of them have experienced that neither the result obtained nor the path followed to reach it, are exactly what was expected; requiring many adjustments to be carried out as earlier proposed.

Traditional engineering and its rationalist roots might be satisfactory in well-defined projects with local outcomes, but, when confronted to fieldwork activities related to global challenges, [cit.] "*classical perspective does not take account of the systemic context of the object*" (Morin, 2014b), in particular the inherent complexity of the social aspects that inevitably appear as "the human factor" (Avenier, 2009) and that will be discussed in section 3 and 4. Typically, the simplistic modelling of social impact by total job creation within a unique cost decisive criterion (Miret et al., 2016) exonerates oneself from the global context and the subtle social interactions and local economics that would be decisive if inhabitants' social acceptance was also a criterion. Provocatively, dealing with global challenges requires more than job creations.

What proposes constructivism? Before Descartes' exclusive focus on what can be reasoned, described and explained, humanist's view already favoured concrete experiences. Le Moigne describes the history of alternative thinkers that have led to constructivists epistemologies of Piaget, Simon and Morin as an alternative to rationalism (Le Moigne, 2011). Constructivism states that the production of knowledge is an aggregation of human-made constructions that can mobilize not only science, but also experimentation and intuition altogether (Avenier, 2011). Like rationalism, constructivism postulates that reality exists in itself. But, it shifts radically the posture of any person with respect to what is real. In constructivism, anyone is a modeller that builds its own experience of what is real. At the same time, it is not separable of what it investigates because its individuality (identity, history, culture, competencies) affects her relation with reality. For example, one knows that the experience of each team members impacts the course of a project and its outcomes. Besides, the personality of each team member impacts team's member relations and possibly its running.

Within Morin's "Complex Thought" paradigm, constructivism relies on projectivity, on intersubjectivity rather than objectivity, and viability rather than truth, acknowledging incompleteness of knowledge, path dependency, partiality and uncertainty as components of what anyone experiences in the world. Morin has enunciated several principles to support its approach. They are for instance, the ability to make connections, the non-linearity, the bifurcation, the recursivity or the emergence. What constitutes the so-called "general complexity" approach (Morin, 2005) does truly qualify as systemic but it goes far beyond cartesianism especially in terms of a non-dominating posture regarding objects of investigation. Indeed, it entails a holistic approach, dialogical in the meaning that contradictory reasoning is welcomed and hologrammatical in a recursive sense that the global system influences the behaviour of the local elements constituting the global system. Another of Morin's principle is called the "ecology of action" that is useful to imagine the alternative and more collective project management approach to be discussed in section 4. It recognizes that the investigator is no longer overlooking the object in a top-down manner but that it is fully involved in a process of exploring the object and that as action proceeds, everything changes in an uncertain way that will inevitably affect the path of action (Morin, 2005).

Morin's 'Complex Thought' paradigm emerged in the 70's (Morin, 1992a) and was further put in action within the "Acting/thinking in complexity" approach (Le Moigne, 2009, 2011). Le Moigne's approach has then been put in practice in many domains like management (Genelot, 2017) and engineering (Rossignol, 2018). In compliance with Morin's ecology of action principle and with Kolb's experiential learning approach (Kolb, 1984) also inspired by Simon's invitation to acquire understanding by acting (Simon, 1969), Le Moigne's extension of Morin's thinking invites engineers to run projects differently within a global changing world. The novel approach should not solely focus on reaching the target objective. It should focus on the project processing, be fully aware of the project topic consequences and other interactions with the surroundings and acknowledge the importance of all participants' intentions and expectatinos, so as to reach a result that is satisfactory for all stakeholders. Results matter, but the path matters most (Rossignol, 2018). Section 4 will provide examples of how that constructivist perspective is at work in a novel PSE project approach.

2.3 Change curve, motivations and emotions

Taking a path of action in transition is a conscious process; like the paradigm shifting I've suggested but also when managing a project. It requires intention and information and that awareness will generate emotions. Regarding information, if it reduces to providing knowledge, it does not always foster action, and frustration may emerge. For example, evidences about climate change have been released for decades without much stirring both in global politics and in local actions among earth inhabitants. But at the same time, many people despair about this inaction. This encourages us for clarifying the mechanisms of change that lead to action or inaction, and how they impact our emotions.

At the individual level, change mechanisms are triggered both by an emotional process (Leybourne, 2016) and by a deliberate commitment to change. The emotional process can be represented thanks to the Fisher's transition curve (Figure 2) (Fisher, 1999, 2012) inspired from the earlier Kubler-Ross' grief cycle (Kubler-Ross, 1969). The commitment to change is progressive and, according to the transtheoretical model, it proceeds in six phases supported by many processes of change (Prochaska and Velicer, 1997; Prochaska et al., 2002). The six phases are the precontemplation phase that change is not an issue, the contemplation phase that one could change, the phase of preparation to change, the phase of action of effective change, the phase of maintenance of new behaviour and the termination phase. The first three stages before action are often triggered by a shock or stimulus that shatters the person in its core convictions, like climate deregulation awareness might trigger personal impact against which I should take measures. Indeed, change is facilitated by fostering the intrinsic motivation of each individual in compliance with its interests and values, rather than by a motivation relying upon external drivers, incentives and regulations (Legault, 2016).

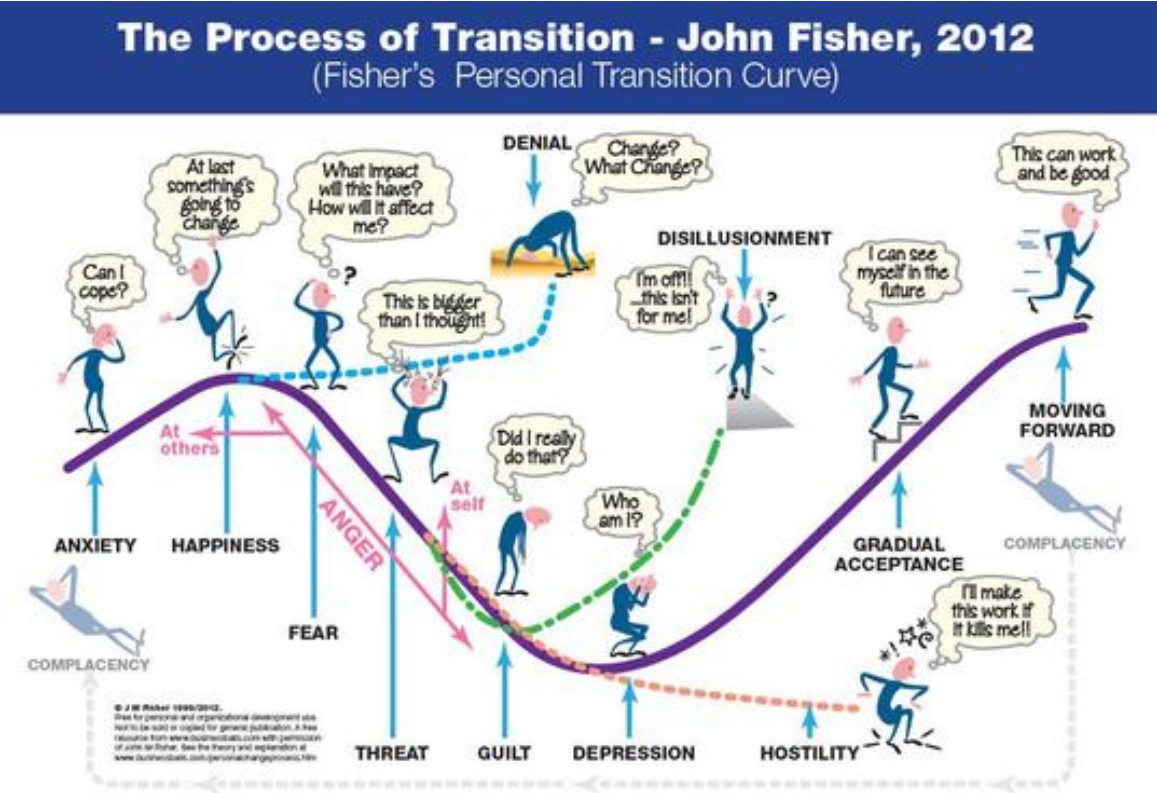


Figure 2. The transition curve (with permission from Fisher, 2012)

Any person undergoing a change trajectory, as a PSE member intending to address global changes issues more keenly, will experience several emotional states along the process and I shall point out in this paper some of those I have experienced. Typically, the overshooting of planetary limits and shortfall of social foundations (Figure 1a) may generate anxiety, fear and worry that can boost behaviour changes (Panu, 2020). However, Figure 2 shows that many other emotional states, like happiness, depression, acceptance etc., can be involved in the

process of changing effectively, and that alternative change paths can lead either to hostility or disillusionment as well.

An epistemological interpretation can be brought in the discussion. Indeed, to elaborate further on the importance of emotional aspects in the sciences of nature, a false common belief is the split of reason and logic, roots of natural sciences, on one side of the brain, and of emotion and intuition on the other side. Dating from the XIXth century, this postulate is another example of Cartesian reductionism as brain functioning is far more complex (Karolis et al., 2019). Indeed, any activity mobilizes interconnected parts of the brain that cover many aspects of human singularity, incl. logic, reasoning, intuition, creativity, emotion, ... Engineering activities are thus affected by all these traits, not only by logic and reasoning.

To conclude section 2.3 where I have insisted on emotions and individual determinants for undergoing change, one should mention that the individual transition curve is perfused with social dynamics at all stages. Indeed, external factors, like group affiliations, collective support, cultural determinants, moral values, social acknowledgement, etc., are both barriers for impeding and key levers for enforcing and boosting change. For example, the success of an engineering project, seen here as a transition heading towards the satisfaction of the project objectives, is due to the success of the individual tasks but also to the surrounding support: company's infrastructures, access to external resources, etc.

3 PSE facing global challenges

This section explores how PSE activities are equipped to face global challenges. Sometimes, statements will be caricatural and approximate for the good of highlighting the arguments in favour of a paradigm shift. The message is first that facing global challenge is an old concern in PSE and that tangible efforts are made, as exemplified below. One can give credit to PSE to be familiar with system, multi-scale and integrated approaches, which seem suitable for addressing global challenges encompassing multiple issues like those displayed in Figure 1. Second, however, these efforts are often rooted in the aforementioned restricted complexity. It mainly contributes to attenuate impacts and adapt existing processes, but it falls short of the requirements set by designing a living system coping with the planetary limits.

3.1 PSE traditional practices

Describing the activities in process system engineering is out of scope of this paper but it can be brushed by using domain ontologies such as Marquardt's group OntoCape (Morbach et al. 2007) which provides a modular and multilayer structure based on conceptual modelling languages like UML and OWL for categorizing PSE activities. It shows that PSE contributions range over various layers. Upper layer items, like frameworks, oversee conceptual layer items where lie system approaches, like concepts, chemical processes, material and energy concepts, conceptual models and IT systems). Below, the application-oriented layer covers generic processes and unit operations, material and energy system and thermodynamics,

process modelling softwares and numerical solution strategies. Finally, the application-specific layer lies at the bottom and encompasses activities focussed on dedicated applications.

A few years later, Klatt and Marquardt (2009) gave their personal view on the perspective for process system engineering. They recognised that the traditional achievements of PSE in terms of methodologies and tools for modelling, simulation and optimization were no longer a specialty of PSE since it had diffused as a commodity in most of the domains where chemical engineering was at work. They also promoted a system thinking and system problem solving, that is familiar to PSE. But, they highlighted the need to support it by multiscale approach and a sustainability strategy (cit.) '*not anymore restricted to PSE experts*' and that will include (cit.) '*a recalibration of the interfaces of PSE to the other sciences... the interfaces to the natural sciences and to the core disciplines of chemical engineering*'.

In recent updates on PSE trends (Gani et al., 2020, Pistikopoulos et al., 2021) a multi-layered view of the PSE domain was used to evidence the multiscale and holistic approach based on system engineering that PSE contributors cherish (Figure 3).

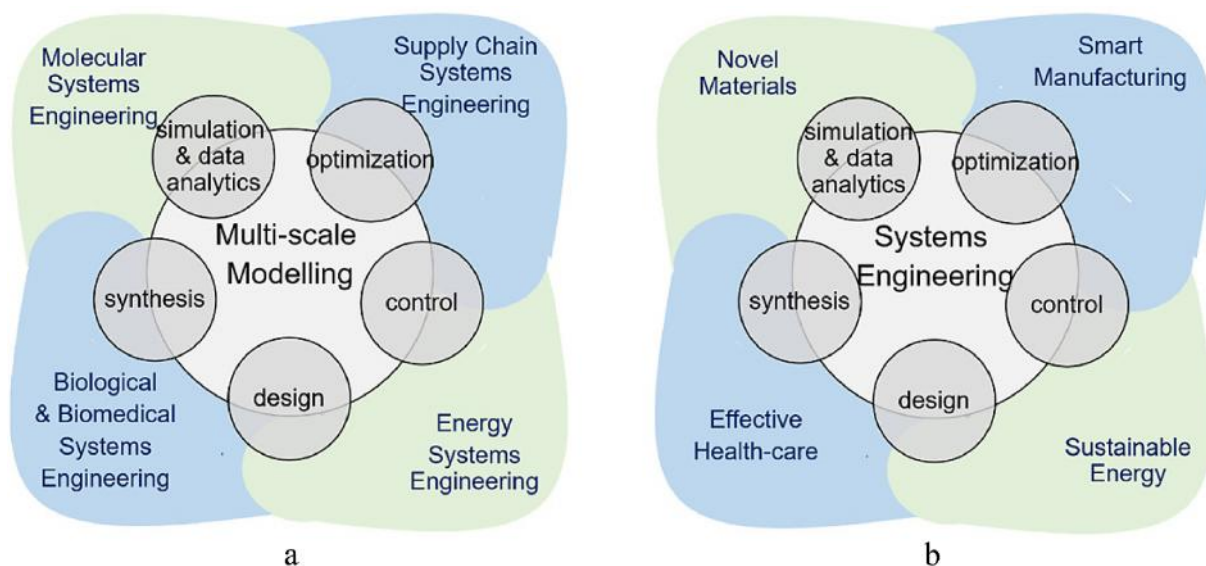


Figure 3. Link between layers: a) multiscale modelling links the core PSE topics to solve problems in different engineering domains; b) systems engineering links the core and/or middle layer PSE topics to provide solutions to society. (with permission from Elsevier, Pistikopoulos et al. 2021)

Gani, Pistokopoulos and co-authors showed that, starting from core chemical engineering issues, PSE gradually solved problems covering all kinds of manufacturing process and then further addressed problems related to sustainable development, circular economy among other broader issues, where PSE's multiscale system thinking proved adequate and useful. They noted that PSE expansion towards larger scale problems came at the expense of facing a growing uncertainty, both in terms of less and uncertain available input data and in terms of the elusive robustness of the performance indicators to assess new issues such as social or environmental impacts. Comforting a constructivist viewpoint, uncertainty has always been present both in the mind of humans and in their daily living, and that includes scientists. In that

sense, scientists draw away from Descartes' quest to stick to certainty by reasoning everything. However, they may promptly handle uncertainty by twisting it into rational thinking solutions, like stochastic algorithms, deviation functions and parameters.

3.2 *Some PSE response in the Cartesian paradigm*

PSE can be given credit to its acquaintance with system, multi-scale and integrated approaches and that seems suited for addressing global challenges. Hence, the anxiety caused by acknowledging the world-wide changes in progress, may be substituted by a sense of happiness, the next emotional state of the transition curve shown in Figure 2. But is integrated, multiscale system thinking enough for global challenges? In practice, PSE activity adjustments to face global challenges can manifest as including sustainable growth, developing integrated frameworks, optimising processes for lowering impacts, promoting process intensification and energy savings, exploring industrial ecology, and so on. Some of these topics are discussed below. A feedback is that these adjustments raise criticisms that we develop below, as they mostly proceed within the Cartesian and positivist paradigms and often contribute to greenwashing in a sense that they are not so operative for mitigating the effects of global changes as illustrated below.

3.2.1 Revisiting energy savings and process (de)intensification

Let's first have a look at energy savings and process intensification in the PSE domain. Both qualify as representative of an efficiency objective: more with less under a quality constraint. What PSE achieves as energy savings and costs with these process-driven topics is effective to lessen planetary impacts on a local scale. But, at the larger scale that is to be explored to grasp the global challenges, more issues arise, such as energy usage competition, rebound effect or operability of highly intensified process to keep deliver expected function.

Regarding energy savings, they are now valued not only as local cost savers but also as important contributors to the proclaimed global scale energy transition. However, from a broader perspective, firstly, energy transition is a myth both in total energy and in energy sources substitution; secondly, energy savings may induce rebound effect and thirdly, energy usages need to be investigated as well. Firstly, energy transition is wrongly advocated as the paramount solution to climate change but the underlying substitution of fossil-fuel energy sources in the future by less impacting sources is a wish that is not corroborated by historical analysis so far (Fressoz and Locher, 2012, Fressoz and Bonneuil, 2017). For example, historians have shown that the 19th century shift from wood to coal as main energy supply did not stopped wood usage, that were heavily needed to brace mines. As any diagram of global primary energy consumption evolution also shows (Richie et al., 2020), energy transitions have not shown substitutions (wood by coal, coal by oil, ...) but have always shown additions of the new energy source production to the previous productions, because the total demand is steadily rising every year. Hence, the current claim of renewable energy substituting fossil

energy is unlikely from a historical perspective. Evidently, this prompts for a drastic effort to save energy both for profitability and for the planet. The contribution of the PSE community is noteworthy in that sense, not only for optimising energy consumption but also with many waste energy recovery techniques (Jouhara et al., 2018). Secondly, energy savings are often a satisfactory solution at local scale but the situation is more perverse. Indeed, rebound effect may occur, i.e. saved energy is spend on other usages, and it is a well document side-effect that diminishes the total energy savings expected (Exadaktylos and van den Bergh, 2021). Thirdly, this invites us to question also the demand side and the usages of energy, typically manufacturing, services, residential or transportation (IEA, 2021). Energy is one of the main drivers of material prosperity (Ayres and Warr, 2009). At a plant scale, energy savings are welcomed without much discussion. However, at larger scales, energy usages compete with each other's. For example, in eco-industrial parks or regional energy systems with shared energy and material flows who should support cuts in a perspective of global energy reduction? Because of the diversity of usages and of the specific context of each actor, trade-offs will need to be debated among stakeholders. Besides, the stakeholder list should reach far beyond scientists and industry actors and include policymakers and inhabitants to discuss energy spending. The final energy consumption by sector is variable among world countries and reflects also global trading. Nevertheless, it shows that the industry share is important but not overwhelming, amounting from 17% in US, 26% in EU and 48% in China, and that transportation, household and services shares are also significant (IEA, 2021; Eurostat, 2022) and they should be given a voice in debate.

Regarding process intensification (PI), Tian and co-workers' review shows how PI helps to lower energy consumption and costs in typical PSE problems (Tian et al., 2018). But shortcomings similar as those pointed out for energy savings also hold, and intensified process development raises other questions as well. Tian et al. (2018) mention (cit.) "*operability and optimality of intensified structures while delivering their expected functionality*". In this sentence, operability and optimality are favourite concerns in PSE. However, the functionality term is not defined and it obviously refers to performing a task. In PSE models, it can instantiate as a list of requirements and constraints but it also calls for discussing the needs and functions that process outputs are covering. This lies within the scope of functionality economy, a derivative of circular economy. Instead of focussing only on selling goods, functionality economy describes solutions that provide services for needs to be satisfied and rationalise the purpose of material goods. This suggests two paths of investigation for PSE that I think relevant for global challenges issues and that take an end-user viewpoint more than usual in PSE. The first direction of work is about low-tech engineering, which would aim at designing and at operating devices and processes fit for a resilient and sober world. The second direction of work concerns distributed systems of production and services to improve robustness of operation and mitigate global crisis events impacts.

Firstly, low-tech engineering relies upon several principles: it should produce artefacts which functionalities match some needs and requirements. It should also be moderate in resource consumption, repairable and recyclable over its life-cycle. Finally, it should be accessible to most people, both affordable and technologically simple. All domains are potentially concerned: energy, food, water, waste management, building materials, etc. PSE community could be a central actor at all stages of low-tech studies since they require high-skilled knowledge and engineering in addition to innovation and design. PSE could use familiar thermodynamics, physical and chemical concepts and system thinking to reason the low-tech principles into requirements for designing and manufacturing artefacts. Low-tech devices could be operated standalone but should be likely designed in interrelation with surrounding systems; another familiar approach in PSE. Multiscale modelling may intervene as well, to design low-tech unit operations and process plants. This may be coupled with nature-inspired engineering mechanisms, which could help increase process efficiency and favour resilience (Coppens, 2005, Gerbaud et al., 2020) and contribute to process intensification (Coppens, 2021).

The second direction of work concerns the design of distributed systems of production and services. Within a network, they constitute a way to improve robustness of manufacturing process operation, which can help mitigate global crisis events impacts. It is already a PSE topic but it needs more effort. On one side, PSE advocates for a strong spatial integration of processes, like eco-industrial parks (Boix et al., 2015) or multi-platform biorefinery (Budzianowski and Postawa, 2016). It is compatible with mass market consumption but less likely with global crisis incitation to reduce human footprint. Alternatively, one should imagine local units producing from local supply chains to local consumers. An illustration of distributed local units in the PSE domain is provided by modular chemical plants, such as the F3 factory modular equipment project, bringing flexibility in low- and medium-scale productions (Buchholtz, 2014). It requires evidently working on material and energy networks as well as on the sharing of information, well within PSE expertise. But, flexibility should also extend to automation as well as to logistics and supply chain (Weber, 2016). With this in mind and relying upon information technology, Hougbe et al. (2019) used a model driven engineering framework to conceive a distributed set of local producing units as a virtual factory of services. It is operated as a collaborative network with a mediation information system. In Hougbe's framework, the focus is not on material flows but on a flow of services related to stakeholders. Stakeholders provide 'services' to meet a flexible demand described as 'collaborative objectives' within a 'context' about location, weather forecast, consumer, biomass physical property information (Hougbe et al., 2018, 2019). Context and demand processing in the mediation information system generates an ad-hoc production pathway that is materialized as an assembly of blocks providing services. That so-called 'servitization' sets a challenge for the process and information workflow management, which can be tackled by using ontologies appropriate for decentralized information systems as proposed for eco-industrial parks (Zhou et al., 2018).

In these two directions of work, low-tech and distributed production systems, PSE can contribute but it will have to develop stronger interfaces with other sciences as recommended by Klatt and Marquardt (2009). Indeed, in both directions, social aspects are too lightly treated. Social aspects should not be instrumented as often in science of nature projects via a checking of acceptability of technical solution by local stakeholders or end-users. Typically, low-tech devices do not only make sense for their functionality and sober-world compliance, but they are relevant in dedicated contexts of usage and the concerned users' needs must be satisfied. Similarly, the servicisation of production units monitored by a mediation information system is not just another IT stuff but it involves stakeholders that must be also included in the decentralized solution.

3.2.2 Sustainable growth and industrial ecology

As a transition with the last remark of the previous section about stakeholder's involvement, people's concern is one of the three pillars of sustainable growth. Sustainability is now a routine concern of any company including among PSE domain industries since none can discard its concern about planet and people. But, the enforcement of strong sustainability into the core of companies' achievements is more fragile and greenwashing is prompt to loom everywhere (Berlan et al., 2022).

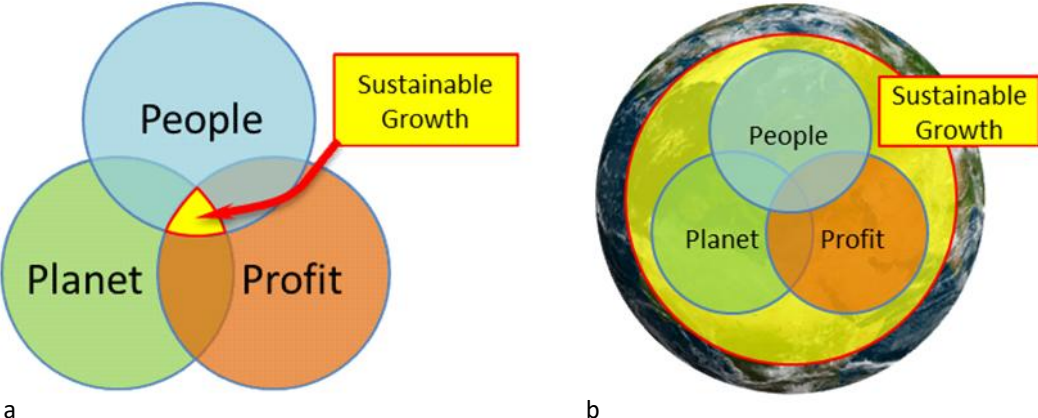


Figure 4. Viewpoints of sustainable growth a) at the convergence of people, profit and planet pillars. b) as the global challenge that all three pillars must converge at (Rossignol, 2020).

Since its popularization with UN Bruntland's report in 1987, the sustainable growth label has raised some controversy. A popular representation sets it at the convergence of profit, planet and people's pillars, a quite small converging area, compared to ambition of the right artwork encompassing the three pillars within a finite natural world (Figure 4). Bruntland's report adopted a so-called strong sustainability viewpoint stating that 'sustainable development requires the conservation of plant and animal species', so as to maintain the capital for the next generation. But it quickly confronted economy-first growth goals and the sustainability ambition was reduced (Pearce et al., 1990, Cato, 2009), to the benefit of promoting weak sustainability. Compared to its strong counterpart, weak sustainability accepts interchangeability between natural (e.g. water, fossil fuels) and technological (e.g. infrastructure,

skills, knowledge) stocks, referring respectively to the planet and people's capital, if valuable services are provided for the benefit of people. This is an anthropocentric view that can be paralleled with the anthropogenic causes of global crises (Droz, 2022) and that is rooted in mainstream rationalism.

Industrial ecology is a typical example of sustainable growth implementation in PSE activities, aiming at reconciling profitability and environmental protection, with help of material, energy and information flow modelling and optimisation. Studying eco-industrial parks or promoting circular economy are instantiations, but several drawbacks are known: studies of eco-industrial parks often lack systematic social/societal objectives formulation (Boix et al., 2015, Mousque et al., 2020) and circular economy struggles to thrive in high climate and environmental impact industries like chemical industry which is a historical domain for PSE contributors (Winans et al., 2017). Besides, they rely upon the concept of recyclability that is always limited. Indeed, physical economy theories that analyse economic processes from the angle of energy and material flows (Georgescu Roegen, 1971, Ayres and Wares, 2009) point out that global recycling generates entropy that degrades the processed material ability to be usable in the next cycle. Note that this ability can be addressed by the concept of exergy. Finally, circular economy encourages an economy based on waste management optimisation but the depletion of planetary resources evidences that it is illusory to rely only on that circular approach and that global resource usage should be also lowered. Indeed, sustainable growth qualifies as an oxymoron since growth inevitably uses resources, like fossil fuels that are quickly depleted over decades whereas they regenerate over million years, raising concern about its sustainability for the future generations.

3.3 Critical analysis of some PSE practice in addressing global challenges.

3.3.1 Multiscale approaches in PSE systemic approach

The first criticism concerns a bias of representation related to PSE's familiar multiscale modelling (e.g. molecules aggregate in mixtures that react and split in unit operations, that are part of a chemical plant). The art of engineering is to manage the loss of some details as one scales up, while at the same time capturing the dynamics of key phenomena across scales. Often, time and spatial scale uncoupling is favoured because of solving strategies (e.g. various time-scale dynamics leading to quasi-steady state hypothesis) and difficulties to bridge theoretical frameworks across scales (e.g. quantum level molecular interactions with macroscopic thermodynamic model; e.g. local tray phenomena hydrodynamics with distillation column MESH model).

As another example in line with sustainable development concerns, my coworkers and I implemented a model-driven engineering approach to propose a chemical-enterprise model and a decision-making framework for the design of sustainable chemical products (Heintz et al., 2014). In Figure 5, the pyramid axes aim at capturing the pillars of sustainable engineering

principles, society, environment and economy and split it into multiscale modelling and multi-stakeholder's decision levels. The deliberate distinction of economics and sustainability issues in this framework was implemented as distinct economic and EHS (environmental health and safety) criteria for the computer aided design of biosourced solvents embedded in a multi-stakeholder multiple criteria decision process (Gerbaud et al., 2017). But, as a co-author of these works, I must admit that the pictured framework contains some bias in the pretention to devise a systemic approach exemplary with respect to sustainability. One bias concerns the use of the hierarchical pyramid representation that is a dominant characteristic of companies and institutions organisations in our socio-technical regime. This recalls the Cartesian attitude of splitting elements for understanding that was criticized earlier. Other biases are related to the mathematization of social and environmental issues and are discussed in the next paragraph.

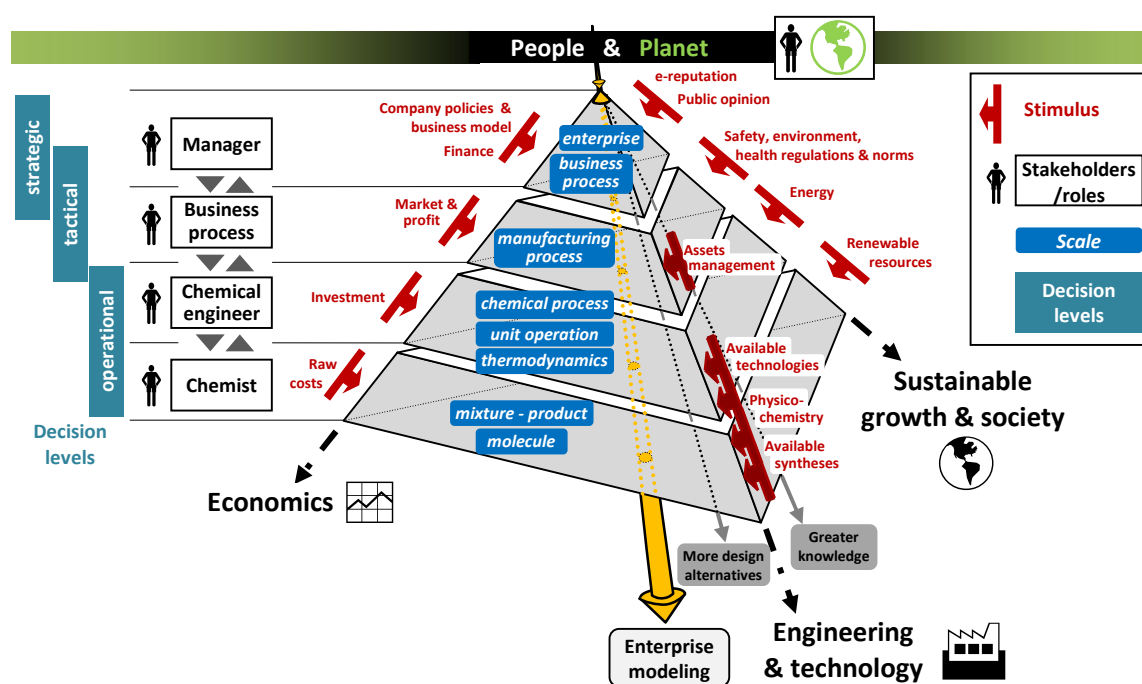


Figure 5. Decision levels across the chemical enterprise for the design of sustainable chemical products (with permission from Elsevier, Heintz et al., 2014)

3.3.2 Including environmental and social concerns in PSE activities

A second criticism concerns the oversimplification of models used to describe complex factors related to environment and social issues. As an example of environmental issue, the use of EHS evaluation models for selecting newly designed biosourced solvents (Gerbaud et al., 2017) proved not to be a panacea since these models are entailed a significant uncertainty (Hukkerikar et al., 2012). Typically, such models are often developed with a limited set of data, that impede their predictability power. Besides, these EHS properties, like bioconcentration factor, global warming power, lethal concentration etc..., aggregate in a macroscopic parameter value the outcomes of complex and multifactorial processes that are far from fully decrypted and understood at lower scales in living organisms. One way we devised to reduce the impact of model's irreducible uncertainty on project outcomes, was to use these models

within a decision-making process involving stakeholders at all phases. Figure 6 highlights in blue rectangles that numerous stakeholders can be involved in the design of biosourced solvents supported by a decision-making process (Gerbaud et al., 2017). The expertise displayed during the choice phase should involve EHS expertise to give a fair assessment of the EHS models limitations. In practice, I struggled to hire such experts in practice and was left with a list of biosourced solvents with not-so reliable EHS indicators.

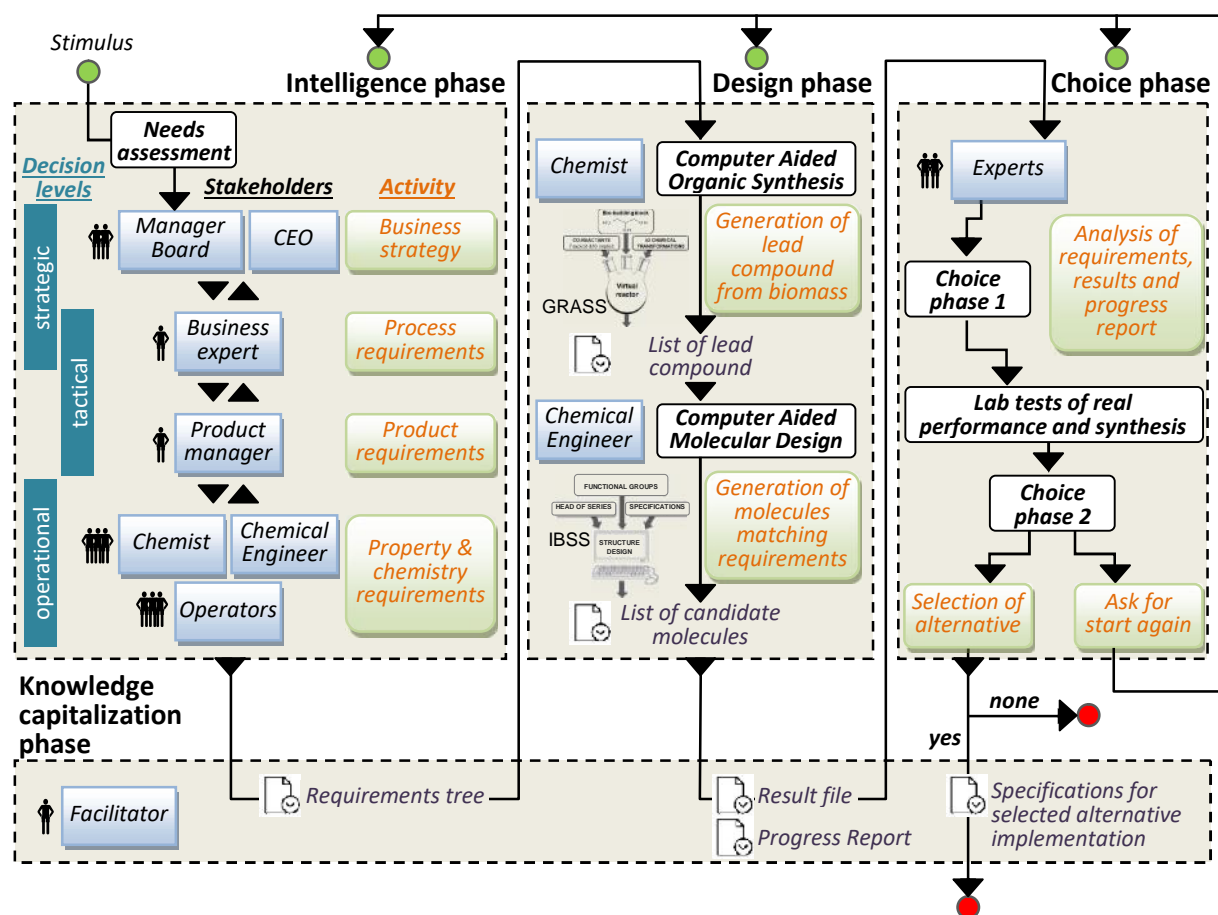


Figure 6. Multiple stakeholder decision making process for the design of biosourced solvents (with permission from Elsevier, Gerbaud et al., 2017)

Regarding an example about handling social issues in PSE works, my colleagues Miret et al. (2016) compared several bioethanol production supply chains with respect to economic, social and environmental criteria. They used a multiperiod, multiobjective MILP goal programming and multiscale modelling of the supply chain, accounting for biomass seasonability, geographical availability, biomass degradation, process conversion technologies and product demand. The environmental issue was assessed using the Ecocosts method based on life cycle assessment and translated into costs. The social issue was not handled from a sociological viewpoint but more simply as the numbers of jobs created directly (plant size, ...), indirectly related to the supply chain (transportation, storage) and via jobs induced based on geographical location. However, the authors clarify that “employment quantification relies on economic data”. All three criteria were then compared on a financial basis.

Displayed as a dark circle in Figure 7, the suggested solution is a trade-off between the eco-cost, economic cost and job creation criteria. It corresponds to a mix of corn and wood supplies, and a multiplication of biorefinery locations. A post analysis of the multiobjective solution shows that profit can be increased and environmental impact cost can be lowered at the expense of less jobs created. Although it was out of scope from Miret's work, the final decision choice could have strong social consequences in the geographic areas where the units would be built, and affect local economics far more than on its financial aspects.

For both examples, one should further ask the epistemological question of the value we assign to these models: what is the relevance of monetising jobs as the sole social indicator? What is the relevance of EHS indicators? Such attempts to include environmental and social concerns in PSE activities are so far disappointing both in their pretention to represent satisfactorily complex phenomena and in the fair assessment of true impacts and consequences. Hence, it falls short from matching the expectation that current PSE activities are effective for addressing global challenges properly.

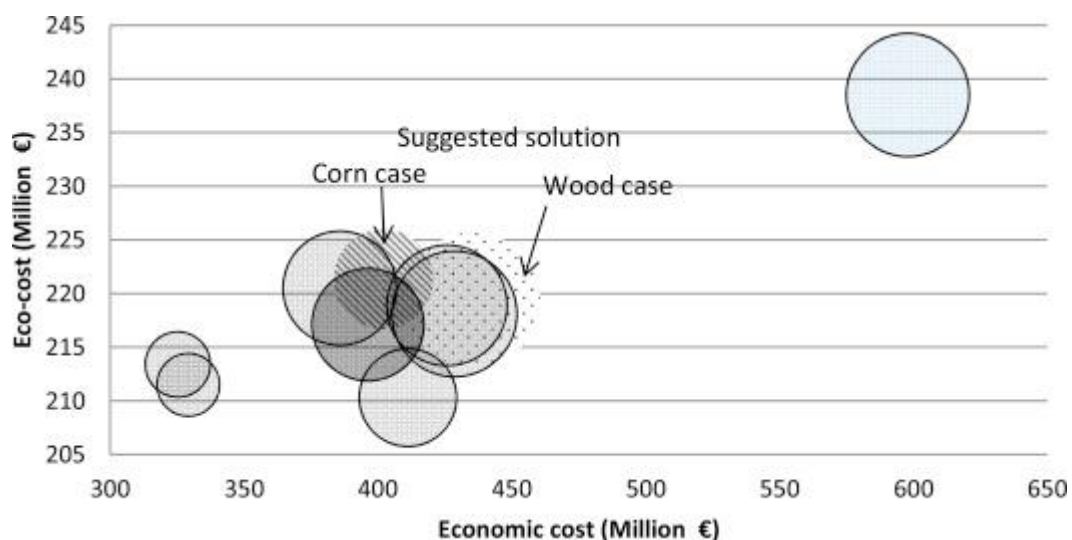


Figure 7. Comparison between economic cost Ecocosts and jobs creation for wood and corn biorefineries (with permission from Elsevier, Miret et al., 2016)

The emotional consequences of this disappointing statement are worth examination. As I was acknowledging that my PSE efforts for addressing global challenges were not sufficient, it set me into states of guilt, of disillusionment and near depression as illustrated on the transition curve (Figure 2). Retrospectively, I'm now aware that this disappointment was mainly due to an unconscious settling in the Cartesian paradigm and in the rationalism epistemology that forced me to use reductionist models for accounting for complex issues such as social and environmental issues. Furthermore, one should also include complexity in the third pillar of sustainability, economics, since capital and operational costs, use in PSE are indicators of a finance-dominated economy that does not reflect real economy and its complex detailed mechanisms. Adopting a constructivist posture with the acting/thinking in complexity approach, helped me overcome these emotional states and the next section presents how this can be devised.

4 PSE prospective changes in a Complex Thought paradigm

This section discusses proposals for the PSE community members to develop an ability to contribute to address global challenges, taking advantage of their expertise in system, multi-scale and integrated approaches. Section 3 noted that PSE expertise is fit for finding locally relevant solutions but it shows limitations when put in a global perspective and can generate unpleasant emotions. Familiar objects of study in PSE are mostly static ones and reproducible experiments can be made, especially because human related issues are not detailed but are reduced to numbers and equations. But, systems related to global challenges are evolving systems in transition. Much like the objects of study in economics and social sciences, they involve human beings explicitly, both as end-users and as co-designers and they are therefore not reproducible.

This prompts for several shifts, covering methodological, epistemological and metaphysical intertwined aspects. The first expected shift concerns methods and tools for producing future knowledge and engineering expertise that would bring out attenuation and adaptation solutions to address the current challenges. The previous section showed that current attempts are partly satisfactory and partly inadequate, in particular when reductionism is at work and about the misleading superficial inclusion of social and environmental issues. Hence, a methodological shift alone cannot be sufficient. It calls for an analysis of epistemological and metaphysical aspects underlying these methods and tools, so as to explore within the complex thought paradigm the world in transition and heads towards not only economically sustainable solutions but also desirable solutions matching long term needs that have been debated.

4.1 Epistemological and metaphysical revisit of economics, social sciences and environmental issues

Constructivism epistemology encourages a non-dominating posture shared with others to explore reality. It can partly be grasped by breaking down disciplinary frontiers and dealing with global challenge issues need interdisciplinary approaches merging science and technology studies with humanities, social sciences, economics, etc. In practice, this raises a challenge concerns the understanding of each other's paradigm. Indeed, the use of expert vocabulary by expert scientists within a domain community is suitable and necessary to catch all the nuances of concepts, methods and tools, but it makes it difficult for sharing outside the domain, even sometimes among specialties within a domain like chemical engineering, as I have experienced. This is even more true when diving into new sciences like economics, environmental sciences and social sciences. At first, experiencing disorientation when confronted to these sciences, I was then reassured as I grasped in these unusual domains some concepts surprisingly familiar to my PSE mind, that helped me in gaining and sharing understanding about socio-environmental and economic issues.

In physical economics and bioeconomy, one such concept familiar to PSE is the use of material and energy flow analysis to describe economical flows in a non-financial manner. Initiated decades ago (Georgescu Roegen, 1971), physical economics can help to explore prospective scenarios and thus contribute to the study of systems in transitions. For example, economists that have contributed to the IPCC report with working group 3 about Mitigation of Climate Change (IPCC, 2022b) have studied the socio-economic conditions of global low-energy scenario satisfying decent living standards. They have used a multilevel framework for relating biophysical resources and human needs and multivariate analysis (Rao and Min, 2018, Millward-Hopkins et al., 2020, Vogel et al., 2021). Another example at a smaller scale is that environmentalists have studied biorefinery alternatives with a combined physical flow based territorial metabolism – life cycle analysis approach (Croxatto Vega et al., 2019). Again, the tools and methods in these studies look familiar to PSE community.

Both economic study examples fall within broader economic frameworks like the analytical multi-level perspective (MLP) (Geels and Schott, 2007) that echoes with multi-scalar approaches in PSE. The MLP reveals the determinants of transitions pathways undergone by socio-technical systems and proposes a four-item classification, namely transformation, reconfiguration, technological substitution, and de-alignment and re-alignment pathways. Even though such a classification falls into a Cartesian framework to explain what is going on, it can help describe and understand a system trajectory. The three MLP levels are, first, the socio-technical landscape level (the general context) where may occur some economic shock inducing transition, second, the socio-technical domain level where dominant activity proceeds, driven by policies, markets, technology, science and culture, and third, a refined level describing niche activities and actors that may contribute to decisive transformation of the socio-technical regime. Inspiring for PSE practitioners with its multilevel perspective, Geels (2007, 2022) was always concerned to address economists' criticisms when building his framework. A first criticism was about his focus on an intertwined multilevel representation. He said that his MLP framework was mostly a mesoscale viewpoint that averaged detailed economical and socio-technical processes and that it should be complemented with multiple studies from other levels. Another criticism concerned the implied causality and explanatory intention of transition pathways in terms of interlinked events, when real situations usually exhibit non-causal factors, nonlinear response, feedbacks, rebound effects, etc. Again, this invites PSE to explore, like Geels (2022) did, the epistemological attitude behind any modelling activity.

In social science, one has earlier mentioned that the reductionist attempt to bringing ideas from physics to explain the social world, like using jobs number for handling social issues, is open to strong criticism from a sociological perspective. Indeed, although social scientists are also eager to investigate the social and individual patterns of human societies, and they have numerous theories for that (Johnson, 2008), it is presumptuous to pretend to capture their complexity with technical science models as in the examples described in section 3.

Contemporary social theories inevitably adopt a so-called 'multi-level approach' as Johnson's book title tells (Johnson, 2008). Again, these are the same words than in Geels' MLP model and the same claim than in the multiscale approach rooted in PSE activities. At the microscale, theories take into account explicitly human agency (capability of action) and choices, and people interaction dynamics. At meso and macro levels, theories focus on groups, structure and collective behaviours and society. An engineering approach would be to smooth microscale behaviour into average figures or macro indicators, like job creation numbers. However, things are far more complex. For example, power relationships traverse the scales. They are often explicit at the microscale. Some attempts have been made by the PSE community to incorporate player games using game theory, for example in the design and optimization of water exchange networks in eco-industrial parks (Sala et al., 2020). But, meso and macro scale groups and social classes also enforce subtle power relationships, that people often take for granted without notice or questioning. Furthermore, meso and macro-scale societal attributes like history or culture, are constructs of individual and group actions and beliefs. Conversely, meso- and macro-level characteristics shape the identity of individuals and define the constraints and frontiers of their living system, leaving some place for the emergence of local collective entities that evolve on their own and impact all scales. Everything is entangled.

These examples from economics and social sciences reveal the complexity of real systems. It weakens further the oversimplification pretention of PSE community when accounting for economics and social issues in their studies. It also shatters the expert attitude of natural scientists embedded in a positivist postulate that physical laws and equations under expert mastering can reveal alone the essence of reality. Instead, one should welcome a constructivist exploration of reality by multidisciplinary teams.

Mobilizing concepts familiar to PSE, some attempts to explore the complexity of real systems are made in the studies of social-ecological systems with the help of Integrated Assessment and Modelling (IAM) approaches (Allain et al., 2020). IAM approaches claim to develop models at the interface between science and society to analyse how complex system respond to changes and how to design sound sustainable management and development strategies (Pahl-Wostl et al., 2000).

For the last two decades, the French INRAE institution has supervised within its laboratories the design of MAELIA, a multi-agent simulation (MAS) of ecological systems. MAELIA has been used for investigating multiannual transition scenarios related to resources management or agricultural activities (Bousquet and Le Page, 2004, Gaudou et al., 2013, Mazzega et al., 2014). Such simulation systems mobilize a multidisciplinary expertise in computer science, for the UML modelling and multi-agent implementation, geographer, sociologist, environmental science specialists and territorial policy makers. Illustrated as a frame of interacting multiple layers (Figure 8), MAELIA addresses not only the temporal evolution of the systems in terms

of physical flows, environmental impacts, crop coverage, etc. but also includes issues about individual behaviour, governance and regulating policies (Gaudou et al., 2014).

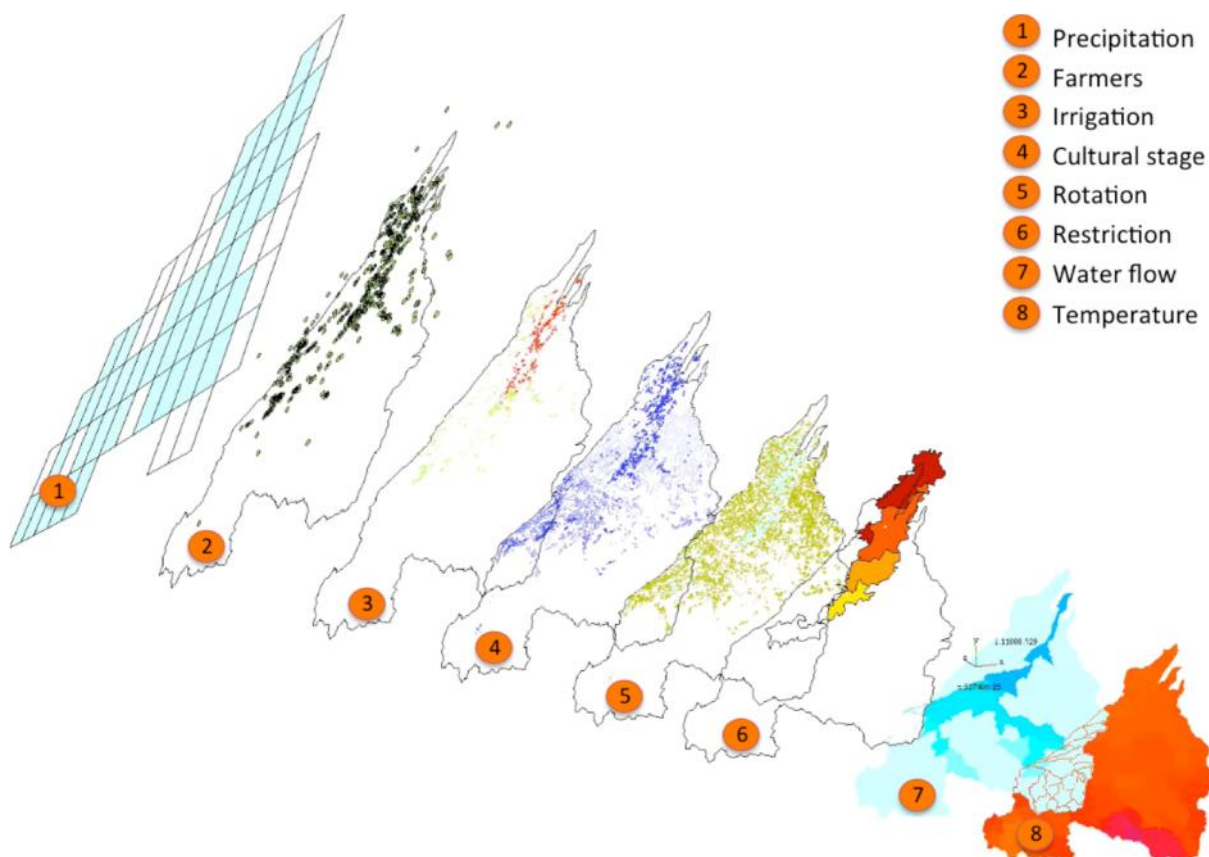


Figure 8. synopsis of the main processes simulated in the MAELIA platform (<http://maelia-platform.inra.fr/>).

In MAELIA's platform, social layers are built upon sociological theories analysing how stakeholders collaborate to reach compromise solutions, like Le Crozier and Friedberg's sociology of organised action accounting for power relationships between actors (Crozier and Friedberg, 1980), the actor-network theory (Latour, 2005) and Ostrom's management of commons precepts (Dietz et al., 2003, Ostrom, 2009). For example, farmer agents can be assigned one among five profiles (neutral, gambler, prudential, experienced, hard-worker) with specific behaviours. Some of MAELIA's contributors made a parallel attempt to play more realistically the social dynamics by designing a multi-agent simulation software tool Soc-Lab® (Sibertin-Blanc et al., 2013) but it proved its limitation in the reductionist enforcement into +/- response curves of each stakeholder's capability to be impacted by other factors and decision.

Hence, IAM approaches can still be seen to head towards a mathematization of socio-environmental and economic issues. But, the full story is that they are not used as a stand-alone tool but as scenario-testing tool within a deliberative multistakeholder process aiming at devising rules for better managing resources; the meaning of the 'better' adjective being 'debated' among stakeholders.

In complement, the issue of better managing resources sparks a motivation for addressing a metaphysical question about the relation between human and non-humans that has raised

from anthropological studies (Descola, 2009). The anthropocentric distinction of a human reality and of a natural reality is far from being universally perceived and it reflects the Cartesian top-down viewpoint earlier discussed, contributing to a dualist cosmology that is dominant in western cultures and subsequently in engineering sciences that have thrived in it. This invites PSE to adopt a minima a reflexive introspection to explore the relation of engineering activities and nature.

At this point, the emotional state of the transition curve might be a state of even more disillusion for some that would stick to the Cartesian framework and, hopefully for many more undergoing a paradigm shift, a gradual acceptance that a new path is opening for practicing PSE activities, more meaningful for oneself and more relevant for addressing the planet global changes.

4.2 The collaborative horizon: participative PSE approach

Through this paper, the emphasis on the reductionist trend at work in PSE approach must not be interpreted as a rejection of current manners of practicing engineering. Instead, it is an invitation to undertake shifts related to complex thought and constructivism epistemology for a more salient investigation of social-ecological systems in transition. At the same time, one has previously insisted on the human factor: including users for low-tech activities, developing IT-based collaborative networks that also include stakeholders, diversifying stakeholders in integrated design and decision processes, accounting for individual and group social and economic dynamics in large scale systems, etc.

This invites us to embed PSE work and capabilities to deploy systemic and multiscale approaches within activities that account explicitly for stakeholders at all stages, both in models and in PSE business process. Developing new interfaces between PSE community and other sciences has been recognized as a top wish in most PSE prospective papers (Klatt and Marquardt, 2009, Gani et al., 2020, Pistikopoulos et al., 2021) but the type of stakeholders to be involved shall reach much farther than scientists alone. Gagnon et al. (2012) already noted in their review that, when compared to a so-called “non-sustainable design process” (NSDP), a sustainable design process (SDP) involved multidisciplinary stakeholders. Indeed, apart from a first task of “team formation” NSDP hides the persons involved. On the contrary, SDP explicitly mentions stakeholders in several process tasks, alike what is displayed in Figure 6 that noticeably displays a facilitator role among other roles more technical (Gerbaud et al., 2017). Gagnon’s list of NSDP tasks covers four usual activities; namely planning and problem definition; conceptual analysis, preliminary design and detailed design. NSDP’s 12 tasks are also worded as ‘define’ ‘generate’, ‘select’ ‘identify’ ‘evaluate’ etc., which makes them generic and not requiring any actor: they could be automatized. Instead, a SDP requires 22 tasks where new wording occur, like ‘validate’ ‘assess’ ‘refine’ and they induce an active implication of stakeholders. This goes in line with the constructivist-backed importance of taking care of the process involving stakeholders that is a characteristic attitude within the complex thought

paradigm. Other SDP tasks refer to multi-criteria analysis and multi-objective optimisation, especially for addressing the sustainability issue itself that was discussed earlier.

My contribution for PSE is displayed in Figure 9 that revisits the business process underpinning usual PSE approach into a participative PSE approach, building upon the proposal in Roth et al. (2021).

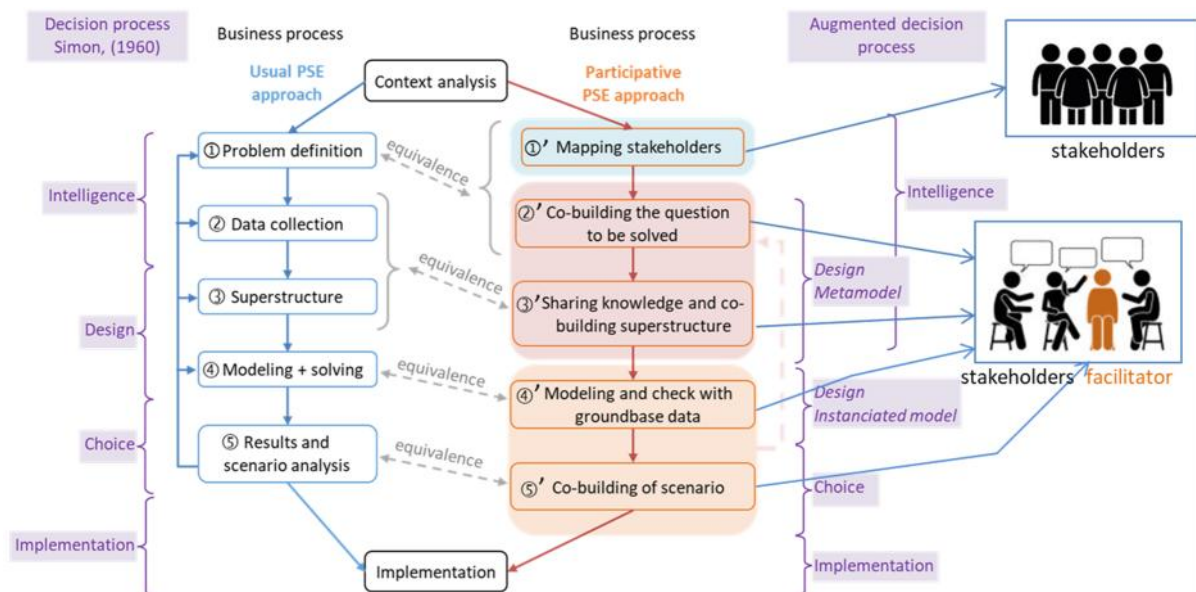


Figure 9. Participative PSE approach.

On the left, the traditional decision process was fathered by Simon (1977); the same author that wrote the “Sciences of the artificial” book (Simon, 1969) that was a corner stone in the history of constructivist epistemology (Le Moigne, 2009). In Figure 9, the novel participative approach is also inspired by “post-normal” science concepts that become relevant compared to traditional problem-solving strategies when either uncertainty or decision stakes are high (Funtowicz and Ravetz, 1993). Post-normal science concepts have been connected in social sciences to so-called participatory science that includes citizens. It has led to the conception of a tangible and operative method, namely the Companion Modeling (ComMod) approach (Simon and Etienne, 2010), that supported deliberative multi-stakeholder processes in which tools like the aforementioned IAMs can be used. ComMod will help illustrate the novel approach along with examples given in Figure 10.

The novel PSE participative approach redefines the phases of the traditional and augmented decision process (left and right of Figure 9) and reorganizes the stages of the PSE approach (middle part). On the right of Figure 9, Simon’s usual sequential decision process is rearranged as the design phase is split into a conceptual part related to metamodeling and an instantiated model part. The metamodel design phase overlaps with the intelligence phase. The instantiated model phase is nearly equivalent to the modelling and solving stages in Simon’s traditional design phase. Along these phases, all stages involve dialog and debate among stakeholders.

To delve further in the new decision process, we now provide some illustrations. The usual problem definition stage is split in two in the novel approach. The first novel stakeholder mapping stage 1' is crucial and should be envisioned largely, by including non-expert people, both directly and indirectly concerned by the topic of investigation. At this stage all implicit elements (intentions, backgrounds, hidden strategies, emotions... see final paragraph) should be revealed and a common vocabulary should be shared, possibly vulgarising expert and disciplinary concepts.

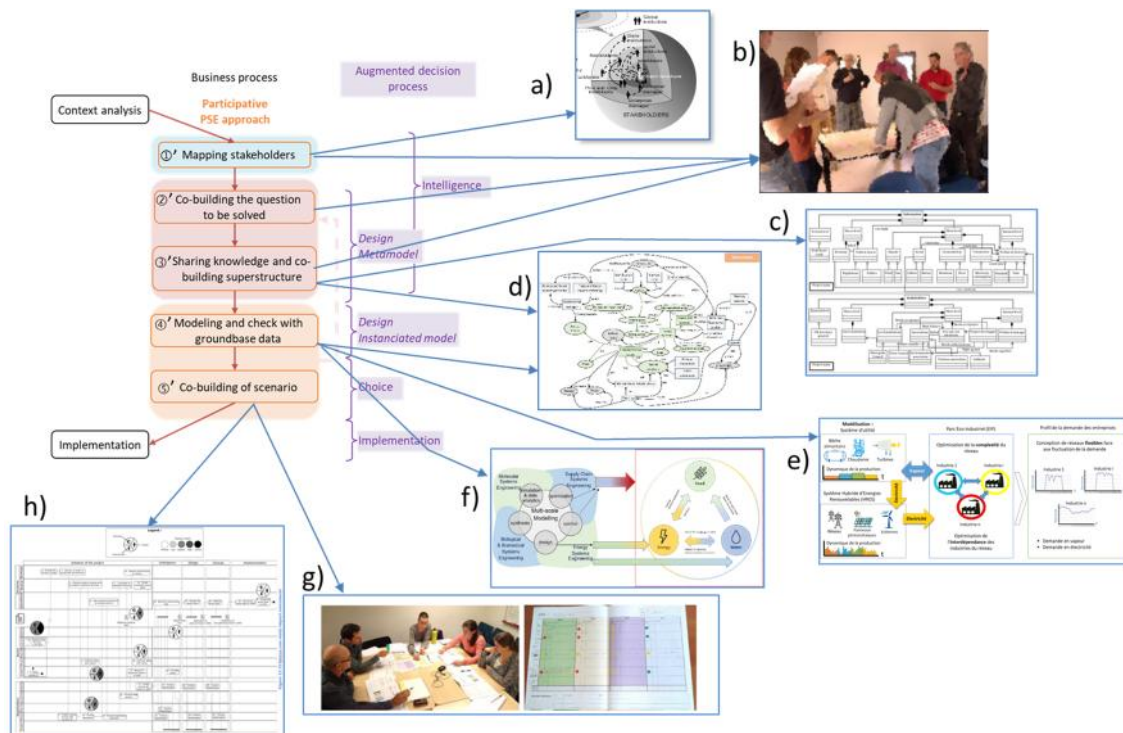


Figure 10. illustrations of a participative PSE approach. with permissions from Elsevier a) c) h) (Roth et al., 2017) b) g) (Allain et al., 2020) d) (Roth et al., 2021) e) (Mousque et al., 2020) f) (Peña-Torres et al., 2022)

Figure 10 shows in picture a) a multistakeholder multiscalar historical representation of a renewable energy production park development (Roth et al., 2017) and a real meeting during a ComMod approach implemented for agricultural water management (Allain et al., 2020). The second stage 2' about co-building the question to be solved, involves also all stakeholders. It recalls a precept formulated by E. Morin's Complex Thought paradigm: "question the question". Indeed, any scientist bears a biased view on the topic of investigation, because of his singular background and his personal and group interests, that should be shared in stage 1'. Therefore, it is fruitful during this stage for all stakeholders first to explicitly state their biases and second to discuss and build the precise question to be examined by the group. Inspired by ComMod practice, stage 2' and all subsequent stages will benefit from a neutral person acting as facilitator. Assigning this role to someone else enables the scientist to participate fully to the debates and to be freed from tedious tasks like meeting facilitation, reporting of minutes, etc. It can also help him drop his expert attitude. Besides, professional facilitators are acquainted with collective intelligence methods and tips that ease debate far more than do scientists.

Stage 3', about sharing knowledge and co-building a superstructure is displayed in Figure 9 as an equivalence to both traditional data collection and superstructure stages, but it revisits them deeply. First, a diversity of stakeholders shall foster a diversity of collected data. Second, as displayed on Figure 9, stage 3' belongs to the design metamodel stage along with stage 2'. Indeed, stakeholders brainstorming during stage 3' may lead them at any time to revisit the question under investigation (stage 2'). This happens in practice, and it may help identify early in the project necessary adjustments. In practice of stage 3', the diversity of people calls for using innovative tools easy to understand for non-scientists, dropping mono-disciplinary concepts and tools. Instead, running stage 3' can be helped with the use of formal representations aiming at a building a common vocabulary and understanding of what is at stakes. Using a mix of meta-concepts and simple representation drawings, the ComMod procedure PARDI (process, actor, resources, dynamics, interactions) produces diagrams that usually allow all participants to grasp the essence of the topic under investigation (Etienne, et al., 2011). One remarks incidentally that the four ARDI steps are close to the ISO 19440 standard recommendations for representing the enterprise by using the four views: organizational (enterprise structure), resource (resource, capability), functional (event-process-activity) and informational (object-data) (ISO 19440, 2020). This is illustrated with diagrams c) from ARDI, and d) from ISO 19400 in Figure 10. Even if stage 3' usually weakens the expert attitude in scientists, which can make them feel unease, this is for the benefit of the collaboration among all participants.

Stages 4' and 5' are aggregated in a new meta-stage and are covering the 'instantiated design' and 'choice' phases. Traditional PSE stages equivalence are modelling-solving and results analysis stages 4 and 5, respectively. As stage 4' involves the design process applied to specific objects, one can readily use items obtained by usual PSE approaches. They will be relevant, especially if they address multiple issues, like flexible resource allocation in scenario building (illustration e) in Figure 10) or like water – food – energy nexus (illustration f) in Figure 10). Stage 5' about choice phase is well known of the PSE community and many techniques can be implemented, like multi-criteria decision-making methods (Peña-Torres et al., 2022). In ComMod practice for studying ecosystem evolutions and management, they can take other formats as well, like role playing games or multi-agent simulators for testing scenarios (illustrated as figure g) and h) in Figure 10). Designing these formats requires a combined engineering of multidisciplinary scientists and science mediation fellows as discussed earlier.

The novel participatory PSE approach displayed in Figure 9 is likely suitable for any project, including current PSE projects. Indeed, I stress that every project is more than solving a problem and deciding which solution is the best. More is always at work than what is described in work proposals and planned, and the project effective outcomes always differ from anticipated outcomes, even marginally. The evident reason is that the project's technical and logistical aspects are always enclosed in socio-technical arenas populated by stakeholders that are humans. Therefore, player games (power relationships, who controls resources

needed for the project), personal decision criteria, undisclosed company's proprietary data, hidden strategies or even personal agendas and personal emotions are crucial elements. They are conveyed by persons as free will opinions or as representative of a group/company. Colleagues in classical PSE projects or non-scientific persons in broader-scope project addressing global challenges, stakeholders inevitably have biased opinions and perceptions that will influence the final decision; be it for choosing the multicriteria solution or for designing new regulations that match their interests (Dowling et al., 2016). Besides, social sciences tell us that stakeholders' historical, educational, cultural and professional backgrounds also influence strongly the outcomes. Depending on the analysis of stakeholders' interactions, which can be greatly eased by mobilizing social theories (Crozier and Friedberg, 1980, Latour, 2005, Johnson, 2008), suitable strategies for problem resolution can be devised and the proposed participatory approach shall be helpful for that. In practice, esp. in stage 1' and 2' of the participatory approach, this can be facilitated with the early enunciation of each stakeholder's personal and group interests and background. The use of collective intelligence tools can also be helpful, like the aforementioned ComMod approach. My personal experience is that revealing intentions is a step as crucial as aggregating competencies and resources, in order to reach decisions and solutions satisfactory for all stakeholders. That's what is recommended in any project carried out in the paradigm of complex thought but also what is expected in any project in general.

5 Conclusions

The world in which engineering has thrived so far is changing drastically because of anthropogenic activities. In this paper we discussed opportunities for PSE practitioners and conditions for shifting the daily practice of PSE engineering towards activities compliant with the limited resources of Earth and contributing to a desirable well-being for people. The path for change taken by any PSE practitioner entails first to acknowledge that it will proceed along a personal transition curve involving both positive and negative emotional states. Secondly, it calls for a triple shift related to methodology, epistemology and metaphysics. The first expected shift concerns methods and tools for producing future knowledge and engineering expertise that would design attenuation and adaptation solutions. This has been already at work in PSE community that can build upon its multiscale and systemic approaches. But, disappointment may emerge as it is far from enough to address the current challenges in a suitable manner. Indeed, it brings some criticism, in particular when reductionism is at work for twisting reality into a reduced complexity. This happens for instance when economic, social and environmental issues are superficially included as numbers and impact factors, under the sustainable growth claim which nuances and limits were discussed.

The roots of reductionism lie in the rationalist epistemology and its cartesian and positivist paradigmatic approaches, that have been supporting the development of hard sciences for centuries. But, cartesianism is poorly fit for exploring the multiscale and multifactorial

complexity of social, economic and environmental worlds. Hence, every PSE member should experiment epistemological and metaphysical shifts underlying these methods and tools. This paper proposed to carry these shifts by exploring constructivist approaches and by questioning anchored concepts such as the human – nature relationship or the association of sustainable qualifier to the growth concept. Such shifts should facilitate the investigation of systems in transition within Morin's Complex Thought paradigm and the path towards not only sustainable but also desirable solutions matching long term needs that have been debated among the concerned stakeholders. My feedback is that such a triple shift requires time and experimentation, but also effort and humility. Actually, practicing acting/thinking in complexity can be helped by incorporating PSE work into participatory science processes involving stakeholders, incl. non-scientists, at all the decisive steps. However, the underlying necessary interdisciplinary approach will be truly effective if, like any other stakeholder, PSE scientists express their personal and group interests, leave out their expert cloak, and both take time and bring effort into the building with all stakeholders of a shared understanding of what is at stake and what would be satisfactory for anyone. Committing to these shifts shall help PSE to develop meaningful activities related to the transitions at work and might reconcile daily PSE work with personal expectations.

6 Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7 References

- Allain, S., Plumecocq, G., Leenhardt, D., 2020. Linking deliberative evaluation with integrated assessment and modelling: a methodological framework and its application to agricultural water management. *Futures*, 120, 102566. <https://doi.org/10.1016/j.futures.2020.102566>.
- Avenier, M.J., 2009. A methodological framework for constructing generic knowledge with intended value for both academia and practice. In: Brogger, B. Eikeland O. (Eds.) *Turning to practice with action research*. Peter Land Publishers. Frankfurt. pp. 141-178. halshs-00526616.
- Avenier, M.J., 2011. Les paradigmes épistémologiques constructivistes : post-modernisme ou pragmatisme ? *Management & Avenir*, 43, 372-391. <https://doi.org/10.3917/mav.043.0372>
- Ayres, R.U., Warr. B. 2009. *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*, Edward Edgar Pub. <http://dx.doi.org/10.4337/9781848445956>.
- Berlan, A., Carbou, G., Teulieres, L., *Greenwashing. Manuel pour dépolluer le débat public*. Le Seuil, coll. Anthropocene. 2022, 256 p. ISBN 9782021492897.
- Boix, M., Montastruc, L., Azzaro-Pantel, C., Domenech, S., 2015. Optimization methods applied to the design of eco-industrial parks: a literature review. *J. Clean. Prod.* 87, 303-317. <https://doi.org/10.1016/j.jclepro.2014.09.032>.
- Bousquet, F., Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. *Ecological Modelling*, 176, 313-332. <https://doi.org/10.1016/j.ecolmodel.2004.01.011>.
- Boutaud, A., Gondran, N., 2020. *Les limites planétaires*, Paris, éd. La Découverte, coll. Repères écologie, 126 p. ISBN 9782348046230. <https://doi.org/10.3917/dec.bouta.2020.01>.
- Buchholz, S., 2014. *F3 Factory Final Report to European Commission*. <https://cordis.europa.eu/project/rcn/92587/reporting/en>. (last accessed march 2023)
- Buclet N., Donsimoni M., 2020. L'économie circulaire : modes de gouvernance et développement territorial – Métabolisme territorial et capacités : une articulation entre enjeux économiques et écologiques. *Nat. Sci. Soc.*, 28, 2, 118-130. <https://doi-org.insis.bib.cnrs.fr/10.1051/nss/2020035>.

- Budzianowski, W.M., Postawa, K., 2016. Total chain integration of sustainable biorefinery systems. *Appl. Energy* 184, 1432-1446. <https://doi.org/10.1016/j.apenergy.2016.06.050>.
- Cato, M.S., 2009. *Green Economics*. London: Earthscan, pp. 36–37. ISBN 9781844075713.
- Coppens, M.-O., 2005. Scaling-up and -down in a nature-inspired way. *Ind. Eng. Chem. Res.*, 44 (14), 5011-5019. <https://doi.org/10.1021/ie0490482>
- Coppens, M.-O., 2021. Nature-Inspired Chemical Engineering for Process Intensification. *Annual Rev. Chem. Biomol. Engin.*, 12, 187-215. <http://doi.org/10.1146/annurev-chembioeng-060718-030249>.
- Croxatto Vega, G., Sohn, J., Bruun, S., Olsen, S.I., Birkved, M., 2019. Maximizing Environmental Impact Savings Potential through Innovative Biorefinery Alternatives: An Application of the TM-LCA Framework for Regional Scale Impact Assessment. *Sustainability*, 11, 3836. <https://doi.org/10.3390/su11143836>.
- Crozier, M., Friedberg, E., 1980. *Actors and Systems: The Politics of Collective Action*. Chicago: The University of Chicago Press. 333 p. ISBN 9780226121833.
- Descola, P., 2009. Human natures. *Social Anthropology*, 17, 145-157. <https://doi.org/10.1111/j.1469-8676.2009.00063.x>.
- Dietz, T., Ostrom, E., Stern, P.C., 2003. The Struggle to Govern the Commons. *Science*. 302, 1907-1912. <https://doi.org/10.1126/science.1091015>.
- Dowling, A.W., Ruiz-Mercado, G., Zavala, V.M., 2016. A framework for multi-stakeholder decision-making and conflict resolution. *Comput Chem Eng* 90, 136-150. <https://doi.org/10.1016/j.compchemeng.2016.03.034>.
- Droz, L., 2022. Anthropocentrism as the scapegoat of the environmental crisis: a review. *Ethics Sci Environ Polit* 22:25-49. <https://doi.org/10.3354/esep00200>
- Etienne, M., Du Toit, D. R., Pollard, S., 2011. ARDI: A Co-construction Method for Participatory Modeling in Natural Resources Management. *Ecology and Society*, 16(1). <http://www.jstor.org/stable/26268857>.
- Exnatura (2020). (last accessed march 2023). <https://exnatura.org/tour-dhorizon-des-limites-planetaires/>
- Exadaktylos, F., van den Bergh, J., 2021. Energy-related behaviour and rebound when rationality, self-interest and willpower are limited. *Nat Energy* 6, 1104-1113. <https://doi.org/10.1038/s41560-021-00889-4>
- Fisher, J., 1999. The transition curve paper, Paper presented at the Tenth International Personal Construct Congress, Berlin. <https://www.businessballs.com/change-management/personal-change-stages-john-fisher/>
- Fisher, J., 2012. Process of Personal Transition (last accessed march 2023), <http://www.businessballs.com/freepdfmaterials/fisher-transition-curve-2012bb.pdf> and <http://www.businessballs.com/personalchangeprocess.htm> (free resources with permission of John M Fisher).
- Fressoz, J.-B., Bonneuil, C., 2017. Growth unlimited: The idea of infinite growth from fossil capitalism to green capitalism. In Borowy, I., Schmelzer, M. (Eds). *History of the Future of Economic Growth: Historical Roots of Current Debates on Sustainable Degrowth*. London Routledge, pp. 52-68 <https://doi.org/10.4324/9781315543000>.
- Fressoz, J.B., Locher, F., 2012. Modernity's frail climate: a climate history of environmental reflexivity, *Critical inquiry* 38: 579–98. <https://doi.org/10.1086/664552>.
- Funtowicz, S., Ravetz, J., 1993. Science for the post-normal age, *Futures*, 31(7): 735-755. [https://doi.org/10.1016/0016-3287\(93\)90022-L](https://doi.org/10.1016/0016-3287(93)90022-L).
- Gagnon, B., Leduc, R., Savard, L., 2012. From conventional to a sustainable engineering design process: different shades of sustainability. *Journal of Engineering Design* 23, 1-23. <https://doi.org/10.1080/09544828.2010.516246>.
- Gani, R., Biscans, B., Brunazzi, E., Charpentier, J.C., Drioli, E., Feise, H., Furlong, A., Van Geem, K.M., de Hemptinne, J.C., Kate, A.T., Kontogeorgis, G.M., Manenti, F., Marin, G.B., Mansouri, S.S., Piccione P.M., Pova, A., Rodrigo, M.A., Sarup, B., Sorensen, E., Udugama, I.A., Woodley J.M., 2020. A multi-layered view of chemical and biochemical engineering. *Chem. Eng. Des. Res.* 155, A133-A145. <https://doi.org/10.1016/j.cherd.2020.01.008>.
- Gaudou, B., Sibertin-Blanc, C., Therond, O., Amblard, F., Auda, Y., Arcangeli, J.P., Balestrat, M., Charron-Moirez, M.H., Gondet, E., Hong, Y., Lardy, R., Louail, T., Mayor, E., Panzoli, D., Sauvage, S., Sánchez-Pérez, J.M., Taillandier, P., Van Bai, N., Vavasseur, M., Mazzega, P.. 2013. The MAELIA Multi-Agent Platform for Integrated Analysis of Interactions Between Agricultural Land-Use and Low-Water Management Strategies. In: Alam, S., Parunak, H. (Eds.) *Multi-Agent-Based Simulation XIV. MABS 2013. Lecture Notes in Computer Science*, 8235. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-54783-6_6.

- Geels, F.W. Schott, J., 2007. Typology of sociotechnical transition pathways. *Res. Policy*, 36 (3), 399-417. <https://doi.org/10.1016/j.respol.2007.01.003>.
- Geels, F.W., 2022. Causality and explanation in socio-technical transitions research: Mobilising epistemological insights from the wider social sciences. *Res. Policy*, 51, 104537. <https://doi.org/10.1016/j.respol.2022.104537>.
- Genelot, D., 2017. *Manager dans (et avec) la complexité*. Eyrolles, Dunod. 420 p. ISBN 9782212565553.
- Georgescu-Roegen, N., 1971. *The Entropy Law and the Economic Process*. Harvard University Press. ISBN 9780674281653.
- Gerbaud, V., Teles dos Santos, M., Pandya, N., Aubry, J.M. 2017. Computer aided framework for designing bio-based commodity molecules with enhanced properties. *Chem. Eng. Sci.*, 159, 177-193. <https://doi.org/10.1016/j.ces.2016.04.044>.
- Gerbaud, V., Da Cunha, S., Shcherbakova, N., 2020. A nonequilibrium thermodynamics perspective on nature-inspired chemical engineering processes. *Chem. Eng. Res. Des.*, 154, 316-330. <https://doi.org/10.1016/j.cherd.2019.10.037>.
- Glaserfeld E. von, 2001. The radical constructivist view of science, *Foundations of Science*, special issue on Impact of Radical Constructivism on Science, 6/1-3, 31-43. <https://doi.org/10.1023/A:1011345023932>.
- Heintz, J., Belaud, J.P., Gerbaud, V., 2014. Chemical enterprise model and decision-making framework for sustainable chemical product design. *Computers in Industry*, 65(3), 505-520. <https://doi.org/10.1016/j.compind.2014.01.010>.
- Houngbe, M., Barthe-Delanoe, A.-M., Negny, S., 2018. Towards Virtual Biorefineries. *IFIP Advances in Inform. Comm. Technol.* 534, 571–580. https://doi.org/10.1007/978-3-319-99127-6_49.
- Houngbe, M., Barthe-Delanoe, A.-M., Negny, S., 2019. Servitization of biomass processing for a virtual biorefinery: application to the lignocellulosic biomass in a French local territory. *IFIP Advances in Inform. Comm. Technol.* 568, 477–486. https://doi.org/10.1007/978-3-030-28464-0_41.
- Hukkerikar, A., Kalakul, S., Sarup, B., Young, D., Sin, G., Gani, R., 2012. Estimation of Environment-Related Properties of Chemicals for Design of Sustainable Processes: Development of Group-Contribution(+) (GC(+)) Property Models and Uncertainty Analysis. *Journal of chemical information and modeling*. 52. 2823-2839. <http://dx.doi.org/10.1021/ci300350r>.
- IEA, 2021. *Key World Energy Statistics 2021*, IEA, Paris <https://www.iea.org/reports/key-world-energy-statistics-2021>. (last accessed nov. 2022).
- Eurostat, 2022. *Energy statistics. An overview*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Final_energy_consumption (last accessed march 2023).
- IPBES. 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (Eds.). IPBES secretariat, Bonn, Germany. 56 pages. <https://doi.org/10.5281/zenodo.3553579>
- IPCC, 2021. Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 3–32, <https://doi.org/10.1017/9781009157896.001>.
- IPCC, 2022a. Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Lösschke, V. Möller, A. Okem (Eds.)]. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Lösschke, V. Möller, A. Okem, B. Rama (Eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3-33, <https://doi.org/10.1017/9781009325844.001>.
- IPCC, 2022b. Summary for Policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J.

- Malley, (Eds.]. Cambridge University Press, Cambridge, UK and New York, NY, USA.
<https://doi.org/10.1017/9781009157926.001>
- ISO 19440, 2020. Enterprise modelling and architecture — Constructs for enterprise modelling.
<https://www.iso.org/en/contents/data/standard/07/44/74491.html>.
- Johnson, D.P. 2008. Contemporary sociological theory. An integrated multi-level approach. Springer
 New York. 630 p. ISBN 9780387765228.
- Jouhara, H., Khordehghah, N., Almahmoud, S., Delpéch, B., Chauhan, A., Tassou, S.A., 2018. Waste
 heat recovery technologies and applications Thermal Science and Engineering Progress 6, 2018,
 268-289. <https://doi.org/10.1016/j.tsep.2018.04.017>.
- Karolis VR, Corbetta M, Thiebaut de Schotten M., 2019. The architecture of functional lateralisation
 and its relationship to callosal connectivity in the human brain. Nat. Commun. 10, 1417.
<https://doi.org/10.1038/s41467-019-09344-1>.
- Klatt, K.U., Marquardt, W., 2009. Perspective for process system engineering – personal views from
 academia and industry. *Comput. Chem. Eng.* 33, 536-550.
<https://doi.org/10.1016/j.compchemeng.2008.09.002>.
- Kolb, D.A., 1984. *Experiential Learning Experience as the Source of Learning and Development*.
 Englewood Cliffs, NJ Prentice Hall. ISBN 9780132952613.
- Kubler-Ross, E., 1969. *On Death and Dying*, Routledge/Tavistock Publications, London. 272 p. ISBN
 9780203010495. <https://doi.org/10.4324/9780203010495>.
- Latour, B., 2005. *Reassembling the Social: An Introduction to Actor-Network-Theory*. Oxford: Oxford
 UP. ISBN 9780199256044.
- Legault, L., 2016. Intrinsic and Extrinsic Motivation. in: Zeigler-Hill V., Shackelford T. (Eds)
Encyclopedia of Personality and Individual Differences. Springer, Cham.
https://doi.org/10.1007/978-3-319-28099-8_1139-1.
- Le Moigne, J.L., 2009. L'Intelligence de l'Action appelle l'exercice de la Pensée Complexe.
 Pragmatique et Epistémique sont inséparables. *Synergies Monde* 6, 23-48.
- Le Moigne J.L., 2011. From Jean Piaget to Ernst von Glasersfeld: An epistemological itinerary in
 review. *Constructivist Foundations*, 6(2), 152–156.
- Leybourne, S.A., 2016. Emotionally sustainable change: two frameworks to assist with transition', *Int.*
J. Strategic Change Management, 7(1), 23–42. <https://doi.org/10.1504/IJSCM.2016.079633>.
- Longino, H.E., 1990. *Science as Social Knowledge: Values and Objectivity in Scientific Inquiry*.
 Princeton, NJ: Princeton University Press. 280 p. ISBN 9780691020518.
- Mazzega, P., Therond, O., Debril, T., March, H., Sibertin-Blanc, C., Lardy, R., Sant'ana, D., 2014.
 Critical multi-level governance issues of integrated modelling: An example of low-water
 management in the Adour-Garonne basin (France). *J. Hydrol.*, 519, 2515-2526.
<https://doi.org/10.1016/j.jhydrol.2014.09.043>.
- Millward-Hopkins, J., Steinberger, J.K., Rao, N.D., Oswald, Y., 2020. Providing decent living with
 minimum energy: a global scenario. *Glob. Environ. Change*, 65, 102168,
<https://doi.org/10.1016/j.gloenvcha.2020.102168>.
- Miret, C., Chazara, P., Montastruc, L., Negny, S., Domenech, S., 2016. Design of bioethanol green
 supply chain: Comparison between first and second generation biomass concerning economic,
 environmental and social criteria. *Comput. Chem. Engin.*, 85, 16-35.
<https://doi.org/10.1016/j.compchemeng.2015.10.008>.
- Montuori, A., 2008. Foreword Edgar Morin's path of complexity. In Morin E., 2008. *On Complexity*.
 Hampton Press. pp. i – xlv. Available at <http://archive.mcxapc.org/docs/apc/0901montuori.pdf>. (last
 accessed march 2023).
- Morbach, J., Yang, A., Marquardt, W., 2007. OntoCAPE—A large-scale ontology for chemical process
 engineering. *Engineering Applications of Artificial Intelligence* 20 (2007) 147-161.
<https://doi.org/10.1016/j.engappai.2006.06.010>
- Morin, E., 1992a. *Method. Toward a study of humankind. Volume 1: The Nature of Nature*. Translated
 from *La méthode. I. La Nature de la Nature*, Seuil, Paris, 1977 and introduced by: J.L.R. Bélanger.
 Peter Lang, New York.
- Morin, E., 1992b. From the concept of system to the paradigm of complexity. *Journal of Social and
 Evolutionary Systems*, 4, 371–385. [https://doi.org/10.1016/1061-7361\(92\)90024-8](https://doi.org/10.1016/1061-7361(92)90024-8).
- Morin, E., 2005. Restricted complexity, general complexity. Presented at the Colloquium Intelligence
 de la complexité: Epistemologie et pragmatique, Cerisy-La-Salle, France, June 26th, 2005. Transl.
 from French by C. Gershenson. Available at <https://arxiv.org/abs/cs/0610049> (last accessed march
 2023).
- Morin, E., 2014a. *Introduction à la pensée complexe. Le Seuil, "Points Essais". 160 p. ISBN
 9782757842003. [Originally published in 1990]*

- Morin, E., 2014b. Complex thinking for a complex world – about reductionism, disjunction and systemism. *Systema: Connecting Matter, Life, Culture and Technology*, 2(1), 14–22.
- Mousque, F., Boix, M., Montastruc, L., Domenech, S., Negny, S., 2020. Optimal Design of Eco-Industrial Parks with coupled energy networks addressing Complexity bottleneck through an Interdependence analysis. *Computers & Chemical Engineering*, 138, 106859. <https://doi.org/10.1016/j.compchemeng.2020.106859>.
- Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. *Science* 325, 419–422. <https://doi.org/10.1126/science.1172133>.
- Panu, P., 2020. Anxiety and the ecological crisis: An analysis of eco-anxiety and climate anxiety. *Sustainability (Switzerland)* 12(19), 7836. <https://doi.org/10.3390/su12197836>.
- Pearce D., Barbier E., Markandya A., 1990, *Sustainable Development, Economics and Environment in the Third World*, Earthscan ed., London. 230 p. ISBN 9781134159062.
- Peña-Torres, D., Boix, M., Montastruc, L., 2022. Optimization approaches to design water-energy-food nexus: A literature review. *Comput. Chem. Eng.*, 167, 108025. <https://doi.org/10.1016/j.compchemeng.2022.108025>.
- Piaget, J., 1970. *Psychologie et Epistémologie ; Pour une théorie de la connaissance*, Ed Gonthier, 187 p. Available at https://www.fondationjeanpiaget.ch/fjp/site/textes/VE/JP70_PsychologieEtEpistemologie.pdf (Last accessed march 2023).
- Pörtner, H.O., Scholes, R.J., Agard, J., Archer, E., Arneeth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W.L., Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M. A., Handa, C., Hickler, T., Hoegh-Guldberg, O., Ichii, K., Jacob, U., Insarov, G., Kiessling, W., Leadley, P., Leemans, R., Levin, L., Lim, M., Maharaj, S., Managi, S., Marquet, P. A., McElwee, P., Midgley, G., Oberdorff, T., Obura, D., Osman, E., Pandit, R., Pascual, U., Pires, A. P. F., Popp, A., ReyesGarcía, V., Sankaran, M., Settele, J., Shin, Y. J., Sintayehu, D. W., Smith, P., Steiner, N., Strassburg, B., Sukumar, R., Trisos, C., Val, A.L., Wu, J., Aldrian, E., Parmesan, C., Pichs-Madruga, R., Roberts, D.C., Rogers, A.D., Díaz, S., Fischer, M., Hashimoto, S., Lavorel, S., Wu, N., Ngo, H.T., 2021. IPBES-IPCC co-sponsored workshop report on biodiversity and climate change; IPBES and IPCC. DOI:10.5281/zenodo.4782538.
- Prochaska, J.O., Velicer, W.F., 1997. The transtheoretical model of health behavior change. *Am J Health Promot.* 12(1), 38-48. <https://doi.org/10.4278/0890-1171-12.1.38>.
- Prochaska, J.O., Redding, C.A., Evers, K., 2002. The Transtheoretical Model and Stages of Change. In K. Glanz, B.K. Rimer, F.M. Lewis, (Eds.) *Health Behavior and Health Education: Theory, Research, and Practice* (4th Ed.). Wiley and Sons. 592 p. ISBN 9780787996147. pp. 97-122.
- Pistikopoulos, E.N., Barbosa-Povoa, A., Lee, J.H., Misener, R., Mitsos, A., Reklaitis, G.V., Venkatasubramanian, V., You, F., Gani, R., 2021. Process systems engineering – The generation next? *Comput. Chem. Eng.* 147, 107252. <https://doi.org/10.1016/j.compchemeng.2021.107252>.
- Rao, N.D., Min, J., 2018. Decent living standards: material prerequisites for human wellbeing. *Soc. Indic. Res.*, 138, 225-244, <https://doi.org/10.1007/s11205-017-1650-0>.
- Raworth, K., 2017. A Doughnut for the Anthropocene: humanity's compass in the 21st century. *The Lancet Planetary Health.* 1(2), e48-e49. [https://doi.org/10.1016/S2542-5196\(17\)30028-1](https://doi.org/10.1016/S2542-5196(17)30028-1)
- Ritchie, H., Roser, M., Rosado, P., 2020. Energy. Published online at OurWorldInData.org. Retrieved from: '<https://ourworldindata.org/energy>' [Online Resource] (last accessed march 2023).
- Rossignol, J.Y., 2018. *Complexité. Fondamentaux à l'usage des étudiants et des professionnels*. EDP Sciences. 260 p. ISBN 9782759821945.
- Rossignol, J.Y., 2020. Private communication. Usage with permission from the author.
- Roth, A., Boix, M., Montastruc, L., Gerbaud, V., 2017. Holistic framework for land settlement development project sustainability assessment: comparison of El Hierro Island hydro wind project and Sivens dam project. *Comput. Chem. Eng.*, 100, 153-176. <https://doi.org/10.1016/j.compchemeng.2017.02.002>.
- Roth, A., Pinta, F., Negny, S., Montastruc, L., 2021. Importing participatory practices of the socio-environmental systems community to the process system engineering community: an application to supply chain. *Comput. Chem. Eng.* 155, 107530. <https://doi.org/10.1016/j.compchemeng.2021.107530>.
- Salas, D., Van, K.C., Aussel, D., Montastruc ; L., 2020. Optimal design of exchange networks with blind inputs and its application to Eco-Industrial parks. *Comput. Chem. Eng.* 143(2):107053. <https://doi.org/10.1016/j.compchemeng.2020.107053>.
- Sibertin-Blanc, C., Roggero, P., Adreit, F., Baldet, B., Chapron, P., el-Gemayel, J., Mailliard, M., Sandri, S.A., 2013. SocLab: A Framework for the Modeling, Simulation and Analysis of Power in Social Organizations. *J. Artif. Soc. Soc. Simul.*, 16. <https://doi.org/10.18564/jasss.2278>.

- Simon, H., 1977. The new science of management decision. Revised Ed. Englewood Cliffs, N.J.: Prentice-Hall. 175 p. ISBN 978 0136161448.
- Simon, H., 1969. The Sciences of the Artificial. Cambridge MIT Press, Cambridge. ISBN 9780262690232.
- Simon, C., Etienne, M., 2010. A companion modeling approach applied to forest management planning. *Environ. Model. Softw.*, 25, 1371-1384, <https://doi.org/10.1016/j.envsoft.2009.09.004>
- Tian, Y., Demirel, S.E., Hasan, M.M.F., Pistikopoulos, E.N., 2018. An overview of process systems engineering approaches for process intensification: State of the art. *Chem. Engineer. Process. - Process Intensification*, 133, 160-210. <https://doi.org/10.1016/j.cep.2018.07.014>.
- UN, 2015. United Nation Sustainable Goals. <https://sdgs.un.org/goals>.
- Vogel, J., Steinberger, J.K., O'Neill, D.W., Lamb, W.F., Krishnakumar, J., 2021. Socio-economic conditions for satisfying human needs at low energy use: An international analysis of social provisioning. *Global Environmental Change*, 69, 102287. <https://doi.org/10.1016/j.gloenvcha.2021.102287>.
- Wang-Erlandsson, L., Tobian, A., van der Ent, R. J., Fetzer, I., te Wierik, S., Porkka, M., Staal, A., Jaramillo, F., Dahlmann, H., Singh, C., Greve, P., Gerten, D., Keys, P.W., Gleeson, T, Cornell, S. E., Steffen, W., Bai, X., Rockström, J., (2022). Towards a green water planetary boundary. *Nature Reviews Earth & Environment*. <https://doi.org/10.1038/s43017-022-00287-8>
- Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, 68, 825-833. <https://doi.org/10.1016/j.rser.2016.09.123>.
- Weber, T., 2016. Modular Plants. Flexible chemical production by modularization and standardization – status quo and future trends. Dechema. ISBN 3897461912. https://dechema.de/dechema_media/modularplants-p-20002425.pdf (last accessed march 2023).
- Zhou, L., Zhang, C., Karimi, I.A., Kraft, M., 2018. An ontology framework towards decentralized information management for eco-industrial parks. *Comput. Chem. Eng.* 118, 49-63. <https://doi.org/10.1016/j.compchemeng.2018.07.010>.