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Between Innovation in Process Engineering and Creativity

Progress is not an illusion, it happens, but it is slow and invariably disappointing. (Orwell 1949)

Creation consists of both shaping a substance and giving substance to a form. (Rappoport cited in van der Leuw 1994)

To invent something new, we determine the necessary scientific level and arrive at fundamental research to find a solution to a technical problem. (Gille 1978)

Technology does not form an independent system like the Universe; it exists only as part of human culture. (Mumford 2010)

The development of technological changes [is] like a succession of fairly diffuse periods of acceleration, rather than a sequence of discrete moments of inventive insight. This trend becomes all the more marked if we move from the process of invention to the process or processes of innovation development, i.e. to those in which a technological innovation is brought to the state of a workable prototype. (Fox 1994)

The development of the curriculum in chemical engineering has benefited in the past from the tension between, on the one hand, imparting to the students a good understanding of the sciences underpinning our discipline and, on the other, the perceived need to help aspiring engineers to develop and enhance the skills necessary to practice as an effective professional. (Perkins 2002)

> One of the difficulties of the creative process is to fine-tune the times of divergence and convergence, to nourish the process, to open them up and reopen them permanently, to give ideas time to mature, while ensuring that the project succeeds, which implies making choices among the proposals that have emerged. (Paris 2010)

> The center of gravity of existence shifts towards the future and at the same time modifies the relationship to the present. (Meyer quoted by Hottois 2018)

> Creative thinking is one of the main keys to success in a globalized economy, which is essential 'to meet the challenges facing Europe'. Creativity is presented as 'the engine of innovation and the essential factor for the development of personal, professional, entrepreneurial and social skills and the well-being of all individuals in society'. (EU 2008)

> It is no longer the Man of Genius who discovers something [...], it is precisely this anonymous addition of the conditions of the leap forward. When all the conditions are met, there is only a minimal intervention by a Man that produces significant progress. (Ellul 2008)

> The philosophical chemist of 70 years ago was a creator quite disconcerted by his creations. The other chemists, the hard practitioners, were mechanics in their laboratory procedures. In a sense, they put atoms together in a test tube – so to speak – and waited to see what would happen. (Malisoff 1941)

> The more a commercial company gets media coverage, the more it must devote a significant part of its activity to the production of demand, by investing ever greater resources in attention-grabbing devices. (Citton 2014)

> Science is what the father teaches his son. Technology is what a son teaches his father. (Serres cited from Brabandère 2017b)

> The more perfect the technical organization that surrounds Man, the more it must be reduced to a succession of simple functions. (Jüngers 2018)

NOTE.– This chapter, applicable to fields other than process engineering (PE), introduces a number of concepts, or more simply reminders of certain concepts, that will be used during the book. The reader, who has mastered the aspects of progress, creativity, innovation, convergence, interdisciplinarity, boundary object, etc., can engage in reading the chapters more specifically dedicated to the theme of the book.

Dissimilar from the notion of progress, the notion of change has emerged over the past 30 years as a positive and irreplaceable value. Although the notion of change is already old, it is as an ideology that it is imposed today, strongly linked to the context of immediacy, of creation, if at all possible, of a network on which the so-called knowledge economy is based. The idea of permanent change seems to have become a new paradigm. It is obvious that the current overexponential growth of artificial intelligence (AI) associated with more than heavy trends (climate change, overpopulation, etc.) is the subject of attention for many authors (see chapters devoted to the prospective part and AI).

From a technological point of view, what emerges from these two chapters are developing fields such as artificial intelligence, information and communication technologies, quantum computing, augmented reality, transhumanism, synthetic biology, intelligent materials with a pinch of energies and “sensitive” materials. The use of basic technologies (such as energy, processes) is relegated to the sustainable development aspects, at best. Everything therefore seems conceivable in a dream (or nightmare) world, without taking into account the possible, with one problem to deal with, however; it is a society that will see its jobs lost, its qualifications lost, but let us not doubt it, with the opportunity to participate in a great adventure! (see, for example, Al-Khalili 2018).

Among the slogans associated with the future of our consumerist society, we could have found expressions such as: “Data is the new oil”; “Artificial intelligence is the new electricity” and “Internet of Things is the new nervous system”; “Technology is exponential”, etc. (Leonhard 2018). Everything is possible: “We just need to agree on what we want.” There are only social and some environmental reserves for the future that prepares us for transhumanism, augmented humankind, and digital immortality. Affluence is allowed especially if you have some ideas, if possible, disruptive. Fortunately, some have a position closer to reality and rely on knowledge of reality and what is possible to make realistic forecasts (even if they remain deeply technological). But, between the inertia of traditional processes and the explosion of digital technologies, there is undoubtedly a need to define areas of innovation that could make a link between “tradition and modernity” in the context of control, under constraint, of the transformation of matter and energy.

“What is the point of supporting innovation if it is to maintain divides? If we do nothing, we are heading towards a world where robotic lifestyle enthusiasts and those who take refuge in Corrèze, to escape Big Brother, will definitely move away. The future is written too quickly, technology remains without utopia while we all aspire to live as humans in the world that is coming. We are all concerned" (Pène 2018). Indeed, the disruptions brought about by the confluence of all new technologies are transforming the production and distribution of goods and services. This situation should be reflected in the skills of future workers, the employment or even the disappearance of traditional labor, productivity and the inhomogeneous distribution of income. A radical transformation of business models, skills systems and public policies is therefore to be expected. Overall, with the target being gross domestic product, few people are really concerned about the struggle to reduce CO_2 emissions and develop a greener (and less fossil fuel consuming) economy (Daniel 2018; Mallard 2018).

For Daniel, "the academic background is called upon to play an increasingly less important role, first because its content is constantly shrinking, and second because the imagination that drives innovation, even if it is based on experiences and references, is only partially based on transmitted knowledge. In fact, the current 'disruption' must be interpreted as the transition from a hierarchical society where everyone knew their place to a society in motion where everyone will invent their place."

True or false, however, it seems important in a world that is moving fast in certain technological fields (and which consequently attracts the best brains), to find robust solutions based on science – especially processes. Let us remember that this world must find solutions to the major problems of the transformation of matter under particularly constrained environmental conditions with the Damocles sword of global warming (Fischer *et al.* 2018). This chapter, by re-examining the principles of creativity, divergent thinking, incremental innovation and disruption, will propose ways to explore, in which process engineering must find a prominent place.

Incremental innovation

Rather, incremental innovators act from the perspective of developing an economic market system, producing goods, or services, in order to create value. They are management engineers who master knowledge, techniques and processes, who possess multiple skills or know how to bring them together (multidisciplinary), often cross-functional. Radical or disruptive innovators are generally unpredictable in the emergence of new ideas and their effects. Their evolutionary trajectories are unexpected, with risk-taking and failures. "Their capacity for innovation is linked to their personality, to the events they have experienced and to which they have reacted in a way that is specific to them. Their status as innovators stems directly from the evolution of their identity, with which they merge" (Liu 2018).

Product and/or process innovations

Technological product and/or process innovations cover technologically new products and/or processes, as well as significant technological improvements achieved, i.e.

introduced onto the market or used in production. Innovations in this general framework involve several types of activity: scientific research, technological research, organization, expertise, finance, trade, etc. Generally, research (let alone disciplinary training) is rarely a source of innovative ideas, but a means of solving problems. The existence of Western scientific research expertise, a real "facility" in the English language sense, is therefore useful for promoting new ideas, but does not constitute the deep core of an operation where innovation is at work. Disruption is therefore necessary to go beyond incremental activities.

Innovations and training

Doctoral training, which generally consists of training through research via in-depth study, is not considered to be optimized for jobs in industry. This link, which could exist between academic staff and industry, therefore only very rarely occurs through this route. For example, an academic may choose to look for a job related to a particular topic of interest, while a corporate research team is guided by market demands.

The cultural mismatch between university and corporate research is such that there is an entire industry in the United States dedicated to helping graduates move into the private sector. In addition, a doctoral program comes at a high cost for years that could prove highly productive in the labor market (IDSFP 2012).

There is therefore reason to believe that doctoral studies are not ideal for the executives needed by the industry. One possible solution would be to offer a doctoral program more oriented towards industry (the case in France of CIFRE (Industrial Agreements for Research Training) grants and theses carried out via the ANR (National Research Agency) as part of industrial chairs).

According to Bloomberg (Smith 2019), companies may want to think before requesting doctoral students to carry out research mandates within their company. Holders of a master's degree or even a bachelor's degree may also be talented and could acquire more advanced research skills by working in the company, rather than acquiring these specialized skills before hiring (academic training?).

Box 1.1. *Difficulties in the links between academic research and industrial innovation*

1.1. Innovations and process engineering

> I started to think about what drives innovation and what its social meaning might be. The next step was to think: innovators are jumping into the unknown. This led me to believe that it was also a source of pleasure and involvement for workers. (Phelps 2017a)

> Researchers are often like the drunk man who looks for his keys under a lamppost: because that's where there is light. Often, the research will be in vain, until such time as a necessity arises for him to look elsewhere. It is easy to understand why companies have an indolent attitude towards certain research problems. (Le Nouvel Économiste 2017)

Figure 1.1 raises the question of future plant-oriented research in relation to "classical" research in the field of process engineering. On the University of Lorraine website, there are 846 publications in the first case, compared to more than 2,400,000 in "Chemical Engineering". The divergent vision of a future does not seem to be a major priority for researchers in the field. However, as shown in this figure, there is a net increase in the number of scientific papers on the two linked themes of "chemical engineering" and "factory of the future", which are quite linear. It is therefore possible to consider that research work that concerns guidance, the formulation of PE questions, can take three generic forms such as: exploration, problem solving, rationalization/understanding (Gastaldi and Midler 2005).

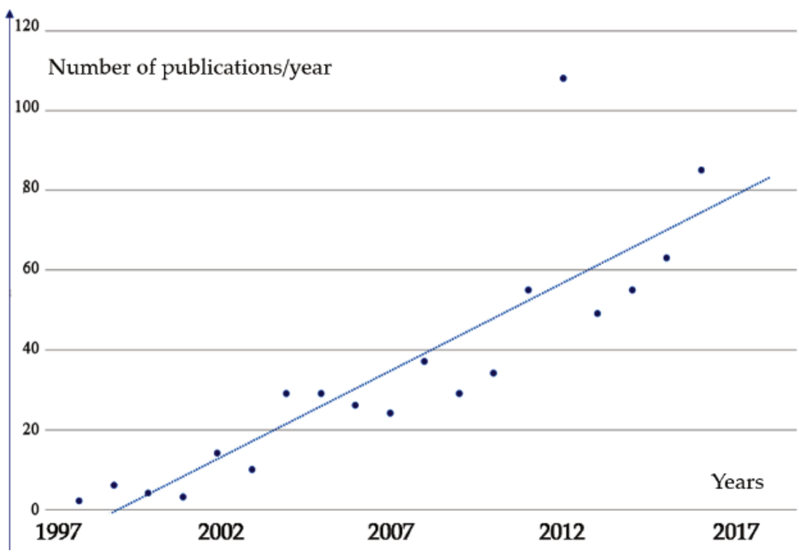

Figure 1.1. *Evolution of the number of publications on the two linked themes "chemical engineering" and "factory of the future"*

Public research laboratories involved in the transformation of matter and energy have their longstanding origins (after the Second World War) in successful local or national socio-economic activities. In a national territory where industrial activity is currently in decline (but a slight decline in the field of chemistry), there is an obligation to explore a “disruptive” transformative power on the part of the world of research and university training, by participating in support for economic redeployment (provided that the academic world, including that of engineering schools, is committed to this desire to effectively support the creation of economic value). This is authorized by the quality and quantity of public research and training participants who can engage in the development of innovative actions (in relation to the social body in a reconquest of economic performance, currently in decline, in France, with the exploration of new markets). It is also important not to miss, as has been the case with biotechnologies, the Clean-Techs, which carry out activities that enable social progress and employment in a difficult and responsible context of sustainable development.

Most technology SMEs invest more in product development than in process development. Overall, two-thirds of the amount invested in R&D are currently devoted to product development, leaving a final third of the total investment for process development. In addition, one-third of companies would completely abandon process development in favor of investing solely in product development. This situation is naturally different for large companies with the necessary skills within them (or under partnership agreements with external research laboratories). With a high critical mass and whose scientific excellence is considered highly satisfactory, the work of these units, which mainly focus on the sciences of chemical and process engineering, is mainly disciplinary (but with openings to other disciplines).

Martin (2019), proposes four areas of support for innovation that correspond to the following themes:

– curiosity (the grass is always greener on the other side);

– the need to be in the race or fear of no longer being in it;

– the desire to create wealth (for oneself and for society) – see business angels, etc.;

– the creation of meaning, feeding the first three items.

In training and in scientific and technological research, involving more divergent thinking, it is proposed to reflect in this chapter on how to engage in the development of scientific creativity by associating, in interdisciplinary approaches, different partners for economic development centered on these aspects as a sustainable issue by society. The aim is to participate in this adventure in a subsidiary way by examining how to manage and develop the creative capacities of the research, innovation and economic communities, etc., based on the pooling of currently too disjointed knowledge.

Koestler (1976) introduced the concept of bisociation, illustrated in Figure 1.2. For him, creativity is based on at least two coherent, but mutually incompatible, frameworks of thought (Cohendet 2016). It is in the association between these two normally separate domains that the idea emerges.

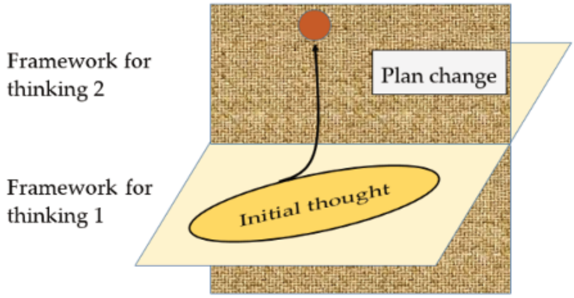

Figure 1.2. *Bisociation. For a color version of this figure, see www.iste.co.uk/schaer/process3.zip*

Box 1.2. *A path for disruption*

It is therefore necessary to set the objective of stimulating innovation for concerted economic development, the creation of start-ups, the training of future managers of the company, covering – in an integrated and multidisciplinary way – the complete lifecycle of material systems from chemical synthesis, development and implementation processes to recycling processes, including the control of these processes, as well as the characterization of products and the study of their properties of use (and if necessary, to bring out the scientific and technical barriers to blow up). The need to address performance in its environmental, economic, technical, social, and even aesthetic dimensions is now universally accepted and is integrated into the project. We speak in English of lifecycle engineering. The best product for a given need will be one that can be obtained through low-cost, clean processes and can be easily inspected, replaced and recycled while allowing the least polluting use possible. They can be green, durable, lightweight, recyclable, degradable, non-toxic, clean, produced by eco-efficient, economical processes – some of which require upstream research.

The implementation of standards, benchmarks or indicators corresponds to representations of an organized system, relatively sustainable, of material or non-physical production, more or less standardized (with the classic risk of oversimplification that does not make it possible to take into account the interdependencies and distributive effects of scientific activities: employment, balance of payments, influence and attractiveness, etc.). This may mean that in

France, but more broadly in the developed West, there exists a dominant form of "legitimate" thought that could be imposed as a revealed and unquestionable truth. There is then a risk of confining the questions and scruples of those on the ground who could be rejected, because they are considered more or less heretical. On these "modeling" bases, necessarily reductive, the management criteria are always simpler than the system itself in its complexity, especially if we associate humans (and how in scientific research to do otherwise) and the instability linked to new scientific developments, to a more open competitive world than before. For process industries, regulatory, environmental and social factors must be taken into account, as well as managing changes in research structures. This situation leads to concern about the tension between adaptation to constraints (deep relevance, creativity, competition) and coherence (incremental deepening activities and regulatory obligations).

Idea generation

Gable *et al*. (2019) showed, in experiments with about 100 intellectuals (physics researchers and writers) that 20% of the most important ideas appeared when people were thinking about something else.

How to stimulate creativity

In a recent article, Wu *et al*. (2019) showed that the size of research teams has a strong influence on creativity and flexibility. However, the trend in recent years has been a decrease in the number of small research teams and solitary researchers or inventors. According to the authors of the study, there are signs that funding agencies tend to prefer large research teams to small ones, even with equal skills. Less support for small teams may slow the development of scientific and technological innovations that are at the heart of economic growth. But it seems that the diversity of members in large teams would allow more complex problems to be addressed, while small research teams would better understand the important innovations of the coming years. Small is beautiful!

Box 1.3. *Conditions for the development of creativity*

1.2. Creativity

> It is not necessary to read too much, so that the mind does not get used to the substitute and unlearn the same thing; that is, so that it does not get used to the paths already beaten and that the presence of a foreign thought does not move it away from its own. (Schopenhauer 2014)
>
> The main difficulty [...] is to try to imagine something that you have never seen, that fits into every detail of what has already been seen

> and yet differs from what has already been thought – this, while making a proposal that is not vague, but precise. (Feynman 1998)

> The mystery of the creative moment and the irrationality of the real process of technical creation are preserved by the identification of the inventor with an exceptional being, dedicated to intercession and who therefore deserves heroic glory, that of the intermediaries between men and gods. (Frizot 1997)

For Techno-Science (2017), creativity is almost impossible to define and therefore to measure (even if there are tests such as (Creative Types 2019)). The authors of the report consider creativity "as an active process, rather than as a destination or final product where value is given by many foreign cultural and social influences". Creativity, innovation and initiative are psychological processes that facilitate the transformation of individual professional roles, teams and organizations into what is desirable (Rank *et al.* 2004).

According to the classical vision of creativity founded by Guilford (1956) on the dichotomous principle of divergence/convergence, the creative process begins with the recognition of a problem. From there, a process of divergence begins and finally ends, by convergence, in a new solution to the problem. Creativity can be defined as the ability to achieve an original (new) result and adapted to the context (Kirschner 2018; Viard 2018), with a performative dimension in the creative process (Ingold 2010). Rather, it is homelessness (dynamic aspect) and not an iteration of an idea associated with a decision to act in a given direction based on emotional or even affective aspects (Goleman 1996). "If an idea does not seem absurd at first, then there is no hope that it will become something" (Einstein, quoted by Coaching Qapa 2017), or "what matters is not what to think, but how to think" (de Brabandère and Gomez 2017).

> Converging technologies (CTs) refer to the convergence towards a common goal of discoveries and technologies in basic science and technology: CTs are diffusing technologies and knowledge systems that complement each other in the pursuit of a shared objective. Together or in isolation, NBIC technologies can contribute to this convergence. (Nordmann 2004)

"Creative rationality is the ability of designers to bring seemingly distinct worlds closer together, to find connections where they did not exist, to see what is happening outside a profession or specialization, to be open to everything. It is a thought of the relationship rather than of substance, it is the thought of adventure which, by the moving and complex order of the knowledge it provides, invites us to face novelty and the unexpected. This transformative relationship, made up of tinkering, adaptation to circumstances and the unexpected, forgetting pre-established models and ingenuity, forces us, in any case, to invent a specific mode of transmission, which is not in the order of teaching abstract knowledge but of learning ingenious know-how" (Faucheux and Forest 2011). But for Nagel *et al.* (2018), being creative could have, in part, genetic origins.

"The other concern is the contradiction of clocks: political, economic, social and environmental time is not set at the same time. The time of politics (the time of elections and power games), the time of financiers (of the highest possible profitability) and especially of the media (the ephemeral snapshot of current events), are much too short compared to the long term of educational, socio-organizational and environmental changes" (Godet 2010). How can we try to anticipate in this constrained space? By taking the problem from the beginning, it already seems necessary to reflect on the emergence of happy ideas, through divergent thinking and creativity. One of the means proposed by Jordan *et al.* (2018) is to use science fiction (normally carried out without constraint) through what is called "science fiction prototyping". Others rely on makers or hackers (Chatelain 2018) or more cynically, wait for start-ups to develop before buying them back (Marion 2018). "Creativity is intelligence having fun," said Albert Einstein; in fact, we must adopt agile methods, without predefined roles, with active and serene listening to other partners to express our ideas (Jouteau 2018). It is on this type of log that MIT (2017) has defined its strategy by supporting creativity. However, as Chu *et al.* (2004) point out, creativity in itself is only one element – certainly essential since it defines a beginning – of the innovation process that will be based on the known.

Creativity describes the ability of an individual or group to imagine or build and implement a new concept, a new object, or rather to discover an original solution to a problem. It can be approached as a psychological or psychosociological process by which one or more people rely on divergent thinking by associating specific objects, concepts and situations in an original way. "Bisociating [see Koestler] is about combining for the first time two ideas, two objects or two universes that have never been combined" (by Brabandère and Gomez 2017). It is likely to bring about a change in the perception, use, or materiality of a given public. It can also call into question serendipity; the ability to bring out a disruption while looking for something else. It is assessed by response times, production speed, quantity of solutions, effectiveness, efficiency and originality (defined as the opposite of banality). Also at issue is the disruption defined by Gomez (2017) as "a way of producing the same thing, but according to a different process". For Catellin (2014), the success of this word is a symptom of the unease of researchers confronted with the evolution of the system. "Today, this word takes on the value of a concept, essential to express the importance of freedom, subjectivity and dialogue in discovery and to defend a humanist conception of knowledge."

All this is true, but how do you become creative? How creative are we? Livio (2017) gives us some indications that our brain needs a promise of pleasure, a certain amount of reward, whether it is an addiction (sport, alcohol, drugs, always being right (Burton 2010)) or to bring out ideas. One difference is the habituation in the first case, which requires an increase in "doses" so that the feeling of satisfaction is maintained. For this author, the brain would seek to maximize the emotional states related to the feeling of success, without going through rational reasoning. Creativity seems to present itself with emotion. It is only after the happy idea, supported more or less intensely by rigor, that the final reward could emerge.

According to the classic vision of creativity founded by Guilford (1957) on the dichotomous principle of divergence/convergence, the creative process begins with the recognition of a problem. From there, a process of divergence emerges and finally ends, through convergence, in a new solution to the problem (see University Governance and Creativity 2018). But, at the same time, by bringing knowledge and imagination together, should we owe it to the example of Einstein, who wrote "imagination is more important than knowledge", to be satisfied with an innate capacity for some, a fantasy base oriented towards satisfying societal needs, without delving into certain disciplinary fields? This is basically an issue of the book which raises the question accumulated training without its obvious interest being awarded in order to achieve an operational end of utility and relevance for the Process Engineer. For them, learning has been defined as initiating the resolution of problems in the form of "trial and error" or "conjecture and refutation" (Berten 1999). With the generic idea of producing top technicians adapted to problem solving (Arrow 1962; Von Hippel 1993), learning is subordinated to effective training based on modeling concepts and the most in-depth knowledge possible of the existing system (with limitations linked to the short training time).

This search for efficiency can conflict with the need for creativity, even if it is about learning to learn because it is important to be able to be involved in a fault-tolerant environment, with the opportunity to review ideas and confront them with reality (Winnicott 1975). "To consider the environment as a cognitive, error-tolerant landscape is to highlight the versatile resources available to the subject, but which become significant insofar as they are marked by floating and transversal intentionality" (Berten 1999). At best, in training conducted in too rigid a framework, it will just be possible to practice scholarly DIY (in the sense of Lévi-Strauss 1990), in a closed universe, by making arrangements contingent with the "means at hand". Creativity is therefore naturally associated with a certain freedom. "All these heterogeneous objects that constitute his treasure, he questions them to understand what each of them could 'mean', thus contributing to the definition of a set to be realized, but which will finally differ from the instrumental set only by the internal disposition of the parts" (Lévi-Strauss 1990).

On this aspect, Hunyadi (2010) wrote: “Imagination would no longer be a simple call to explore possibilities that are fictitiously unprecedented, but a new way of conceiving the very relationship between theory and practice [...]. This means that it is no longer knowledge, but imagination that guides action. However, until now, imagination has been considered a power of fiction, far from all practices. This is why it has often been the victim of a kind of ontological discredit, because it has been dedicated to what is not, whether in the mode of fiction, unreality, fantasy, possibility or utopia, so it was far from all true ambitions.” Between the need to change to stay in the race and efficient conservatism, the mass is therefore not said.

Thus, perhaps it is necessary, at least in part, to get closer to hackers (see, for example, St Leger 2014) who, in IT, engage in DIY, sharing (collective intelligence), creativity, all validated by the result (Dutertre 2010). However, costs and times are very different from those involved in industrial processes, where a design error can be costly for the company, especially if it leads to accidents (e.g. the problem of a heavily degraded image). But, as Rugarcia *et al.* (2000) point out, an education system is closely linked to the fabric of the society in which it operates.

On these bases of renewal, the imagination that must result from the coupling of person and training is either:

– reproductive: analysis of the present, of its perception;

– imitative (past): linked to memorization and therefore to scientific, technical, and cultural achievements (some form of conservatism);

– prefigurative (future): creation of images before the actual presence of the object, relationship of the real with what could exist, etc.

It is understandable that there may be a correlation between the capacity for imagination and the capacity for divergence, intervening in creativity and the ability to prevent “thinking in circles”. Weber (1963) raised the question of the decision to cross unknown frontiers by writing: “The Man of action is the one who, in a singular and unique context, chooses according to his values and introduces a new fact into the network of determinism. The consequences of the decision are not strictly predictable even if the economic situation is unique. There is only a succession of events that can be repeated, in other words, reports that have emerged from the concrete and have been elevated to a certain degree of generality. Nevertheless, a reasonable decision requires that all the abstract knowledge available be applied to the situation, not to eliminate, but to reduce and isolate the element of unpredictable singularity.”

Without wanting to go too far on this subject in this chapter, we will come back to these aspects that have been made more and more necessary in a world that is moving much faster and differently than in the previous century (Clark 1971). As a reminder, divergent thinking searches in several directions, invents as many answers as possible, seeks new solutions, unexpected and sometimes risky answers. Indeed, reality has many points of view. Learning processes are therefore far from linear and the roots that generate knowledge are multiple (Guilford 1957). It competes or makes a significant contribution with deductive thinking, it inaugurates: “not everything that would be virtually possible to say is said […]. It is on this point that we call for creativity and intuitive audacity in bringing people together and associations in order to broaden the virtualities of the conceivable” (Stengers and Schlanger 1991).

Figure 1.3, based on the work of Buys and Mulder (2014) and Loch (2017) on the one hand, Jahnke *et al*. (2017); Rank *et al.* (2004); Mitchell and Walinga (2017) and Iddriss (2017) on the other hand, in conjunction with the various elements presented in these sections, allows a number of personal, interpersonal, and external factors to be brought into creativity. This analysis (difficult to quantify) can give some indication of an individual’s potential to be creative. The use of games and competition in groups chosen to be heterogeneous can participate in this analysis which, whatever we do, has a qualitative aspect.

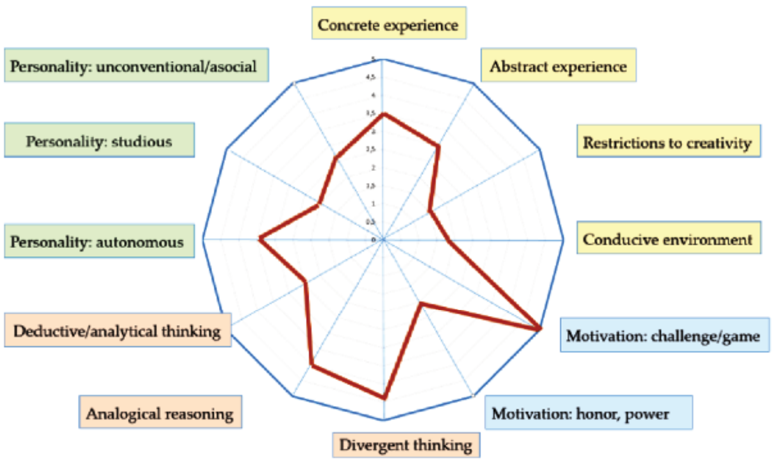

Figure 1.3. *Appreciative mapping of creativity in a person. For a color version of this figure, see www.iste.co.uk/schaer/process3.zip*

The originality of von Hippel’s (2005) reasoning shows that “incongruity” may be sufficient to give rise to an innovation likely to have, as it spreads, global consequences that are disproportionate to its starting point. This may be due to the fortuitous rapprochement between a use and a know-how that seemed to have no connection with it before the innovation (Boutet 2010).

This example, recreated by the authors, is useful for several reasons:

– at the beginning of the process, the subversive function of utopia and the strength of the idea makes it possible to explore a certain range of possibilities; simulations take on all their interest here (Varenne 2004); the constraints linked to the knowledge of reality and the possible appearance after;

– objective-based research is based on a deliberate action to transform the ways in which scientific knowledge is accessed and, in the case of 3D printing, the ways in which it is produced and/or manufactured (Hugon and Seibel 1988);

– it is then that a real alternative to existing technical devices is built within the framework of real projects. “Whereas in the previous phase, model meant tension towards an ideal, it becomes the formalized diagram of a technique to be realized, the project that must be built” (Flichy 2001);

– by voluntarily relying on intellectual, technological and professional opportunities, in a transversal way, located at the boundary of disciplinary fields and traditional professions, while taking into account reality and the possible, it is necessary to find ways of acting that go beyond the simple juxtaposition of knowledge, to move beyond narrow expertise to generate new ideas; in this unstable context, the space of responsibility must be large (risk-taking), but at the same time, the space of freedom must be strengthened and valued if the hierarchy supports constructive spaces of transgression (Shinn 2000);

– the example shows the importance of the presence in the action of minds unprepared or relatively disjointed from it with the risk that they constitute obstacles to dynamics; their added value probably lies in an ability to exploit reasoning by analogy; the consideration by a project group of notions of disruptions, new temporalities, irreversibility, creative disorder or interaction must lead them to consult enlightened observers, disruptive actors called “fuzzy thinkers”, few in number (Foucart 2011, see also Knack 2017);

– the difficulty is to find the right disruptors who, combined with the current action, can contribute to the operation; apparently there are not many rules;

– knowledge resources are distributed among many actors where the degree of complexity of innovation determines the extent of heterogeneity of knowledge (van de Ven 2005; Chesbrough *et al.* 2006; Boland *et al.* 2007; van de Ven *et al.* 2008; Yoo *et al.* 2008, 2009);

– in the context of disjointed populations, in terms of diverse knowledge and appetite for different forms of scholarly, technological and secular knowledge, there must be room for debates based on the known and considering heuristic approaches that can exploit, for example, fuzzy decision-making principles (Rosental 1998; Piette 2011; Openclassroom 2013; Yang *et al.* 2016). By showing that it is possible to integrate knowledge from various sources, it may be possible to propose different solutions and help to make the object of the research a reality, particularly in emerging situations (in the case of so-called academic research);

– the mission is to achieve a reasonable, optimal construction that best meets the objective in a co-construction context; the technological lock then structures the operation;

– in research circles, it is necessary to accept the imperfect criteria that are often linked to "doing with one's immediate environment", or even with colleagues already known, from related disciplines. This situation of constraints naturally raises the question of flexible organizational choices that are adapted to changing practices, but also to a change in the scientific and technological cultures of staff engaged in original couplings, where the instrument has an essential place in the dynamics and originality of research;

– the coordination and motivation of professionals outside any clear organizational framework are key elements; participatory approaches have yet to be built in that they must involve as many people as possible and require responsible bases for discussion between stakeholders;

– the existence of collective training, the heart of the action, allows strong associations with potential users.

Heading towards slow science?

For many, a return to the fundamentals of creative scientific research should be required. The activity must be made of patience, perseverance, rigor, possible forks, questioning and serendipity, unpublished failures, etc. The standard criteria for measuring pseudo-excellence are therefore not very adequate to judge this quest, which leads to a profusion of publications whose originality and conceptual investment can be criticized (originality, mediocrity, scientific scope).

In an attempt to combat these trends, which pose risks to the legitimacy of the research community, scientists propose to deconstruct this inadequate system by developing the idea of "dis-excellence" and "alter-excellence". Actions have been taken and measures put in place, including the San Francisco Declaration (2013), which calls into question the impact factors. Berlin has created the Slow-Science Institute with its Slow Science Manifesto[1], an advocacy campaign to ensure that the time required for research is respected. All these developments are aimed at a different definition of excellence based on the researcher's love of scientific work, their feeling of freedom and autonomy, their desire to understand, their taste for "good work" and the satisfaction they derive from it. The evaluation system should then value quality over quantity, support intellectual risk-taking and take into account the pace of scientific production. It is a way of respecting what Virilio wrote in 2010: "with speed we lose the sense of lateralization,

1 Available at: http://slow-science.org/.

which is an element of infirmity of being in the world, of its richness, its relief, its depth of field."

Creativity thresholds?

Depending on the degree of creativity on a given subject in a scientific publication, for example, rapporteurs, often without ill will, may tend to see it as an intrusion into their field (they should have thought of it), which may lead to desires to reject the article. If this disruption is modest and cannot overshadow anyone (including the reporter(s)), the article, as long as its content respects the rules of the discipline, can be accepted. If the proposal is a real breakthrough, there may be misunderstanding on the part of the reviewers of the article, a desire to block it, etc. There is probably no strict rule, but it takes a good dose of will on the part of the creative to get their message across (with, otherwise, possible aspects of self-censorship (Duriez 2019)). Between insignificance and a clear break (which will be followed later by some echo), there may be a threshold (Gaucherel 2013).

Natural inertia

Multiple strategies help the brain to compensate for uncertainty. A "Bayesian integration" or probability-based model would be used by the brain to process potentially conflicting data and weight them according to their reliability and perceived credibility, taking into account past experiences (Remington *et al.* 2018).

Constrained by training

In these studies on creative subjects, audiences with more "scientific and technological" backgrounds seem to be the most classical, because they are trained, while profiles such as "human and social sciences" or "designers" seem to have greater capacities to explore new territories (Caillez 2013). Perhaps it is in our interest to associate them?

Procrastination

"Procrastination is also a way to explore what you think about a subject. A well-considered decision, a long-term revised work, an idea that is born and expands slowly but surely. It is the best and wisest thing.... The little time you have left to complete what you need to do will be a time of hyper-concentration on a single task." (Rocci 2019)

Box 1.4. *Considerations regarding creativity*

Being a little creative implies being able to think "outside the box" (divergent thinking); this is probably true, but it is difficult to know if this is learned, probably by boredom or coercion forcing the waking dream. Then comes the question of the happy idea, the result of this thought that will emerge, which will only become tangible when it is confronted with reality and the possible (otherwise, it will quickly be buried, so that it is no longer discussed). This means that in association with this construct, it is possible, even necessary to dare. If you are very “learned”, it may seem difficult – if only because of peer judgment – to take risks. This is probably why many people consider that you have to be young to be creative, whereas in the end, it is enough to have a little common sense and average competence (or incompetence) on a subject.

This element of incompleteness of knowledge seems important to underline, because it allows the exploration, at least partially, of other disciplines, which allows on the one hand, the renewal of the creative experience even if it means continuing the learning, to play on some elements previously disjointed to associate them in an original way, on the other hand. This situation corresponds to a paradoxical state of mind that is both vagrant and superficial, associated with the possibility of dreams that require scientific and technological knowledge that is sufficiently robust or consistent enough to move forward. This consideration is shown in Figure 1.4, where a proposal is made between “café du commerce” and deepening disciplinary knowledge.

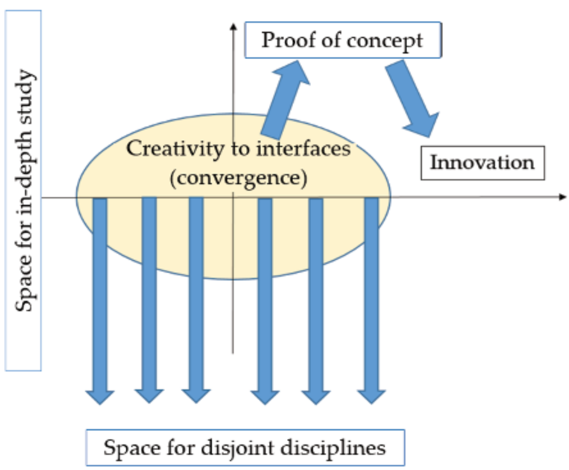

Figure 1.4. *Creation at interfaces*

1.2.1. *Creativity and pedagogy*

> Our natural tendency is to imagine and judge at the same time when we think, and we must learn to separate these two moments from creative thinking. (de Brabandère 2017a)

Engineering schools, in many respects, leave little room in the training they provide for the learning of creativity. In this sense, they are the heirs, to varying degrees, of a function of applying science, whereas it could be advantageous to support an adventure pedagogy (Romina *et al.* 2009; Forest and Faucheux 2013). The teaching of formalization and experimentation has been improved, but the teaching of design has declined to such an extent that graduates are poor when it comes to using their knowledge [...] in product or process design (see National Research Council 1991).

In the work of engineers and in the training that allows them, it is necessary to consider transformative relationships made of DIY, adaptation to circumstances and the unexpected, forgetting established models and ingenuity. This critical situation, which is essential in the lives of engineers, requires, in any case, the invention of specific transmission model(s) (see collective intelligence). So, the teacher must invent an adventurous pedagogy that considers knowledge not as the object of duplication, but as part of a journey that requires the student to set his or her certainties in motion and transform them.

Convergent thinking is associated with the accumulation of knowledge; divergent thinking, on the other hand, with functions by analogy with the possibility of being structured more quickly, of forging, of understanding through possible relationship modes and not by absolutes. Similarly, normative education is a means of sustaining what has existed (and worked well) with, as a result, a secure image.

Essential characteristics revealing creativity (Csikszentmihaly 1996):

– review and devote time to meditation (creative incubation);

– observe what is around you, including others;

– work at the chosen hours;

– take the time to be alone;

– work around life’s obstacles;

– seek new experiences;

– do not consider failure as a step without return;

– ask the right questions;

– take risks to make things happen;

– find opportunities to express yourself;

– realize your true passions;

– surround yourself with beauty;

– be able to connect the dots (envisage the field of possibilities).

Creativity factors (Caux 1973):

– perception of problems;

– fluidity (ability to think and behave in a goal-oriented manner);

– flexibility (flexibility in dealing with problems);

– originality and audacity;

– the ability to restructure a situation.

Very often the collective imagination is convinced that creativity is the artists' own, while engineers would be content to apply mathematical formulas. Of course, it is not the engineering profession that decides on the capacity for innovation. Unfortunately, there is no dedicated training for this. Innovation depends more on an attitude. Creativity is within each of us, it is enough to free it and training can be a way to let it express itself (or not).

Like everyone else, engineers are able to innovate knowing that it is obvious that some are more creative than others. It can be a question of talent, but above all of attitude towards innovation. Where the engineer really needs to prove himself is that, more than anyone else, he must keep an open mind and his versatility is essential. He must be able to move rationally from one subject to another by transposing in passing a method he has used to solve a problem on a medical project to an automotive project, for example. Finally, the best way to identify an innovative engineer is still, in their ability to overcome the constraints to achieve freedom and, at the same time, that of the group that will embrace and benefit from such innovation (Lorotte 2015).

The "innovation task force", the engineering offices, are already able to spend six months on an automotive project, two on a medical project and four on a luxury project. In other words, they are not experts in any field except "innovation".

1.3. Innovation and boundary objects

> Imagination is what allows us to create a world for ourselves, to present something of which, without imagination, we would know nothing, we could say nothing. (Castoriadis 1996)

> France is a nation of inventors, pioneers, entrepreneurs and producers. Our history is a glorious one, from the steam engine to the high-speed

> train, from the car to the microchip, from the cinema to the rechargeable battery, from hot air balloons to the plane. We have a duty to continue this story. (Holland 2013)

> If a scientist announces that one thing is probably true and another rigorously demonstrates it, which of the two has contributed most to the advancement of science? (Gleick 2008)

> The problem is that innovation, the real innovation, the one that is said to be disruptive or radical depending on the mood of the day, seems to vanish behind the speeches that take it to the naked eye like never before. How many large companies have actually reorganized their value chains? How many revolutionary products have emerged in recent years? (Bonnet 2019)

"Invention does not guarantee innovation. Innovation is an industrialized invention that is brought to market. Invention is an idea, innovation requires its concrete realization at the service of users and customers" (Durance and Mousli 2010; Rapporteurs 2010). In research, we should be in between invention and technological innovation. With regard to creativity, which, to use the same expression, is the first of its kind, innovation generally results from a need for improvement for which a roadmap can be defined. In this sense, a disruptive innovation is based on the emergence of a possible follow-up of deepening activities, possibly with recursive approaches. "Creative genius is about one percent inspiration and 99 percent perspiration," Thomas Edison (cited by Baker 2015) is quoted as saying. During this rationalization and measurement activity, if the data collected invalidate the idea, it is still possible to take advantage of its partial failures, to lateralize the idea towards other possible niches, to capitalize on the methods used. However, Silverzahn (2017) teaches us that disruption is a process, not an event. It can be emerging, sometimes for a long time without being perceived, recognized (following the example of additive manufacturing invented in 1984 which took about 30 years to develop real visibility). At some point, it switches to accelerated mode with the inability to control the true non-linear nature of the failure (see Swiss Science and Innovation Council 2017).

According to Krieger (2019), innovation is multifaceted, with increasing degrees of uncertainty depending on the field:

– classical engineering, using basic technologies (in PE, as far as we are concerned), to deal with a given problem;

– "development where the challenge is to develop differentiating technologies, by transferring and/or adapting existing know-how";

– disruptive research that will lead to emerging technologies.

However, the only bottom-up approaches of scientific and technological origin that are far from problem-solving can lead to economic failures, which scares some boards of directors and authorities who prefer to limit this type of risk.

Box 1.5 summarizes knowledge related to boundary objects:

The boundary object concept was introduced by Star and Griesemer (1989) (see also Star and Ruhleder 1994; Star 1999, Fischer 2001, 2005; Law and Singleton 2005; Cardon and Aguiton 2007; Henke 2007; Star 2007, 2010; Star and Griesemer 2008; Trumpet and Vinck 2009; Boutet 2010; Verchères and Anjembe 2010; Fox 2011; Barley *et al.*, 2012; Yiannoutsou and Kynigos 2013; Allen 2014; Fominykh *et al.* 2016; Balint and Pangaro 2017). Initially, boundary objects were considered to be an arrangement that authorized/allowed/imposed different groups, normally disjointed, to work together without the presence of prior consensus. "The boundary object is 'multiple': abstract and concrete, general and specific, conventional and user-specific, material and conceptual (a database, a protocol). It constitutes a partial and temporary bridge, weakly structured in its joint use and highly structured in its use within one of the worlds present" (Trumpet and Vinck 2009). Boundary objects have the property of being "flexible enough to adapt to the particular needs, to comply with the constraints of the different groups that use them and yet robust enough to maintain a common identity on their different sites" (Star and Griesemeier 2008). Their forms are not arbitrary insofar as it is the need for shared information that structures the boundary object, allowing the best possible cooperation.

In fields where science is being built, relying on technology to be able to produce something new, the boundary object is defined on the following bases:

– the project team and its leader, who have a great deal of autonomy, can choose their means, but they must either achieve the set result objective or agree to stop their action within the project which, itself, cannot in principle be sustained;

– the object of the research is based on an instrument to be designed and constructed which is constituted as a set of working arrangements that are both material and procedural and which is located between several social worlds (or communities of practice) where it is poorly structured (a fairly classic situation between the worlds of design and that of operationalization);

– research based on techniques takes forms that do not systematically respond to a desire to know, but aim for a tangible result. The instrument considers the success of the experiment more than a relevance of the explanatory representation (disjunction between science and technology). It is anchored in the context, articulates practices "in order to transform and domesticate energy through the materialization of the idea of the action to be carried out" (Davallon 2004);

– the use and development of discipline-specific languages or working methods can constitute a major obstacle, not only to the dialogue necessary for the interdisciplinary, systemic project, but also to its dissemination in the various disciplines examined; all of which should be documented and anticipated before any project;

– "the technical object is the shaping and measurement of a set of relationships between completely heterogeneous elements. The technical object cannot be confused with a material device any more than with all the uses 'fulfilled' by this device: it is very precisely defined as the relationship built between these two terms" (Akrich 1987);

– "when necessary, local groups work on the object, which retains its vague identity as an ordinary object, while making it more specific and more suitable for local use, within a social world and thus more useful for work that is NOT interdisciplinary" (Star 2010);

– knowledge management concerning research on a boundary object can no longer be thought of only as a process of introducing new specialists, but must consider the renewal of collective forms of decision-making and prescription in the organization; communities of practice must contribute to the renewal of blurred visions (at the beginning of the project) of the object and thus to an integrated capacity for innovation (Hatchuel *et al.* 2002). It is a way out of routines;

– in an organization oriented towards innovation and design, the "weak prescription" consists of setting work objects, targets that are also objects of knowledge, based on the rapprochement between research professions; in the constructive debate expected, a direction and a provisional distribution of tasks is therefore allowed, better, desired;

– groups that cooperate without consensus alternate between these two forms of the object (Star and Griesmeyer 1989).

These MLAs are summarized in Figure 1.5.

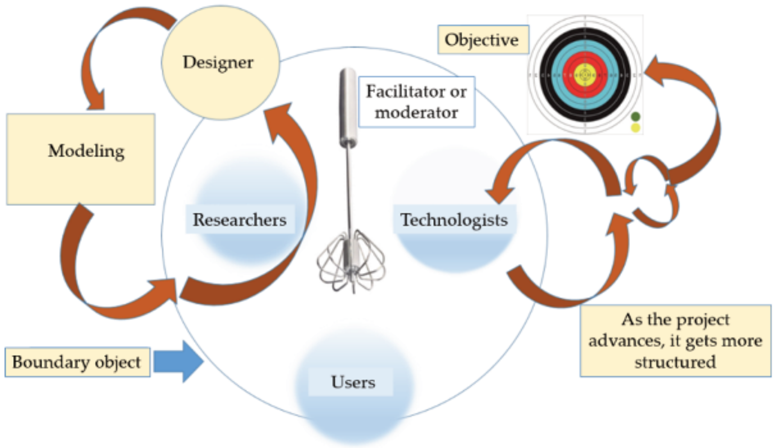

Figure 1.5. *Transition from the design stage to an instrument, product or process*

Clearly, scientific publications – the (often useful) residue of human actions, a form of mutilation of reality (what has been and not what it could have been if we had known) – report, in an agreed script, tangible results giving the impression of a logical, almost linear continuity in the action. It is therefore difficult to appreciate the extent of the discrepancies between formal representations, including publications and unreported "behind-the-scenes" work. However, the development of boundary objects requires local adaptation as an invisible form of work for the group as a whole and in the way in which a common representation, perhaps rather vague yet useful, is constructed.

Box 1.5. *Boundary object*

However, using the humor of Barbellay's (2018) drawing of a boundary object that is an elephant, each discipline that examines the object sees it only in terms of its disciplinary competence. This is illustrated in Figure 1.6 where this poor elephant is described in correct terms and/or names, but which do not reflect what the object is. There is therefore a need to share and pool knowledge in order to define the objectives for reaching a boundary object, which is far from easy, as will be analyzed below. Figure 1.6 illustrates this difficulty of an analysis of an object seen by several disciplines.

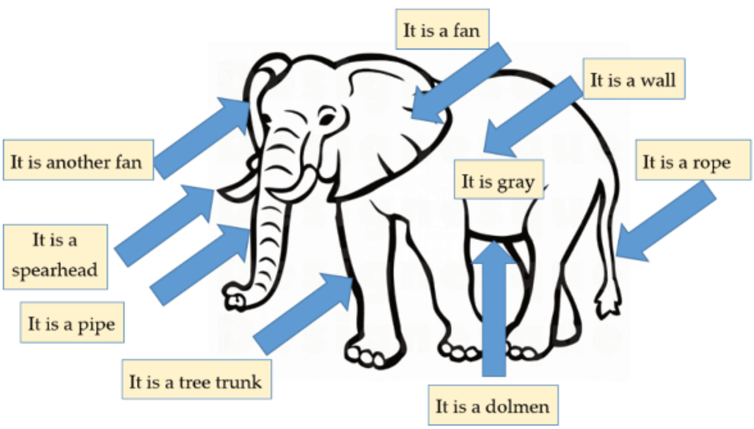

Figure 1.6. *Disciplinary difficulty in representing an object*

But, "during the design process, creativity plays a crucial role in the initial or conceptual design stages, during which the designer defines, in broad terms, the characteristics of the product to be developed. Creativity also influences other phases of product development – for example, by affecting the methods and devices that will have to be used to manufacture this product. Achieving creative design solutions can be an advantage over competing products" (Bonnardel 2009, see also

Amabile 1996; Dorst and Cross 2001). This stage is, in principle, free of any disciplinary coloring.

In a world subject to irrepressible technological progress, the disciplinary sciences can only coexist through sharing, through the interface with other specialities to achieve cohesion or even a certain form of technical and/or social utility. Halleux (2009) reminds us that the invention was already based, two millennia before our century, on two mechanisms: chance and/or serendipity (mines discovered following the partial melting of minerals after a forest fire); imitation of nature (see the boat imitating the shape of the fish). However, today, the criteria of scientific excellence defined by many evaluation structures only make it possible to organize these exchanges in a linear form, in an imperfect way. It is necessary, indeed, to accept paying the price openness. But Gaudin (1978) believes that it is easier for disciplines that have already innovated to receive funding from decision-makers on a continuous basis. Moreover, when it is not possible to remain in its context, Paty (1990) points out that, "the difficulties of transmission are often language difficulties, obliteration of conceptual meanings under purely formal signifiers and which do not call for meaning. What, on the speaker's side, is conceived in a coherent and concrete way is often rendered by his speech [...] in a mutilated, dried up manner and reduced to a slurry of content, a mixture of esoteric terms and technical details, the amount of information [...] that they carry is quite impossible to assimilate". This vision is largely supported by the opinions of Lévy-Leblond (2006) and Ganascia (1999).

The evolution of disciplines is a matter of conceptual, relational forms of transgression. In this setting appears the "serendipity" which corresponds to a heuristic approach that consists of finding something interesting in an unexpected way, by looking for something else, if not nothing in particular (Marti and Martinet 1996). Van Andel and Bourcier (2009) recall that "serendipity is inherent in human conduct. It is considered the ability to discover, invent, create or imagine something new without having sought it, during a surprising observation that has been correctly explained". There is therefore reflection on the unexpected and scientific rationalization of facts leading to innovation. This change is then authorized, according to Feyerabend (1988), by a provisional form of epistemological anarchism induced by disturbances of various origins that break with the course of things (disruption linked by an unexpected phenomenon founded or not). From the demonstrated existence of the effects of serendipity on technological innovation (see the classic example of the "post-it"), some have concluded that it is a privileged mode of invention and social progress. Serendipity is not a stance that consists of relying on chance (in the sense of "accidental"). It involves an attentive and thoughtful position. "It could also be defined as the human capacity to be surprised and to pay attention to it, which encourages investigation and opens the doors to creativity" (Catellain 2017, see also Catelin 2017).

In recent times, innovation based on technological mastery has explored various changes in spatial and temporal scales (Dodet 2001), with significant epistemological problems related to the exploration of subjects requiring interdisciplinary convergence actions (Tsai *et al.* 2013; André 2017a). Recent developments in science that also escape normality, predictability, and in a word, linearity, are associated with this change in traditional scales. These show strong couplings between systems that open up new areas of research at the same time as applications launched 20 years ago: optoelectronics, nanomaterials and nanotechnologies, NBIC convergence, new information and communication technologies, security, health (bio-printing, advanced medical imaging, telemedicine, personalized medicine, etc.).

According to the Academy of Sciences (2017), technological elements are sources of acceleration (see Chapter 2):

– digitization and automation of production;

– intelligent systems, in particular in the field of renewable energies, transport, mobility, and human/machine interfaces;

– artificial intelligence, for its ability to transform areas such as transport and health;

– biotechnologies and biomedical technologies, which exploit new knowledge opened up by genomics;

– sustainable technologies that could redirect production and consumption towards conserving natural resources, mitigating climate change and improving environmental quality.

In addition, particular attention must be paid to emerging technologies, which have the potential to change almost all economic activities, but which require mastering aspects of convergence:

– nano-, bio- and quantum technologies, which offer the ability to control matter (from inorganic to living) at the atomic level, opening up an unlimited field of applications in industry, fine chemistry, health and infrastructure;

– data science (Big Data), which makes it possible to obtain new knowledge and action capacities through algorithmic analyses, etc.

While the field of material and energy transformation is still very promising in economic terms, it seems appropriate to try to address its evolution and examine how the concept proposed by St Leger (2014) of "Gengineers" can be explored. Figure 1.7 recalls some elements to be taken into consideration when estimating future needs, based on new scientific paradigms, the field of economic possibilities, social, political aspects, reserves, environment, etc. This figure defines possible objectives, but does not take into account the means by which to achieve them, in particular in the context of training young people through/for research.

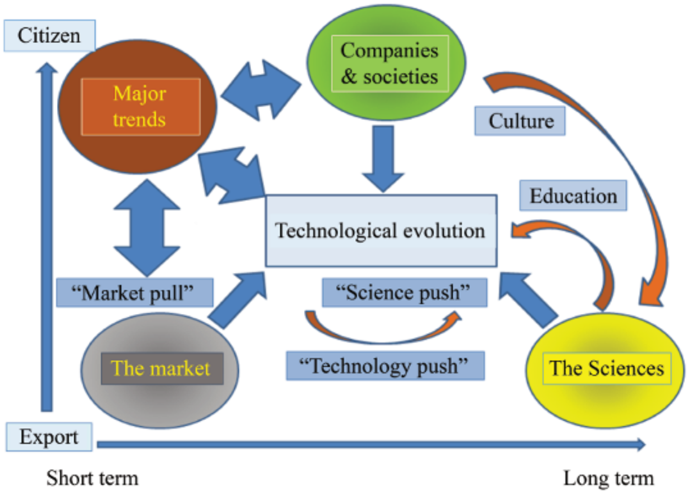

Figure 1.7. *A vision of links to be considered in technoscientific foresight*

The conditions of industrial activity, which is increasingly globalized, must evolve against a background of guidelines favoring innovation and adaptation to different constraints: global warming, depletion of reserves, recycling, environmental regulations, production quality, safety, flexibility, etc. The notions of performance and efficiency of production systems are broadening to include both short and long term, within the current material and human constraints where technical, economic, societal and human uncertainties and variability have never been so important. Most competitiveness depends more on product quality, variety, the richness of the services associated with it and their degree of innovation, than on costs, leading to new research. But since rationality must remain a standard of access to innovation, so-called robust methods exist to support ideas and bring them to application (see, for example, Abramov *et al.* 2015).

However, according to Bonnet (2019), innovation requires innovation patterns specific to each economic sector. "The starting point for innovation is often a new look at assets that we already had at hand but were underutilized. Sometimes, this energy wanes, strategic assets are lost, the heaviness of structures takes precedence over the ability to move. But to regain this sometimes exhilarating energy, there is no point in breaking everything with a war cry. On the contrary, to distinguish the wheat from the chaff, discipline is needed, but also and above all, a certain humility that is sorely lacking today." This remark is important for processes, including those such as the Solvay process, presented and discussed at the beginning of the book, there is time and assured knowledge about the process and its socio-economic environment. If disruption is to occur, it will mean significant investments and challenges to methods that may be prohibitively expensive. Nevertheless, this case study does not cover the entire field of the transformation of matter and energy.

The new technologies are transversal, diffusing into various scientific (instruments in particular), economic and industrial, combinatorial (their development makes sense only in a whole: the microprocessor has no use as it stands, unlike the hand-held tool) and contagious, because it irrigates neighboring technologies. There is therefore both deepening and broadening, leading to the loss of the causal link in the act of producing, between components and the final product. We live in complexity, in ever shorter temporal evolutions exploring different forms of innovation ranging from "marginal" thanks to continuous process improvement, to "radical" (nuclear for example, an element of "Big Science") to technological revolution (synthetic biology, for example, not to mention 3D printing). All the new technologies that appear almost simultaneously upset the relationships between science, technology, economics and society (Lesourne 1995). Under these conditions, "the deepest problems escape us. There is an uncertainty embedded in the very conception of complexity, that of the incompleteness of the resulting knowledge" (Benkiran 2000).

Flichy (2001) reminds us in addition that, "one of the characteristics of the project-based organization that has been implemented in many companies is the objective of results. The project team and its leader have a great deal of autonomy, they can choose their means, but they must achieve the objective set. The principle of the project structure is in opposition to the traditional rationalist model that radically separates design and execution". To say that a loop system has become accepted is one thing, probably a little less accepted when the loop is driven by the sales representative, in collaboration with the user (Forgues *et al.* 2009). But this is not considered in academic research. The European Union in its H2020 (2018) program recommends the application of the following criteria for innovation (Mazzucato 2018):

– inspiration and audacity, which in turn brings major relevance and contribution to society;

– ambition, with realistic and innovative research actions;

– the encouragement of interdisciplinary and intersectoral innovation;

– the implementation of targeted, measurable and time-bound guidelines;

– the implementation of multiple solutions with a bottom-up approach.

The designer who has explored and broadened their initial idea can put forward a number of hypotheses on the elements of their perception of reality with a projection towards their use. They are able to propose a draft of the uses (based on the already old example of Minitel, a reminder of the diversions not initially envisaged towards the pink Minitel). But as long as a demonstrator is not built, the project remains in a state of a chimera. At least two actors must be taken into account: the designer and the user (this can be the same person). "We must constantly go back and forth between the designer and the user, between the designer's user-project and the real user, between the world inscribed in the object and the world described by its movement [...]. It is the reactions of users that give content to the designer's project, and the user's actual environment is partly specified by the introduction of a new device" (Akrich 1987).

When recalling this important context, involving the transmitter and the receiver of a signal (information), the transducer represented by the instrument or machine should not be ignored. While the latter were made in ancient times by researchers themselves from materials purchased to make models, the current situation of complexity and time pressure has changed the situation by forcing mergers of knowledge that are not only interdisciplinary but are also of professions. It is at this stage that the importance of the concept of the boundary object lies.

1.4. Teleological approach, convergence, and interdisciplinarity

> We are living in the accident of the globe, the accident of instantaneousness, simultaneity and interactivity that have now gained the upper hand over ordinary activities. (Virilio 2010)
>
> A model is not more convincing if it integrates as much data as possible into the system, quite the contrary. There is a risk of encountering the pitfalls of over-interpretation and lack of robustness of predicted behaviors, if they depend on the choices of details taken into account or neglected. (Bourgine and Lesne 2006)
>
> If the best experimenters still retain a theorist's soul, the opposite is not true. Despite this, the prestige reflects on the theorist. (Gleick 2008)
>
> In all examination of nature reason rightly calls first for theory and only later for the determination of ends. No teleology or practical purposiveness can compensate for the lack of the former. (Kant 2014)
>
> Implexity refers to the notion of chaos, fundamental disorder, inexhaustible heterogeneity. Yet, like everything else in the theories of self-organization, it is indeed an organizational disorder: it is the

> chaos of researchers' implications that weaves the order of a science as an organized reality. The regularities and constants of scientific production function 'in' and 'by' the disorder of implexity and not 'against' it. (Castoriadis 1983)

According to Vallet (2018), to generate the same annual growth rate as 30 years ago, the cost of R&D would have increased by a factor of 15, while the number of publications is growing exponentially. There would be a need for better trained R&D personnel (in disciplinary and interdisciplinary fields) with, however, a need to manage the complexity of emerging fields requiring both increasingly sophisticated equipment and scientific and technological approaches that are more creative. In fact, in agreement with Cowen (2011), we are approaching the end of "simple" ideas. He writes: "We can't understand why we can't do it anymore. All these problems have only one cause, but it goes unnoticed: we have lived for at least three hundred years on fruit that was just waiting to be picked... However, for forty years, these fruits have begun to become scarce and we have acted as if they were still there. We didn't want to acknowledge that we had reached a technological plateau and that the tree was much more stripped than we wanted to admit."

> In cultural terms, no company is built on dreams alone and no company is built outside of them. Successful action, is by necessity the result of practical considerations. But the purpose of any action is explicitly defined by the deep nature of the human being, their dreams, their vision of life, their culture. The dynamics of life, the challenge of risk and uncertainty require a new effort of creativity that will lead us to the reconstruction of the notion of progress, the one that philosophers, ideologies of certainty, have damaged and almost destroyed. There is no true human culture except that which progresses with the process of creating real life, in the continuous evaluation of each of our companies with an image of the future that we will shape by ourselves. (Giarini and Stahel 1990. See also on this subject: Baumol 2002; Lubart 2003; Ganascia 2006; Vanderburg 2010; Axup 2014)

Maldonado and Cruz (2012) recognize that the development of engineering, including the development of material and energy transformation processes, is increasingly investing in complicated and even complex situations. According to these authors, it is necessary to move away from proven deductive methods to new educational approaches to these emerging phenomena. It is not so much the multiplicity of components, or even the diversity of their interrelationships, that characterizes the complexity of a system: as long as they are practically and exhaustively countable, we are dealing with a complicated system, whose combinatorial enumeration could (if we have the time and means) make it possible to describe all possible behaviors (and thus to predict its effective behavior at any time as soon as the rule or program governing them is known). In mathematical terms, we are dealing with a "polynomial problem". It is the potential unpredictability (not calculable *a priori*) of the behavior of this system, linked in particular to recursivity, that affects the functioning of its components ("by functioning, they transform", giving rise to emergence phenomena, sometimes intelligible, but not always predictable). The observed behaviors of living systems provide countless examples of this complexity and bioprinting is one of them (André 2017).

"Interdisciplinarity is at the heart of our approach. But it is not enough, as Charles de Gaulle said in his time, to promote caricatures of the blissful admirers of the European Union, to jump on his chair like a kid by shouting 'interdisciplinarity!, interdisciplinarity!', believing that it will happen by itself, in a natural and peaceful way"(Garcia-Acosta and Musset 2017). To overcome the (major) difficulties, several disciplines are therefore at work, which leads to the "modeling" of mixtures of domains that probably have different behavioral equations, multiple and singular interfaces, non-linearities, changes in scale (Charpentier 2009, 2016) associated with possible fractal shapes, etc. Complexity invades the domain in several ways: that of geometric arrangements, complexity of dynamics and functionality, competition between systems, non-linearities, etc. (Gleick 2008; André and Larger 2016). A related question concerns a given action, the effect of a stimulus on it, with a possible comparison between the amplitude of the input stimulus and its effect (Cunchillos 2014) with aspects that at least appear to be contingent, spontaneous, and intentional.

It is true that on open topics, the debate between bottom-up supporters (those who, as pioneers in an emerging field, use trial and error methods to try to produce proofs of concept and be among the first publishers) and those who consider top-down thinking before any action runs the risk of appearing in a stabilized heuristic approach like a discussion that does not have robust foundations because it is impossible to make a decision and move forward. It should be remembered that a heuristic approach is based on empirical rules, derived from experience, analogy or association, or even bisociation. Unlike a mathematical or even scientific approach, a heuristic approach makes it possible to state relationships, usually non-hierarchical and non-exclusive, without necessarily having to demonstrate their existence in a logical way.

Who should we believe between those who promise and those who hit the brakes who, like Plick and Plock (Christophe 1985), want to think before acting? The latter wish to find meaning in a heuristic approach defined in Figure 1.8 ("a scientific discipline is thus characterized by a voluntary self-limitation in relation to the philosophical project and therefore, by a heuristic efficiency and another epistemological legitimacy" according to (Wissmann 2010)); by their modeling, their willingness to co-contract, they envisage being "border crossers". To debate, however, is to try to get out of promises that are difficult to keep, out of certain paralyzing stereotypes, out of application desirabilities, out of competitions, out of emotions and the search for recognition, even simply out of “grabbing fairs” (conflict where everyone defends their interests). For Marc Giget (2018), an innovation strategy means “understanding the society’s unspoken needs before mobilizing technologies”! (see also Hargadon 2003; Guérin *et al.* 2016; Negny *et al.* 2017; EU 2018; Huault and Petit 2018). Under these conditions, innovation, which uses knowledge of the possible and the real, is only partially based on transmitted knowledge. For Daniel (2018), “in fact, the current ‘disruption’ must be interpreted as the transition from a hierarchical society where everyone knew their place to a society in motion where everyone will invent their place.”

> Simulation, which focuses on the numerical implementation of knowledge models, can, from a certain point of view, also be considered a phenomenological model. While the modeling stage itself aims to define the representation of knowledge and the calculation formalism that will be best adapted to the question asked, the simulation aims to effectively implement the calculation model to answer questions such as ‘what happens if...?’ by constructing scenarios allowing US for example to consider the effect of the chosen parameters. (Maslow 1966)

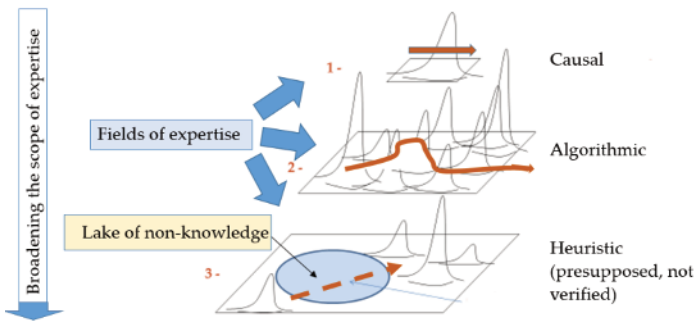

Figure 1.8. *Fields of expertise: the approximate Gaussian terms represent the scientific achievements resulting from previous research. Depending on the forms of expertise, the field is covered (causal, algorithmic) or partially covered (heuristic) (André and Masse 2002). For a color version of this figure, see www.iste.co.uk/schaer/process3.zip*

The heuristic approach can be defined as an empirical, approximate, intuitive but quick and bold method to find a possible solution to a question for which not all knowledge is stabilized and therefore have a field of expertise, partially deductive and can perhaps accelerate the resolution of the problem whose possible solution is highlighted. No “good” idea is born: it represents only a new hypothesis, which can perhaps become a good idea (De Brabendere 2017a), following the example of the oil that was used for its tar, then for lighting and finally to replace coal as a primary energy source. He writes: “It took a real mental revolution to find its other uses, which blew up the oil.” Since, usually, there is no single solution, there is a confrontation of ideas with scientific and technical knowledge, the market, the company’s brand image, risk taking, opportunities, which may allow a certain prioritization of proposals before an innovation decision is taken (see Caronia 2014; Tiberghien *et al.* 2014).

The innovator can show themselves, according to Millier (2013), more systematically by asking themselves the following questions:

– What fatal, unavoidable evolution can we identify in this field and what are the consequences on our activity?

– What trends can be identified in this area and what are the consequences for our business?

– What utopian evolution can be identified in this field or what ‘unattainable dream’ can we imagine, and what are the consequences on our activity?

– What constraints can we identify in this area and what are the consequences for our business?

Figure 1.9, based on the same reference, presents the heptagram of innovation, a necessary simplification at least at the beginning of creative approaches.

Figure 1.9. *Innovation heptagram*

This same author defines somewhat artificial sub-domains that guide the creative person, ones where one has to commit in order to gain a hybrid zone for society, or even for those who remain free of any commitment, as well as those who lie between these two extremes. Perhaps it is not necessary to introduce such considerations from the outset?

“Cognitive psychology research has shown that in creative situations, individuals and groups tend to be “fixed” and fail to generate original paths” (Le Masson 2018). In addition, it should be recalled (and remembered) that we are still working on an incomplete body of knowledge whose degree of generalization at larger as well as smaller scales can be questioned. The idea, however, is to study the control parameters – those that are known (temperature, various flows, various heterogeneities, etc.) – in order to try to examine the existence of attractors and their deformation(s) induced by the environment by approaching real conditions with appropriate devices. Indeed, most of the processes responsible for the functioning of living organisms, of humans, at all scales – from the cell to the ecosystem – result from the interactions of tens, hundreds, even thousands of factors: presence or absence of an ion, a molecule, a nutrient, a gene, conformation of a protein, etc. Deepening their understanding therefore requires mastering tools that can represent and analyze these complex interactions (Vandeginste 2012), particularly in disruptive innovation.

For example, Chatillon (2017) offers creative methods to generate ideas. His work implies the need for a multi-level analysis to get closer to reality and the phenomena to be taken into consideration, the importance of the contexts of the situations studied, and finally, the attention given to mechanisms rather than regularities. It extends other methods, for example: TRIZ (Rahim *et al*. 2015), helical anthropological innovation, brainstorming, learning organizations such as Fab Labs (EU 2017), organizational creativity (Chaouch 2017), design-thinking (Leifer and Steinert 2011; IDD 2017; Zochetti 2017), fuzzy logic (André and Gnansia 2017), JUGAAD or frugal innovation (Radjou *et al.* 2013, etc.). The presentation of these methods is beyond the scope of this work. However, it should be remembered that these methods make it possible to combine different intellectual fields, including economics, software, and speculative fiction, but all must have a strong explanatory value when considering decisions aimed at transformation. For Barnard (2017), a classic rule is to examine whether a possible solution has more weight in one of the disciplines convened, whilst being equal in all the others. This solution will probably dominate. Hierarchies can then be expressed.

It should be recalled that in linear systems, parameter changes lead to quantitative changes, but do not modify the behavior (steady state) of the system. In non-linear dynamic systems (NLDS), a small variation of certain parameters, called control parameters, can, under well-defined conditions, in the vicinity of a critical value, cause a complete change in behavior at the equilibrium of the system. This is called a fork. Figure 1.10 displays a “fork bifurcation” (Delignières 2015).

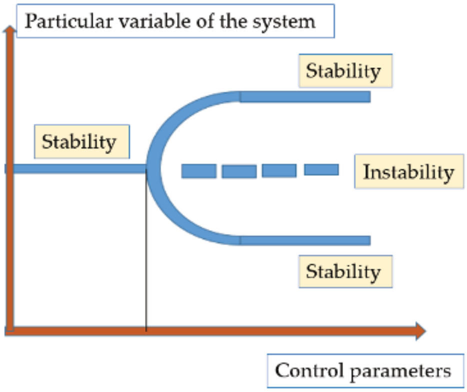

Figure 1.10. *Fork bifurcation*

The realization of complex processes controlled, in principle, to high standards (provided that one has at least a partial vision of reality and consequently, a fairly robust modeling base) can be at the origin of innovations that will require experiments that will be the basis for the effective reinforcement of the concept (or that will invalidate it) (Guespin-Michel 2005; Laurent 2013). Such a scientific approach should make it possible to determine whether a certain degree of predictability can be achieved. It is then a question of having the tools and study instruments required in order to validate a conceptual framework to consider a satisfactory solution to a biological issue, especially if it must one day be applied without risk to productions that are of interest to people (risks in particular).

Non-linear systems

A non-linear system introduces f_i functions (i being between 1 and N) that are not linear, and stability conditions can be achieved for values of the x_j parameters. To study the stability of the system in the vicinity of these stability positions, the x_j in the vicinity of the stability values should be "slightly" modified. If the objective is not disturbed, the system can be considered stable. This principle assumes that everyone knows x_j and that we are able to follow the transformation in its dynamics. It also assumes that it is possible to modify parameters incrementally; if it is possible on the physico-chemical, or even hydrodynamic aspects, nothing says that it is possible on the biological aspect (this is the case for example for bioprocesses).

Robustness of scientific information

In relation to the artist and other intellectual professions, scientists validate their work, their competence, their performance in writing, which serves as the main basis for the evaluation process. There is therefore no science without writing, a standardized mode of communication which makes it possible to accumulate knowledge on different types of media. It is a kind of (non-linear) transcription process of turning “built” knowledge into knowledge. It is also the exploitation of this “ore” that serves the scientific community to participate both individually and collectively in the progress made by science.

Contrary to what Mrs Michu, an enthusiastic reader from the Republican East, thinks, just because it is written in the local newspaper does not mean it is correct, whether it is a scientific publication or not. It may therefore be interesting to consider the role of publication in its relationship to society as a whole. If writing can be controversial, it also (especially?) serves the researcher’s career, but also to put down a marker. No discovery exists until its written form is completed and validated outside the researcher. It is therefore a means and a goal, with a consequent activity in the daily life of the scientist, led more and more to produce, rather than to think about their research.

But in this activity, creativity only plays a small part. The writing is conforming, stereotypical, formatted, constrained because it must aim to express a truth with a universal outlook, one that is probably provisional. Following a personal activity (or in a restricted group), the objective of a “neutral” publication must be to eliminate any reference to subjectivity (i.e. any researcher of the same quality and competence must be able to reproduce the experiments and verify in depth the models used or developed).

In fact, in its forced rationalization, scientific writing, imbued with facticity, smoothes the conditions for the production of new knowledge and it is generally difficult through this dehumanization to, through reading, grasp an in depth understanding of what science is doing, why and how. But then, how can we access the living, the masked non-rational, the unwritten? How can we access the creative processes (where they exist) that have supported scientific action? How can we know how cultural, financial, and technical constraints have stimulated or reduced activity? In short, the representation that can be made of the advancement of science and its possible disruptions is probably inaccessible simply by reading the scant publications produced by scientists.

By respecting the surrounding paradigm, that recognized by the “federation”, scientific writing uses specific symbols, “ideograms” of group recognition, of belonging, which may give the impression of sectarian approaches because the form of discourse is imposed (or almost), based on rationality centred, in the case of the LRGP, on the transformation of matter and energy.

But then, in the questions asked by society that require interdisciplinary approaches, how can we meaningfully exchange with other disciplines? This means that it would then be desirable to get out of utilitarian jargon, to learn or relearn a form of disrespect for the conservative expectations of the scientific system (beautiful, paradoxical injunction). But, in the end, do we want to because the game, for many good (and perhaps bad) reasons, is certainly not worth it?

Self-questionnaire on research

"We are in a world of 'Sunday drivers'," as George Friedmann writes, "people who have never looked at their engines, and for whom things are not only for their function, but also for their mystery of functioning" (Baudrillard 2001). However, in the context outlined in this book, the author hopes that we can go against this proposal, which corresponds on the one hand to his vision of research that is often/sometimes too much embedded in the too conceptual because it is "relevant", in line with aspirations and adapted to a "sound evaluation" carried out according to traditional models that are ultimately from another age or rather another world. In this situation, which is necessary to better share and, in essence, to refocus its actions towards the "basic" mission and thus to be more effective, it will be possible to be recognized as actors of living, autonomous and useful scientific inter-disciplines for society. But as Henry (1998) points out, "the evaluation of scientific products always has to do with the 'territory' of a discipline. Each one advances its own definition, by definition of borders, of an inside and an outside, transfers being sometimes condemned, sometimes accepted, but in a logic of transfiguration to be imposed as legitimate." This opinion is largely confirmed by Larrère (1994), who considers that the industrial paradigm divides knowledge between the natural sciences and the human and social sciences, constituting an "anthropocentric epistemic paradigm". This context, when there are scientific-technical-societal links, must therefore be taken into consideration to achieve more optimal forms of judgement of activities.

Indeed, self-evaluation is necessary (see Table 1.1); so is external evaluation. In both situations, it is probably useful to have quantitative criteria, which must be taken into account for what they are worth (but probably no more). In particular, the desired intrusion of technology sciences into the social field severely limits the usefulness of such purely quantitative criteria. Thus, it must be possible to make judgments about interdisciplinary operations in different ways:

– global: assessment of the general interest of the research action;

– analytical: the most precise possible identification of its advantages/disadvantages;

– comparative: analysis of alternative solutions;

– analog: transfer to the proposal of previous judgments about scientific activities that are considered as being similar (Barthélémy 1999).

Box 1.6. *Considerations regarding interdisciplinarity*

> Even if we must avoid 'butterflies' which are not good enough in any of the disciplines, current scientific research requires the ability to accommodate both 'ballistic' and 'Brownian' researchers. (Federal University of Toulouse 2019)

I – Construction of the research object	YES			NO
	Strong	Medium	Low	
Action to satisfy a social demand	☐	☐	☐	☐
Methodological research, basic research	☐	☐	☐	☐
Development of scientific competence	☐	☐	☐	☐
Anticipation of future problems requiring specific investment	☐	☐	☐	☐
Different types of research				
Scientific	☐	☐	☐	☐
Technological	☐	☐	☐	☐
Evaluative	☐	☐	☐	☐
Actions	☐	☐	☐	☐
Exploratory	☐	☐	☐	☐
Descriptive	☐	☐	☐	☐
Speculative	☐	☐	☐	☐
Other forms of action				
Consulting (collective expertise)	☐	☐	☐	☐
System exploring complexity with feedback	☐	☐	☐	☐
Observation of the “social reality”	☐	☐	☐	☐
Logic of social utility of the study	☐	☐	☐	☐
Good relationship between the objective of progress and the disciplinary angle chosen	☐	☐	☐	☐
Relevance of the choice of the social objective	☐	☐	☐	☐
Clarification of the theoretical framework in relation to the objective	☐	☐	☐	☐
Adapted choice of assumptions	☐	☐	☐	☐
Appreciation				
Some time	☐	☐	☐	☐
Human resources	☐	☐	☐	☐
Financial resources	☐	☐	☐	☐
Relational modes (interdisciplinary project mode)	☐	☐	☐	☐
Support from management and leadership	☐	☐	☐	☐
The “quality/price ratio” for the innovation in question	☐	☐	☐	☐
System exploring complexity with feedback				
In the short term	☐	☐	☐	☐
In the medium and long term	☐	☐	☐	☐
Details of the proposal				
Dimensions of the proposal	☐	☐	☐	☐
Others’ perception of the idea	☐	☐	☐	☐
Relevant working assumptions	☐	☐	☐	☐
Identification of the factors involved	☐	☐	☐	☐
Approach to the complexity associated with the proposal	☐	☐	☐	☐
Preliminary bibliographic approach	☐	☐	☐	☐
Optimal methodology	☐	☐	☐	☐
Interest in operating internally	☐	☐	☐	☐
Interest of opening, sharing, subcontracting	☐	☐	☐	☐

II – Research approach	YES			NO
	Strong	**Medium**	**Low**	
Quality approach	☐	☐	☐	☐
Association of all partners necessary for the research	☐	☐	☐	☐
Relevance of data collection	☐	☐	☐	☐
Relevance to data processing	☐	☐	☐	☐
III – At the end of the research				
Are we out of the descriptive framework?	☐	☐	☐	☐
Satisfactory confrontation between assumptions and conclusions	☐	☐	☐	☐
Critical analysis of the work	☐	☐	☐	☐
Return of the results to the "society"	☐	☐	☐	☐
Directly	☐	☐	☐	☐
Via relays (transfer)	☐	☐	☐	☐
Nature of this transfer				
Other study	☐	☐	☐	☐
Training	☐	☐	☐	☐
Information	☐	☐	☐	☐
Communication	☐	☐	☐	☐
Other (specify)	☐	☐	☐	☐
Nature of the recipients of the work				
Scientific world	☐	☐	☐	☐
Societies	☐	☐	☐	☐
Companies	☐	☐	☐	☐
Strengthening the legitimacy of technosciences through activity	☐	☐	☐	☐
Social utility of the result	☐	☐	☐	☐
Reactivity (on time: YES, or too late: NO)	☐	☐	☐	☐
A need to develop the work	☐	☐	☐	☐
Networks	☐	☐	☐	☐
Forward-looking management of jobs and skills	☐	☐	☐	☐
Thematic clusters, critical mass	☐	☐	☐	☐
Openings	☐	☐	☐	☐
Mobilities	☐	☐	☐	☐

Table 1.1. *Research and interdisciplinarity*

1.5. A look back at the notion of convergence

> The few scholars who have chosen to be nomads are essential to the intellectual well-being of established disciplines. (Mandelbrot, quoted by Gleick 2008)

> By practicing engineering sciences, we do not only seek to know how this or that complex device works (by seeking its 'truth' and verifying that it follows this or that law of behavior). First, when it was designed and manufactured, an effort was made to ensure that its operation fulfilled a predetermined objective, i.e. was part of a useful function, produced a 'good' for society. (Schmidt 1992)

> Thinking and decision-making systems correspond to what John Greville Agard Pocock (1997) calls the Machiavellian moment, a way of conceiving the time and space of politics. Such a Machiavellian conception of politics has the particularity of giving a place to contingency against necessity, to transience against permanence, to becoming unknown against providence and eschatology, in order to face a historical moment that is also singular when the city is subjected to a chaos of events whose course it has little or no control over. (Foucart 2011)

By working on boundary objects aimed at the creation of instruments, machines and software, scientific aspects must integrate broader forms of convergence concerning uses, and human and economic aspects, as well as go through integrated work with technologists to integrate their skills (or even develop them, as well as those of researchers) as far upstream as possible in order to satisfy in a robust way the application need (both research-oriented and societal, see, for example, Tirri *et al*. 2017).

In the field of processes, knowledge construction still has a tactical advantage that is generally lacking in the study of the control of natural (or simply complex) phenomena, because we know how artifacts have been designed with very plausible assumptions, close to disciplinary knowledge. It is undoubtedly here that the exploratory framework of process engineering has taken and continues to take its full place as a producer of intelligibility and industrial applications. Starting from the disciplinary causal, it is easy to arrive at the "complicated" multidisciplinary. But will the same be true for all the new developments mentioned in Chapter 2 on foresight whenever new systems strongly involve humans? Scientifically, the engineering approach to these fields through complexity is a breakthrough that recognizes the exceptional and problematic nature of life (hard and soft). It may be useful here to invoke, to illustrate the complexity and its study, the necessary acceptance of uncertainty and the heuristic approach in the understanding of so-called "complex" problems related for example to society, health, the behavior of a single person (and in this case, not applicable to the whole population), thus giving a greater value to the qualitative, the sensitive, the heuristic, rather than just the quantitative aspect of process engineering's "heyday".

If it is therefore necessary to consider that the epistemological foundations of the future in process engineering are increasingly based on the complexity paradigm, interdisciplinarity must be developed because it is considered as one of the means of study. The disciplinary approach is too often compartmentalized, hence the idea discover how to percolate across disciplinary boundaries so that the paradigm of complexity can truly unfold, particularly because the recomposition of categories of thought would no longer be based on disciplinary boundaries and objects, but on boundary objects carried by creative people, divergent people, who, unafraid of recursions, legitimately wish to respond to the major challenges facing society. This change in the way research is carried out aims for a real responsible integration of activities that are open to society and that are meaningful, making it possible to make the "indiscipline" in chemical engineering emerge as one of the credible and operational scientific actors of current technoscientific and societal movements. This may be a new way of inventing the factory of the future (Henn 2017; Küpper *et al.* 2017) on the basis of revised criteria, a way that is only imperfectly emerging in practice today. The example of bioprinting, an emerging field, already presented by André (2017b, 2017c, 2017d), consisting of the 3D printing of living materials, illustrates the aim of converging many disciplines, as illustrated in Figure 1.11 (see Figure 1.6 for background).

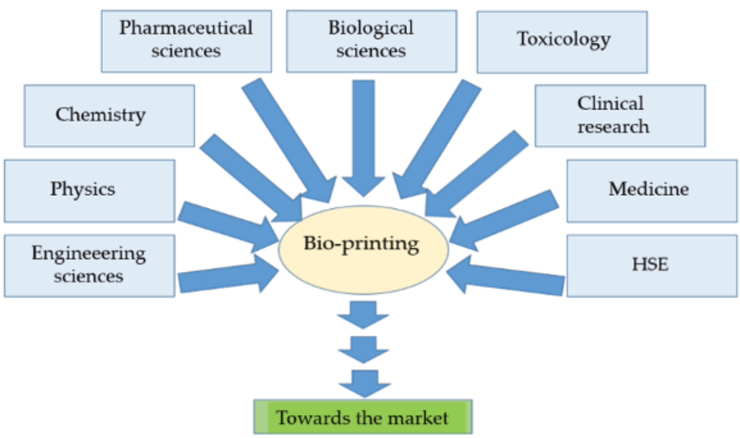

Figure 1.11. *Convergence and bioprinting (HSE for health, safety, and environment)*

Thomas Kuhn (1983) defines the term paradigm in *The Structure of Scientific Revolutions* as a set of observations, questions, methodologies, and interpretations of scientific achievements. A paradigm is thus a representation of the world, a way of seeing things, a coherent model of scientific knowledge that is based on a defined basis (disciplinary matrix, theoretical model or, more broadly, current thinking). Science paradigms are widely accepted in a given disciplinary field. They change according to the evolution of knowledge (transition from Newtonian mechanics to Einsteinian relativity, for example).

For many authors, epistemology (see Schmidt 1998; Varenne 2001; Frezza *et al*. 2013; Ratcliff 2013) is the critical study of science and scientific knowledge. To go a little further, it is a question of updating the conceptual structure of a theory by looking for what is effective in the sequence of concepts and in their organization, to highlight areas of uncertainty, or even a lack of knowledge. It is basically an intellectual game, played alone or with others, which aims to bring out "the meaning, scope and procedures of rationalization in the explanation of phenomena" (Grangier 1986).

In interdisciplinary approaches, on new subjects, the "simple" addition of scientific concepts of more or less independent disciplinary origins does not normally lead to the emergence of a rational path between concepts and experiments. And it is at this stage of generally complex interdependencies that epistemology takes on its full importance, especially if an effective approach is to be achieved. But, if we have the time and resources, it is possible, thanks to well-managed experimental designs, to define this path in a pragmatic way in a partially empirical form that is difficult to extrapolate.

There is therefore a debate between a conceptual approach, where the need for interdisciplinary sharing is an unavoidable obligation, and an experimental basis covering the entire field of evolution of all the different parameters of influence of the system. In "simple" systems where there are obvious "cause and effect" relationships, there is necessarily a connection between the paradigmatic model (validated by experience) and the epistemological approach.

However, in complex systems, it may be the interdependencies between components that prevail over disciplinary paradigms. As long as the latter are not revealed, understood, or studied, the "experimental" scientist can arrive at proofs of concept that illustrate an openness, in an original creativity, towards a field of possibilities. However, there is still a long way to go between the initial idea and industrial development, which requires a real mastery of the phenomena in question.

However, in the current research management system, if it is possible to carry out stimulating proofs of concept, it is more difficult to engage in an epistemological quest because it is difficult (interdisciplinary approach) and has a non-zero probability of failure. Moreover, the "trial and error" approach, which involves a very large number of operators working under standardized conditions, does not really fit into current (at least academic) research practices. Today, we are very far from the Manhattan Project.

Between the epistemological dream and the difficulty of experimenting in a teleological way, there is still room for diverse ideologies and senseless promises.

Box 1.7. *Paradigm and epistemology*

Interdisciplinarity is a process in which a capacity for analysis and summarizing is developed from the perspectives of several disciplines. Its objective is to address a problem as a whole, by identifying and integrating all the relationships between the different elements involved (Ministry of Education and Culture 2015). It attempts to summarize and link disciplinary knowledge and place it within a broader systemic framework. The pragmatic vision of interdisciplinarity, engaged in integrative research, refers to a type of research in which (Redlingshöfer *et al.* 2014):

– disciplinary specialists work as a team to address a problem and come up with recommendations onto solve it;

– specialists share their disciplinary knowledge: concepts, methods, and tools for interactivity with partners (researchers, developers, and other interest groups);

– the research is conducted on behalf of a client or a group of clients whose request sets the framework for the interdisciplinary team;

– the research objectives are development-oriented.

The strengths of interdisciplinarity can be briefly described below:

– Complementarity: since no one discipline can explain everything on its own, the contributions of several of them provide better insight.

– Creativity: interactions between disciplines challenge the opinions of team members and require them to produce more original explanations and methodological innovations.

– Learning organization: development of mutual understanding, sharing of responses and problems to be addressed.

– Return to one's own discipline: a new look at the limits and biases of one's own discipline and the acquisition of a broader knowledge. Taking a step back from your methods and comparing them with others helps you to better understand your own discipline.

It must be recognized that those engaged in interdisciplinary activities may find themselves doubly inclined to worry about their legitimacy. Some consider that the search for effective models that are sometimes heuristic can lead to provisional proposals that lack universality. Evaluating such operations, both in their rigor and relevance, means, on the one hand, analyzing and judging the products of the training and, on the other hand, by comparing them with the frameworks of the disciplines and testing their content and boundaries from the point of view of the categories and rules of action mobilized by the partners involved. It also makes explicit the logic of building and processing training objects. It is true that an analysis of minimally risky scientific work, involving several evaluators, does not directly generate support, because it is not possible to make a clear statement on the accuracy and effectiveness of what is proposed. As essential as it is (recognized by all), it is necessary for it to be put into practice with strong support from the hierarchy.

Innovation is above all about creating new links between disciplines, between know-how, between designers and society, leading to original configurations between otherwise separate elements. Figure 1.12 from Bary (2002) extends the discussion in Figure 1.8 to society as a whole. Convergence aims to unite knowledge “around a common understanding of the challenges, a shared vision of the overall objective, a collective awareness of risks and a concerted assessment of the viability of the innovative solution” (Gramaccia *et al.* 2009). Convergence therefore calls for a form of voluntary, deliberate and collective transgression of disciplinary barriers in order to converge, or even attempt to reunite the disciplines convened in the form of a global approach attentive to both structures and changes, that is to try to approach the fundamental complexity of the real (Wallerstein 1999).

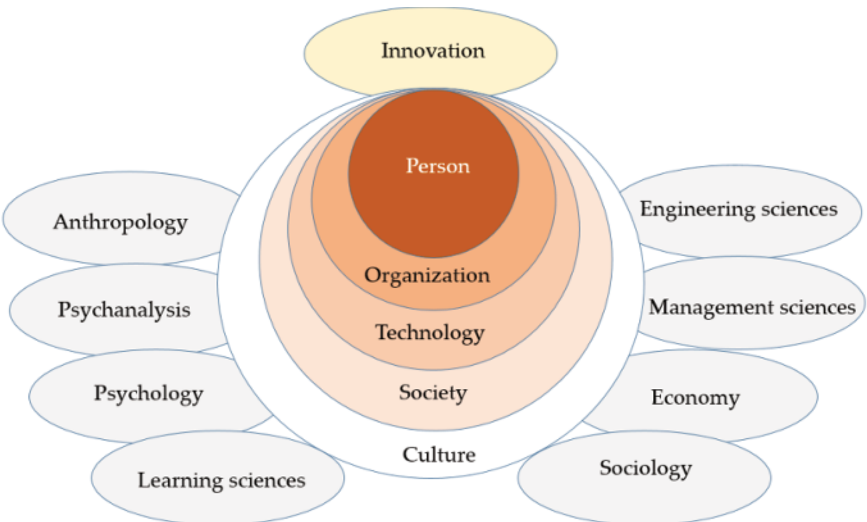

Figure 1.12. *The dimensions of innovation. For a color version of this figure, see www.iste.co.uk/schaer/process3.zip*

On the basis of a more in-depth analysis, redeployment axes should be proposed to enable more responsible, scientific, and flexible cultural developments adapted to the new goals pursued. It is by means of fundamental transformations and risk-taking that we will know whether process engineering will continue to be able to be an efficient actor between disciplinary research and the society of material and energy production. Several avenues for the evolution of production systems are now put forward in many accounts: societal changes, "mass" personalization, circular economy, service and functional economy, territorialization of production and knowledge, knowledge economy, development of new skills, communities of highly interoperable actors, innovation integrated into a continuous process essential to the competitive positioning of research, companies and their performance. However, in initial training, scientific disciplines are divided into sub-disciplines, to the point that the epistemological unity traditionally attached to the "hard" sciences and reasoning are diluted in the new paradigms (Bot 2007). It is the in-depth coupling–opening that constitutes the paradoxical injunction that must be "optimized" for operational purposes (functionality of knowledge and know-how).

The objective of any modeling is, for any "professional" technician, to provide a configurable system (when possible) in order to optimize it for a specific purpose, thanks to a judicious choice of input parameters and a "stable" and robust control in its temporal (or even spatio-temporal) dynamics. The environment of the production systems to be invented will probably require a robust knowledge of the independent and interdependent variables that condition its state at a given time. The more complex this system is, the more traditionally it must be described using a number of coupled equations, if possible, with the smallest possible number of parameters, taking into account what is measurable (and measured). For the engineer, the model that we want to develop is generally between efficiency and truth, where we want an "acceptable" compromise between staying true to reality and simplicity of implementation (principle of optimization). But what are the approximations that make the model operational according to specifications imposed by users? By companies? How can technology bring together points of view and remove (all) constraints? To achieve this objective, it is necessary to combine the knowledge of the different disciplines and professions involved with the associated difficulties (hence the use of the concept of convergence).

By proposing an interdisciplinary and inter-trade approach (see Figure 1.13), the project does not aim to make the approach play a role other than that of serving each discipline and each technical knowledge, by aiming to highlight, for example, the complex approach (Visvanathan 1997) which leads to the formulation of an explanatory or interpretative hypothesis, making it possible to establish a relationship of dialog and mutuality between partners. It should be noted that the project thus sketched presupposes adherence to the point of view of metaphysical ignorance. In this perspective, the project's role should be to stimulate critical reflection on the guiding ideas, founding intentions, guiding concepts, methodological, paradigmatic, anthropological, epistemological, ethical presuppositions of each discipline and knowledge of the field of possibilities of each profession. But at the same time, one must accept to humbly confine ourselves to a task of clarification, of untangling as skillfully as possible, which cannot claim ultimate clarity or a primary and founding truth.

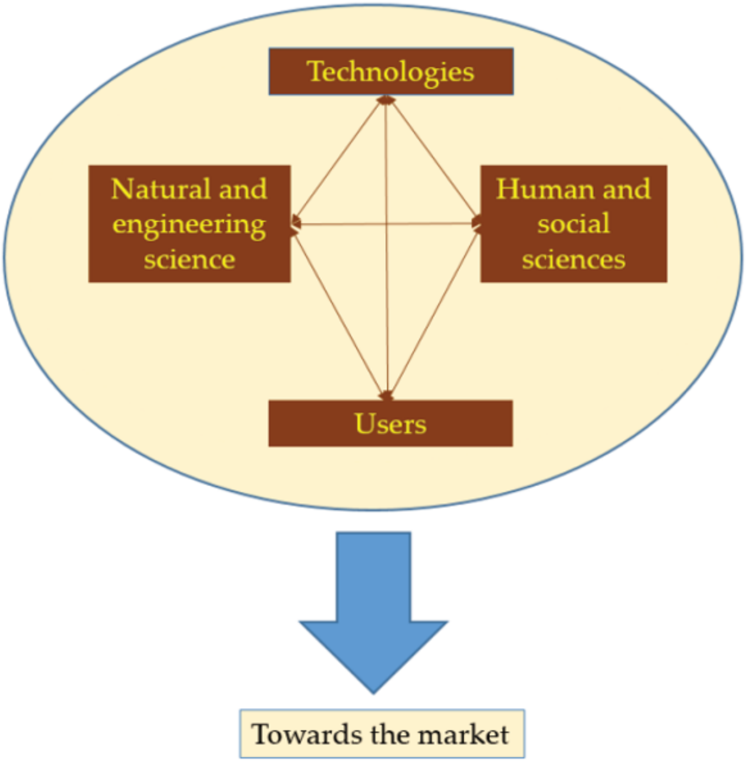

Figure 1.13. *Other form of convergence on the theme (including for the human and social sciences component aspects of social, economic, ethical, organizational desirability, etc. to be included in the operation)*

This is the purpose of this project, which aims to provide real support for the exploration of complexity for the redeployment of new industrial processes into new niches. First, as Figure 1.14 suggests, it is already a question of going beyond simple proofs of concept by checking the reproducibility of experiments (which can sometimes be tedious, but essential).

Second, it is a question of investing in the interdisciplinary and inter-trade technological convergence aspects, the difficulty of which everyone acknowledges. Indeed, if we place ourselves in a broader evolutionary perspective, as proposed, it does not seem possible today to predict the functional, spatial, and temporal evolutions of the new processes by deducting them only from the application of the simple laws that we could have identified, and this, at different scales.

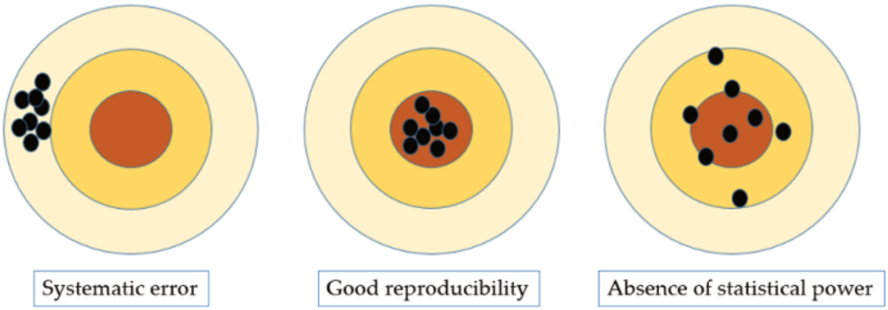

Figure 1.14. *The question of reproducibility in complex systems (Octo Academy 2017). For a color version of this figure, see www.iste.co.uk/schaer/process3.zip*

Presented as highly collaborative fields, process engineering, because of the need to integrate principles of scientific, sociological, and technological convergence, offers a particularly interesting field of observation of interdisciplinarity oriented towards a real application goal with necessary and possibly considerable economic developments. On this basis, disciplinary and inter-trade alliances should, after learning an internal but common language of communication, make it possible to reflect on the best ways to explore these promising fields without it being possible today to know if we will be able to define a causal relationship between the application project and the expected functionalities. In fact, the consultation of different partners from different disciplines and backgrounds must be expressed through a diversity of currents revealing the size, complexity, and tensions of the emerging fields of future processes.

1.6. A look back at interdisciplinarity

> The fraction of articles that mention interdisciplinarity in their titles has fluctuated, perhaps reflecting donor priorities, but the 21st Century saw this proportion reach an all-time high. (Van Noorden 2015)

> In other words, it is from the simultaneous presence of two opposites that the possibility of a healthy critical relationship arises in the face of disciplinary "truths" that represent themselves as being universal and historical, in the face of specialist dogma. It is from the possibility of this recomposed intellectuality, strengthened by the recovery of its lost unity, that the refusal of dangerous simplifications and mistrust in the face of dualistic Manicheisms are born. (Couturier 2005)

This concept involves the voluntary, deliberate and collective transgression of disciplinary barriers to bring disciplines together for an end (Dufoix 2005). Interdisciplinarity must "achieve coherence that respects the heterogeneity of the knowledge it gathers, but which is clearly not provided by any of the disciplines" (Roqueplo 1993). This very broad theme has been the subject of many works (see for example and in a non-exhaustive way Althusser 1967; Bloor 1982; Henry 1998; Lenoir and Sauvé 1998; Morin 1999; Kourilsky 2002; Le Marec 2002; Maingrain *et al.* 2002; Alvarez-Pereyre 2003; Mondada 2005; Camel and Fargue-Lelièvre 2009; Heil 2010; Panisal *et al.* 2010; Hamel 2013; Cornu and Flipo 2014; Darbellay 2014, 2017; Mahy 2014; Endrizzi 2017; de Hemptinne *et al.* 2017; Lemay 2017; MIT 2017; Billaud 2018; National Academies Press 2018).

The only way to ensure that the scientific and technological quality of interdisciplinary work is recognized could ultimately be to translate it into as many versions as there are disciplines, putting it in perspective each time in relation to the literature and research of each discipline. But what a waste of time! Proving that this is not a search for average excellence, or even (we may have to accept) mediocrity, even if it is creative, is essential because interdisciplinarity is generally seen as a means of overcoming "arbitrary divisions of thought" and as a process that goes beyond the simple juxtaposition of disciplinary points of view: implementation of cooperation and integration between specific disciplines and professions around a common object, with a view to co-producing knowledge. "Any new interdisciplinary research activity requires a coordinated approach, in which many different actors with their own interests and agendas must be convinced to collaborate. For this to work, a critical mass, through high quality research groups, funding, small and large companies, regulators and users, must exist. This is not new, of course, and this conclusion has been supported and analyzed in many publications from the interdisciplinary research community of social science and technology studies (STS)" (Malsch 2008).

But for Presse (2009), "the risks of non-communication are high. The researcher must meet certain requirements if they wish to establish the conditions favorable to a possible transfer of knowledge: listen, be attentive, take into account the meaning that the actors give to their actions and the analysis they make of the impasses in which they find themselves." Moreover, for Claessens (2009): "the fragmentation of research has created a limit to the control that this [scientific] community can claim to exercise over its own judgments."

In other words, interdisciplinarity can be defined as the desired result of a lucid, often difficult and controlled attempt by rational humans, but with perverse effects: time it takes to understand, mixing, management of different temporalities, methods, learning a robust language of exchange, etc. Beyond its idealized character, does this type of definition not lead to an extremely restrictive view? By focusing on the result rather than on the means to achieve it and in particular to implement these disciplinary translations, is it not likely to compromise the attempt, if only because no one is adapted to this type of concern?

On the one hand, we can consider that we underestimate the unintended consequences of human conduct and the effects of aggregation between the practices and strategies of different actors and, on the other hand, that we ignore the reality of genuine cooperation and exchanges between researchers and technicians (who have their own careers to manage). "Spokespersons with close representations can maintain good relations but be blind to the stereotypes they exchange because of the lack of critical distance. The second consequence is that acquiring this critical distance, i.e. confronting fairly distant representations, can require considerable effort" (Audran 2016). Interdisciplinarity is probably not only "active" in the sense that it would be based on effective dialog and joint efforts to overcome disciplinary silos, it is also an unwanted and perhaps little perceived product of disciplinary research, a "collateral" but also a real fruit of efforts aiming to achieve another end. Once members of disjointed disciplines have understood the value of this meeting and learned to draw inspiration from uses other than their own, they are generally ready for "active" interdisciplinarity. However, we must have extended an open hand to others for a successful approach.

However, given the evaluation methods, the financial support for this type of research, the sparse hiring of creative researchers practicing disruption and questioning, the silo mode of operation, etc., the road seems to be strewn with obstacles! There are probably as many philosophies as there are people trying to think, which is not based on the principles of "one thought", of momentum of different origins and the inclusion in the consensus induced by paradigms (whose interest in terms of effectiveness must not be rejected). If specialization has played a crucial role in the progress of science, does it not lead to the example of this reflection on process engineering and its future, to a certain fragility? So, returning to basics can be an important cultural asset to participate responsibly in the robust construction of our futures, near and far, in a world of research leading to quantitative reductionism, thus which is not very creative.

Moreover, in a pre-paradigmatic creative phase, the social and economic realities of additive process engineering were quickly decisive, leading to a cultural body that is now in the process of stabilizing, a body that has recognition within the scientific disciplinary system insofar as the field has defined its "doctrine body", reducing by (necessary) disjunction with many disciplines that could contribute to its development. As long as it does not voluntarily seek to confront "recalcitrant" problems, the domain remains alive, as long as it maintains an "acceptable" contact with the anticipation of society's needs (through different channels), which raises the delicate question of the voluntary departure from the habits perpetuated by the "system", its social organization, its ends (a little like in Tex Avery's cartoons where the hero continues to run in mid-air over the precipice before falling). The question of an unanticipated post-mortem survival towards the opening of new fields is however raised in a world that overly supports risk taking, creativity, and ruptures a *posteriori*, but which recovers from them with ease.

These are indeed systemic innovations that are expected. How then can technological innovations be integrated into system solutions in which anticipation of technological needs, procurement, training, and organization form a coherent whole? How to go beyond the core technology to consider global performance and knowledge management for industrial renewal? And then, what research and training in complex systems engineering must be undertaken to meet these needs?

The development of new advanced material and energy production technologies is a priority objective by saving energy and raw materials (André 2015). They are based on increasingly in-depth knowledge of transformation procedures and processes as well as increasingly powerful information technologies (computers, sensors, interfaces, virtualization tools, rapid development tools, models that are increasingly close to reality, multidisciplinary and multi-level models (Jaworski and Zakrzewska 2011), processing methods and tools). A first difficulty has been confirmed, of conceptual and scientific origin but, as has already been pointed out, a point on which it is worth emphasizing in particular, there can only be industrial and medical deployment if we are able to validate the robustness of the processes. The implementation of instrumented experimental devices is therefore an essential condition for achieving this openness to society. On this basis, the "process engineering" border object clearly requires that another convergence be mastered, one induced by the sharing of interests between scientists, technologists, and experimenters (users). It is on this basis that project groups must operate with obviously deeply revisited governance. This is close to what Wissmann expressed in 2010 when he wrote: "Let us mobilize together, with the means at our disposal, the capacity to reason, to discuss critically, from one science to another, and let us demand that the public authorities create the institutional framework to make this sustainable."

Figure 1.15, taken from (Baldé *et al.* 2017), provides an overview of some boundary objects that require significant contributions to the engineering of material and energy transformation processes. It can be a major player in disruptive innovations for ecological transition.

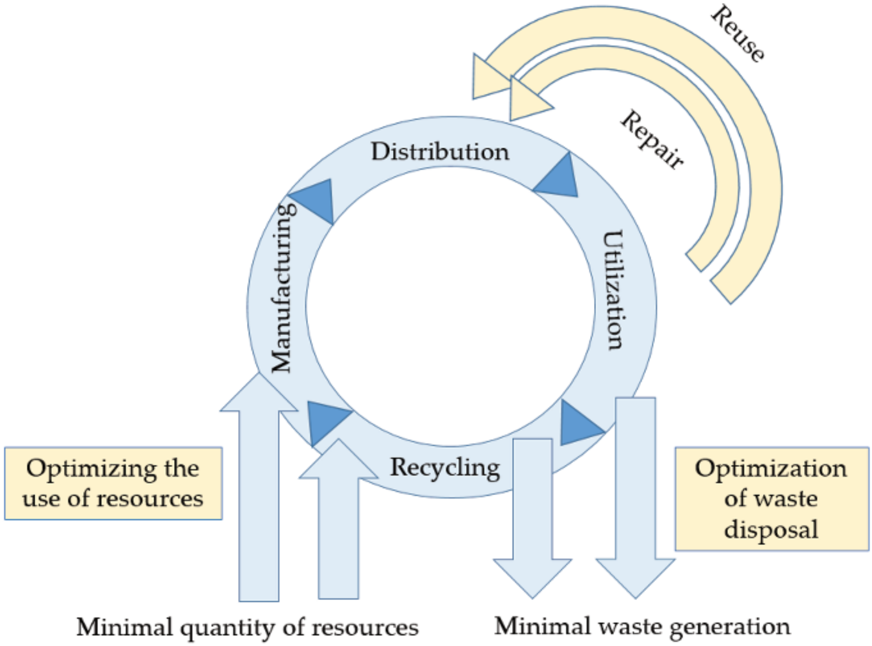

Figure 1.15. *Implications of process engineering in different current and future fields*

1.7. The models

> Modeling is constructed like a point of view on the real. (Le Moigne and Morin 2013)

> Modeling is the main and perhaps the only tool we have to study the behavior of complex systems that we have to consider. (Simon, quoted by Le Moigne and Morin 2013)

This vision of the place of engineering in innovation processes is complemented by other opinions (Engineers Council 1932; Vincenti 1993; Gagnepain and André 1996). Rationality is always privileged as well as respect, in principle, of constraints that concern socio-economics; research invests in complexity. The problems raised push for efficiency and therefore for the search for justified approximations, because they are robust, allowing, at a given moment, to take into account what is possible (principle of optimization). In a necessarily reductive way, there may be an apparent opposition between contingent scientific realism and refinement to reach the truth. It would undoubtedly be possible to discuss this subject *ad infinitum*, which would probably show the existence of a continuum between these two positions, which are non-exclusive (see above). Under these conditions of seeking the best operating efficiency, the sciences of chemical engineering use optimization methods, modeling, simulation and numerical methods, models and demonstrators, destructive or non-destructive tests, etc. Alter (2012) considers that innovators in all fields "succeed because they know the codes, but do not respect them as such." It is therefore necessary to be both compliant and recognized as well as divergent. A beautiful, paradoxical injunction!

However, these digital systems are not accurate and are fundamentally incapable of accurately representing real objects. "Digital materialization proposes an approach, a system and a symbolic basis for the bidirectional conversion between reality and information, where reality is represented as information in a correct and accurate dimensional manner, and as being accessible to human understanding, modification and design" (Turlif *et al.* 2009).

The notion of a model has already been expressed throughout this book, because it is an essential component of PE (which, for its "hard" science component, exploits it, at least in part, through its assertive knowledge of unit operations). "A model [...] is a mediation, more precisely that of a facilitation of mediation, within the framework of a cognitive survey, at least as far as science and technology models are concerned" (Varenne 2016). "Researchers in the field are confronted with a compromise between simplicity (efficiency) and complexity of their models (truth)" (Maslow 1966; Charles 2016). Beuve (2016) writes: "In the case where computer resources are intelligently used, it is undoubtedly true that modeling and simulation prove to be the most effective for the same level of technical and scientific development, because they often avoid many unsuccessful tests of 'physical' achievements and make it possible to converge more quickly towards, for example, an optimal design of an apparatus, a machine, an installation..." But, with research funding unsuited to the cost of experiments, is there not a risk that modeling will be confined to theoretical roleplay, losing its link (and its interest) with reality?

However, modeling and simulation research operations have consequences for society: "Abstraction today is no longer the abstraction of the map, the double, the mirror, the concept. Simulation is no longer that of a territory, a referential being or a substance. It is the creation, by modeling a real that has no origin, without reality: a hyper-real. The landscape no longer precedes the map and no longer survives it. It is the map that precedes the territory" (Baudrillard, cited by Rheingold 1993). These activities, exploring increasingly virtual worlds, are necessary by the reduction they allow and by the efficiency they promote; however, by diffusion and extension, they lead to applications that irreversibly shape our real time as citizens. If we find these activities in all or almost all the natural sciences, it is possible to say that they represent an important common cultural background between all the disciplines that contribute to the development of process engineering. They justify Guillermé's (1971) opinion that "there can be no technology until there is an explicit awareness of rationality and a requirement for mathematization in the history of representations."

Moreover, in his article in the *Encyclopedia Universalis*, he completes his discussion by defining technology as "organic knowledge based on principles; a technique is therefore really a technology only if it is presented as a doctrine; technology is opposed to the empirical technique which can be defined as a practice, based on unsystematic rules which proceed more from trial and error and immediate contact with reality than from a thought-out experience." Wouldn't we be moving closer to the notion of an intentional paradigm, defined as the best way to gather facts in a concept or association of a few concepts, with a view to an end? Thus, in scientific disciplinary approaches, as long as the paradigm is not invalidated by experience, as long as there are personnel engaged in the action and new subjects of study authorized by new possibilities of exploration of the real or artefactual worlds, the system produces new knowledge published – of course, increasingly under time pressure – in scientific journals, qualifying disciplinary excellence. "How can anyone be against excellence? The predominance of the ideology of excellence will be to further increase the hierarchy of the university system" (Rocher 1997). In this evolutionary logic, which is ultimately quite smooth, little use is made of his imagination capacities ("the imagination is nourished [...] by the lived experience, reinvents and constantly generates scenarios" (Bachelard 2005)).

1.8. A little complexity

> Knowledge is blind when it is reduced to its quantitative dimension alone and when both the economy and the company are viewed in a compartmentalized way. However, impermeable partitions between them have become essential. The dominant logic being utilitarian and short-termistic, we no longer re-vitalize ourselves in the exploration of fields, activities, specialties, ways of thinking other than our own, because *a priori* they do not directly and immediately serve the accomplishment of our tasks when they could enrich them. Culture is not a luxury, it allows us to contextualize beyond the furrow that becomes a rut. The obligation to be technically highly efficient in one's discipline causes people to withdraw into their discipline, impoverishing knowledge and raising a lack of education. We believe that the only "valid" knowledge is that of one's discipline. We think that the notion of complexity, synonymous with interactions and feedback, is nothing more than chatter. Should we be surprised then by the human and civilizational situation of the planet? To refuse the

> lucidity of complexity is to expose oneself to blindness in the face of reality. (Morin 2016)

> We must not build a simpler model of society; we must accept it as more complex. We must not design a more solid system, we must imagine it more flexible. We must not organize a single model, we must encourage diversity and movement. (Léonetti 2010)

> Complexity has always existed [...]. For a long time, in their quest for knowledge and wisdom, people have sought simple and logical explanations for the luxuriance of the world. (Donnadieu and Karsky 2002)

> Decomposing complex realities into simple elements to understand their genesis, better understanding the movements, flows and processes they cover, are ultimately the watchwords for enlightened elites. It is about moving from a static knowledge of structures to a dynamic knowledge of functions and operations that can account for both natural and human movements, flows and processes. (Picon 2002)

> Non-deterministic are phenomena linked to a succession of processes, which are themselves deterministic, but of which at least one is independent of the others and/or for which the fields of application of the laws do not overlap. (Charlionnet 2005)

Watzlawick (1991) defines a situation where an observer (who knows neither the game nor the language of the players) observes chess players for a period of time: if given time, the observer can isolate regularities, know that the goal is to reach chekmate, etc. In short, they must learn the rules of the game after a while and become a player themselves. If their time is limited, they may be able to learn some basics or else they won’t understand anything. If however there are crazy players applying a rule with anarchic evolutions, the observer will not be able come up with a legitimate trend model. The same will be true if they are not able to see “things behind things” (see Plato’s allegory of the cave). It is indeed one of the dilemmas in the study of truly new subjects to know if there is a mechanism that is still hidden (and therefore to be discovered, even if it is sometimes illusory when time is limited) or if, on the contrary, whatever the time devoted, the observer will never be able to understand the intimate functioning of the game of differentiation and cell growth. That’s what's at stake!

“We have acquired incredible knowledge about the physical, biological, psychological and sociological world. Science is increasingly leading to empirical and logical methods of verification. The light of reason seems to be pushed back into the depths of the mind, myths and darkness. And yet, everywhere, error, ignorance, and blindness progress as our knowledge deepens. I would like to show that these errors, ignorance, and perils, have a common character that results from a mutilating mode of organization of knowledge, unable to recognize and grasp the complexity of reality" (Morin 2005). Here is, in a few sentences, the introduction to the debate that takes science from causal to complex.

Everyone who has studied a little science must remember the theoretical experience proposed by Maxwell with his famous demons. Each demon regulates the flow of material between two vials of "hot" and "cold" molecules (at a travel speed vs. small relative to the average), which in principle allows them to have a constant overall energy of one hot vial while the other is cold. This would put the second law of thermodynamics at risk. But how, without information, can these demons separate molecules according to their speed? This means, for example, to keep to a basic description, that the containers must be illuminated to achieve the objective. It is therefore necessary to have complementary energy so that demons are informed and open the valves to separate molecules. Indeed, if we do not take into consideration the properties of the demonic observer, there is nothing left since it is not possible to describe the system and act on it.

If we cannot invalidate the laws of thermodynamics (otherwise, we would know), what we learn from this type of simple principle experiment is that by providing energy, it is possible to inform a system and enslave a system to achieve a goal as long as we provide the necessary energy. It is on such bases that the activity of engineers, in particular "processes", takes shape and becomes operational. If we have just described the entropic refrigerator in this way, what we are learning is that it is possible to introduce entropy retarders into a system.

So, in questions related to living organisms where cells are used to organize themselves to produce a material, a nutrient, a (piece of) tissue, we find ourselves analogously in a similar situation: the energy is external to the initial cell cluster and with the creation of a local order. "Morphogenesis is a process of the self-organization of cells that grow, divide, move or die according to the events that they have been subjected to in the past, their 'family history' and the communications they establish with their neighbors" (Jessus 2017). With Maxwell's experience, regulation is a simple process as described above and completed below:

– learn the speed of the molecules;

– compare this speed with a setpoint;

– open the communication port between the two vials;

– repeat the sequence.

For biotechnologies, it would be a simple matter, after a deposition of cells on a given support of:

– learn the intake of nutrients and other influencing factors;

– compare the effects of energy and oxygen inputs with the need for survival and cluster development/differentiation;

– regulate according to a more complex system approach (complex relationships between inputs and outputs);

– repeat the sequence.

Cybernetics occurs when cellular effectors or, simply, actuators or motors are connected to information capture systems, which in turn act on the effectors by different means. Biotechnologies are cybernetic systems, and are certainly complex.

The significant difference between these two types of experiences is that they do not obviously have the same modes of interaction, which are much more complex in the latter case. In both situations, we start from a given situation S(0.0) and for a given time Δt, there can be a whole set of possible situations $S(j,\Delta t)$ which, taking into account the teleological nature of the two experiments, leads to a situation respecting the desired goal adapted according to the internal environment of the cluster and external (selection of the optimal value j0). The regulation of demons remains the same whatever the t, however, since there is an interaction between the environment and the cell cluster (and vice versa); it can be evolutionary according to laws that, at least in part, escape us.

However, when a certain randomness is introduced into the system (noise, lack of understanding of information within the system and its relations with the outside world, etc.), any determinism may no longer be controlled and, by "butterfly effect", lead to bifurcations in the evolution of the system. This situation must be taken into account in the case of bioprinting with effects that may be significant, which is not the case with Maxwell's experiment. Thus, even if local evolution counters entropy, forks require behavior that takes into account the past (Wiener 1989).

"But, without having to be considered as being worth more or less, the 'whole' is now recognized other than the sum of its 'parts'. While there is not necessarily a hierarchy of components, interdependence between them is maintained. Globalization, even more than the totality, constitutes a unity, but diversity, which by a threshold effect (already involving additive, cumulative, almost temporal accumulation) will cause its emergence, is not yet necessarily understood as being intrinsically heterogeneous" (Ardoino 1996). Complexity is the opposite of a way of thinking that is deductive and simplifying, which tends to a univocal relationship by reduction between inputs and outputs of a system. It aims at a global vision that highlights the different contexts that participate in the system in a recursive way, in which inputs and outputs are both causes and producers of what produces them (Morin 1977, 1980, 1982, 1988, 1991, 2005; Varela 1989; Le Grand 1992; Dherse and Minguet 1998; Donnadieu and Karsky 2002). In this spirit, "each level of organization could do nothing by itself if it were not regulated by a control that comes from the level of organization that encompasses it. Reductionism consists in cutting off external control at an organizational level and believing that by describing the functioning of this isolated organizational level, we have understood the entire functioning of the system" (Laborit 1989).

What these few comments tell us, which come in particular from a reading of the writings of Heinz von Foerster (2006) who, among other things, sought to match regulation, cybernetics and entropy delay, is:

– a temporal continuity in the increase of the degree of organization of the cell cluster (the best way!) in order to achieve "its" purpose, defined on the basis of controllable criteria (temperature, spatial distribution of the clusters, rheological interactions with supports/scaffolds or simply, the cell deposition surface, material and energy flows, waste disposal, etc.), but taking into account possible bifurcations; and

– a relatively simple way to characterize the quality of an evolution following a bio-impression that could be a measure of entropy (or local order).

On the basis of this last remark, provided that we know how to measure the organization of the cell cluster targeting a tissue (without, at this stage, considering a shape or volume of the tissue suitable for use in repair), it would be possible to characterize the progress of post-treatment following bio-printing, which would make it possible to select (by trial and error methods?) more optimal ways than the projections of current work that are still too involved in proofs of concept.

The emergence of complexity in the design and production of static, evolving, and/or living objects goes hand in hand with a technical project since the purpose of manufacturing instruments is quite clearly to be used by practitioners ("technology is not applied science" (Rec 1978)); it is at this moment that the notion of a boundary object takes on its full meaning by associating in the most intimate way possible, as much as possible by convergence of interests with regard to a goal, designers, technical services, and users. All stakeholders become collective inventors of a particular process.

Complexity brings about changes in the way we try to control the real world: the first concerns the status of reality using the example of wave-particle duality, the second concerns the articulation of disciplines which complex reflection is based one (see convergence and interdisciplinarity – for example Piaget 1967; Achoff 1970;

Vico 1981; Watzlawick 1988; Araujo-Jorge 1991; Le Moigne 1994; Nicolescu 1996; Atlan 1999; Kourilsky 2001; Le Moigne 2001; Roux-Rouquié 2001; CNRS 2002; Picon 2002; Donnadieu *et al.* 2003; Simon 2004; Charlionnet 2005; Germinet 2007; Beguin and Cerf 2009; Wolf 2009; Mathieu and Schmid 2014; Montchouris 2014).

Figure 1.16, extracted in part from Donnadieu *et al.* (2003), brings together some elements to be considered in a complexity approach.

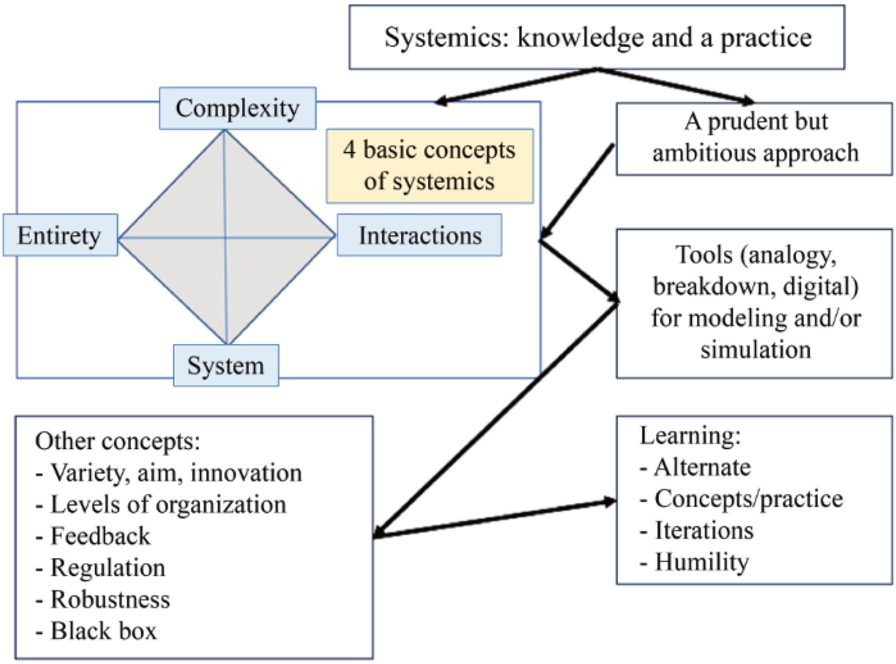

Figure 1.16. *Complexity and systemics*

According to these authors, systemics is "a discipline that brings together theoretical, practical and methodological approaches to the study of what is recognized as too complex to be addressed in a reductionist way and that raises problems of boundaries, internal and external relationships, structure, laws or emerging properties characterizing the system itself or problems of how to observe, represent, model or simulate a complex whole."

NOTE.– Tasks requiring interdisciplinary approaches and the transfer of knowledge, empathy or creativity may be difficult to automate in the long term (World Economic Forum 2017).

1.8.1. *Hyperobjects*

Yves Citton (2016) in the field of complexity applied to process engineering refers to hyperobjects. He writes: “Nowhere are hyperobjects isolable as classical objects because their existence is interobjective: their mode of existence consists of relationships between things that we identify as objects (a glacier, a water level, a harvest, a thermometer). Whether we call them ‘systems’, ‘attractors’, ‘networks’, ‘intrications’, whatever: they exist and operate as a fabric of relationships conditioning the behavior of the objects that hold our attention. Our individual subjectivity, the result of our collective intersubjectivity, is itself only one of the effects of these fabrics of inter-objective relationships. The challenge presented by hyperobjects therefore calls us to alter the inter-objective tissue that frames our inter-subjects, so that they can become attentive to hyperobjects as well as to classical objects.”

These may include areas such as energy (renewable or not), climate, waste management, global warming, reserve management that have links to process engineering, but more broadly, economics (with the example of sub-premiums in the United States), citizen tracking (mobile phones, GPS, Internet of Things, etc.) (see, for example, Baudrillard 1968; Barad 2007; Fischer 2008; Bonneuil and Fressoz 2013; Quessada 2013; Morton 2015). Citton (2016) writes: “hyperobjects are viscous: they tend to stick to beings whose existence is involved in theirs.” We’ll have to deal with it, like Captain Haddock in *Tintin*.

Technological progress increasingly involves complexity and generates analyses concerning, for example, strategy, risks, or expected benefits, analyses that are always subject to uncertainty (see hyperobjects). Some people immediately judge and are inclined to provoke direct confrontation. Others wish to have a serene expertise, taking into account interdependencies and recursions, likely to delay decision-making. And radical solutions, real paradigmatic breakthroughs, can sometimes be found in a context of media turmoil. The speed of change is at the root of major trends, which can explain the difficulty of making good decisions, which try to take into account the complexity of the world and constraints, including that of time pressure in complex expertise (André and Gnansia 2017).

Limits to the use of interdisciplinarity

There may be limits to the proper use (!) of interdisciplinarity, which aims to cross disciplinary boundaries, despite the participants’ desire to cooperate towards a common goal. There may be impossibilities in exploring complex subjects through interdisciplinarity. This may be the case because of a lack of knowledge on a disciplinary axis or when the summary of a consensus cannot be reached from the different disciplinary perspectives and their mutualization. A commitment must then be made to specifically address this lack of conceptual content between disciplines.

An example at MIT (2017)

The MIT organizes interdisciplinary cooperation on complex societal issues – energy, water, food, transport, safety, health, environmental quality, economic development, etc. To make discoveries at the frontiers of science, each work on complex hyperobjects encompasses several major societal problems which are developed, particularly in the context of international openings.

Box 1.8. *Other considerations regarding interdisciplinary approaches*

1.9. Reaching a decision

> It is for lack of knowing what is written up there that we don't know what we want, or what we do, and that we follow our fantasy, which we call reason, or we follow our reason, which is often only a dangerous fantasy that turns out to sometimes be good, and sometimes be bad. (Diderot 2000)

It is undoubtedly commendable to have ideas, but from a societal point of view, it is advantageous to move towards its implementation and for this reason (which is obvious), it is necessary to make choices, if possible, the best in a given context. Berthet (2018) reminds us that we live in a framework of limited rationality; rational on the one hand, but populated by cognitive bias on the other. This result, when the situation is sufficiently complicated or worse, complex, leads the decision-maker to make choices that are not totally rational. Berthet reminds us that humans (of which decision-makers are still part, despite the emergence of artificial intelligence) must make decisions even when there are uncertainties or when knowledge is lacking. Moreover, this rationality is undermined each time we are under strong temporal pressures (as Martin Hirsch (2002) showed several years ago in his analysis related to the "mad cow" crisis) and in a more "obvious" way when we have to explore the complexity of the world. This last field, where uncertainty reigns, allows some people to engage, even in the name of science, in the affirmation of dogmatic choices. This is the area of excellence of many "Yaka" policies engaged in the easy and ideological reduction of complexity and interdependencies.

In this way, it is possible to address the question of the decision, which is by nature reduced. This is based on certain knowledge (in particular those that arrange, but not only...) and on the automatic exploitation of associations such as memories, emotional stimuli, etc. We then play on plausibility and on the appreciation built quickly, at the risk of serious errors. Our brains are telling us stories. "People are not used to thinking well and just trust a plausible judgment that quickly comes to mind" (Kahneman 2003). This situation is all the more true with decision-makers who have been successful without having to question their knowledge (see Edison vs. Tesla). This overconfidence, leading to a deviation from judgment, was previously studied by Kahneman *et al.* (1982), based on work by Kahneman and Tviersky (1973) on the poor predictive quality of a future because its predictability is not sufficiently studied.

Cosmides and Tooby (1997) write about this aspect of things: "the mind is a set of information processing machines that have been designed by natural selection to solve adaptive problems faced by our hunter-gatherers ancestors." So, who is left with the responsibility of declaring war, if the structuring of information is based on unproven stories, overconfidence, and truncated statistical approaches? What confidence can be placed in the work of an engineer engaged in optimizing the main parameters of an industrial system when those considered irrelevant are neglected (Thaler 2015)? Occupational and environmental risks are there to prove that failure to take these elements into account leads to some problems, sometimes fatal, for people and the environment. We remain for years exploring principles of utility limited to the economic framework where the main direct and indirect (insurance) criterion is money. Heuristics is a little bit for others, less for just ourselves.

The current influence of AI in decision-making is a developing process (André 2019) and it has even been discovered that the decision resulting from AI can be more qualified (because it uses objective data without perceptual illusions) than that of a human. We should probably go a little deeper further and investigate the issue further, because this AI was programmed by one or more humans.

So, no, people are not quite reasonable and that's the way it is. But life with totally robotized (i.e. totally rational) people would probably lose, as our reptilian brain points out, its unexpectedness and overall quality. Simone de Beauvoir (1986) spoke of this "brand new little companion, with his smiles and unexpected reluctance". This situation not only has shortcomings; it also allows creativity.

1.10. Findings and proposals

> There is a [...] reason to neglect neophytes. With regard to the law of continuity of societies, as well as the specificities of the intellectual world, they are often the ones who make things happen. (Sévilla 2000)

An "epistemic operation [is] an act (or set of acts) of thought by which knowledge is constituted, whether or not the nature of that act is consciously perceived when that knowledge is constituted" (Paty 1999). Thus, the epistemology to be created between the virtual (realistic models) and the simplified real must be constructed from different disciplines with transaction zones (to be defined and that come out of the present reflection); this iterative (instationary) method results from an obvious interdisciplinary game. Thus, presented as a highly collaborative field, process engineering offers a particularly interesting field of observation of an interdisciplinarity "in progress". On this basis, disciplinary alliances must, after learning a common language of communication, make it possible to reflect on the best ways to explore this promising field, without it being possible today to know if we will be able to define, in all cases, a causal relationship between a project (of transformation of matter and energy) and functionalities expected by the public. In fact, the consultation of different partners from different disciplines must be expressed through a diversity of currents revealing the dimension, complexity, and tensions of the field in transformation (see prospective analysis) that is chemical engineering. This should normally result in difficulties of "cooperation" between highly heterogeneous actors.

So, will it be the same for everything that concerns, for example, living organisms with biotechnologies or the systems in which humans are involved? Scientifically, the approach in engineering sciences to biology and human and social sciences through complexity is a rupture that recognizes the exceptional and problematic nature of the living (hard and soft). Moreover, Atlan (1979) asks us the following question: "What is meant by order and disorder in nature? When we encounter a natural phenomenon, how does it appear to us as more or less gifted with order?" It may be useful here to invoke, to illustrate the complexity and its study, the necessary acceptance of uncertainty and the heuristic approach in understanding so-called "complex" problems related for example to health, to the behavior of a single person (and not a population), thus giving greater value to the qualitative, the sensitive, and the heuristic, rather than the quantitative. Under these conditions, if the target is known, the means to reach it are probably multiple, with fuzzy paths that will have to stabilize according to the progress of the project. How can we usefully advise the technical services (see Figure 1.5) who will participate in the production of an instrumented demonstrator without involving them in a fuzzy decision tree? What then will be the meaning of the experiments in terms of real scientific progress authorized by an effectively relevant instrumentation?

Several scientific considerations/focus areas can be at work in order to make "thought" work in the same way as a "good" process should work:

– Disciplinary considerations: new knowledge; how to know the practical methods of the other disciplines involved in the action?

– Interdisciplinary considerations: how to integrate the different disciplinary elements for the project into a common corpus?

– Ethical and moral considerations: prevention, ethics of life, and the environment, long-term effects.

– From an epistemological point of view, the creation of new knowledge does not normally follow a linear process; how can knowledge from different disciplines then be synchronized? How does the integrated approach bring consistency to the problem associated with controlling a form of determinism in bioprinting?

– Can we strongly affirm that the model method can testify to the different relationships between disciplines and show the existence of a “third epistemic way” or a source of knowledge alongside theory and experience (Varenne 2007)? In the approach, the relationships between model and theory must be dynamic, interactive, and retroactive, constituting levers for experimentation with the acceptance of a form of epistemological pluralism. Then the model reveals the position of its designers (Brun *et al.* 2007); it constitutes for an interdisciplinary team a means of mediation, negotiation, and facilitated exchanges.

– Is the plurality of access and descriptions of reality posed as a basic principle because “pure, non-mediatized knowledge of the world is recognized as inaccessible” (Godard and Legay 1992)? It may be necessary to accept the non-uniqueness of the description to access an intermediary of reasoning, a heuristic means, a decision-making aid, to accept the multiplicity of models (with their limits and their coherence with reality), interactive approaches, the multiplicity of un-disciplined points of view (Jollivet 2009), and the strategies “to tackle” the problem.

– Disruptive innovation requires a better knowledge of the company’s environment, a mastery of processes in relation to a present or estimated demand. “Ultimately, the development of the ‘marketplace of ideas’, brainstorming and design thinking, the promotion of the culture of creativity at the lowest level of production, as well as the animation of innovation workshops around mind mapping and bodystorm are likely to lead to an innovative idea that will turn an existing market upside down, offering technologies that are qualified as ‘traditional’” (Guerraoui Filali 2019).

On the basis of the best possible knowledge of the diversity of representations, it seems necessary to clarify the role/interests of the various actors, to value diversity and the possibility of deepening reflection on particular axes, but also to seek other partners to balance out the debate for action as much as possible. By sharing a significant part of ignorance, it must be possible to assess the uncertainties of scientific and technical knowledge, approximations of knowledge, abuses of interpretation, limits of competence, to measure, at least the extent of unresolved issues and questions. This approach should allow us to distance ourselves from all (?) ideologies, overly reassuring statements, and dangerous simplifications. But to do this, we must have a sufficiently serene or partially “neutral” framework to move forward, with long-term approaches.

But the neutral aspect does not necessarily lead to a neutral decision, based on the search for a soft consensus. To go in the "direct" direction, this is an organizational construction work, to achieve interdisciplinary objectives that are original and for which we do not have, to the authors' knowledge, a great deal of expertise. It is therefore necessary to experiment with long-term support from the hierarchy with volunteers. "We must keep an eye on what appears, what emerges, but there is no reason to forget resilience [...], the weight of rigidities, friction. It is important to keep the process of hybridization, interbreeding and irreduction, but also to think about the perpetuated vulnerabilities and the impossibilities of doing, to analyze for themselves the dominations, their implementations and their experiences" (Pestre 2014).

The idea of other partners being trained by the one who has authority in the movement was analyzed in another framework by Fivaz (1989), who makes a link between emotion and entropy, by transferring this concept of thermodynamics to humans. According to this author, this link is defined by the German term *Schadenfreude*[2] and by a sign characterizing the mental system: if the entropy flow is outwardly oriented, the emotion is positive. The mind is sensitive to the flow of entropy related to the possibility of adaptation to what is new, and well-being situations may arise when the entropy extracted from the mental system is at its maximum. In this context, the key actor (the scientific project manager for interdisciplinary work) builds a detailed image of the evolution of their environment, coherent and rational (order), taking into account what is real and what is possible (knowledge). This image must be able to be used to draw verifiable conclusions (stabilization of the projection). Part of this entropy flow can be captured by receptive partners, making the project a success. If one of the criteria is not met by at least one of the partners (clear understanding of the project insufficient technical competence, relationship problems, etc.), there is negative entropy. Disadaptation creates a gap between the norm and the maximum entropy, thus limiting the change's chances of success.

Box 1.9. *Drive principle*

1.10.1. *Technology: serve and/or partner*

> Above the immediate subject, modern science is based on the project. In scientific thought, the subject's mediation of the object always takes the form of the project. (Bachelard 1934)

> Today, it is clear that the philosopher is thinking about and discussing a world that is beyond their control. For their part, the scientist advances without conscience, in a non-reflexive knowledge that prevents them from progressing. (Jean 2019)

2 Literally "joy of damage", one that is experienced by observing the misfortunes of others.

First of all, as already mentioned, artificial intelligence can contribute, by gathering various types of information, to bringing in elements that contribute to innovation. Forbes points out that, in addition to task automation processes, in which AI plays a major role, there is also noticeable evolution in design and innovation processes (Araya 2019). AI is integrated into the creative professions that are a characteristic element of today's society that is eager for innovation (Bell 1973). Forbes points out that the transition from the information age to the creative age will require a profound change in educational strategies, which will now have to make an effort to combine technology and creativity (see Chapter 2). To go further on this subject, interdisciplinary scientific operations have been launched in North America with the objectives of advancing the development of artificial intelligence in the public interest, security (facial recognition, for example) and better equipping decision-makers in a more judicious and inclusive public technology policy. These operations are aimed at:

– assisting innovators with an in-depth view of AI, the evolution of technological advances and potential applications;

– strengthening the analytical capacities of future managers, so that they can better understand and control the public policy implications of AI;

– contributing to States' initial responses to the emergence of operational aspects of AI (see, for example, Williamson 2015; Washington University 2017; Villeneuve 2018; CIFAR 2018; European Commission 2019).

Moreover, for a think tank, by getting involved in in-depth action, individual motivation, if it can be brought to light, must be able to reveal "collective intelligence", informal support for curiosity and to multiply creative performance. At the same time, however, as illustrated in Figure 1.5, theoretical and simulation approaches will need to be validated through experimentation. For Richer (2019), "collective intelligence is a strategic resource of a community of people (or an organization like a company) consisting of leveraging the interactions between its members at work to collaborate in the search for a common result, to reflect on the organization's own functioning, to optimize lifelong learning processes, to articulate the processes of creativity and innovation in a complex world".

It is still too difficult to get scientists to explicitly explain the gaps and difficulties they are aware of in their research activity. In the face of the impending disruptions, it is be a matter of setting up processes to support incremental change. All over the world, individuals, companies and organizations are imagining and testing solutions. The exchange platforms (including industrial chairs) must make it possible to link these different pieces of the puzzle and to leverage them to disseminate them as widely as possible. It is a question of engaging in research on the engineering of the future. It could be advantageous for a profession, or an industry in a partnership framework, to lead a network created around ideas for systemic change, in order to provide researchers, individuals and organizations with tools and concepts to set these dynamics in motion (ensuring that everyone can appreciate reality as others see it through *Peer Shadowing*, carrying out pilot projects, immersion in the reality of the other and projection into action). It is these sensitive and emotional experiences that, little by little, make it possible to build a shared reality and change one's culture (see "great challenges", Ministry of Education and Culture 2015).

Box 1.10. *Collective intelligence*

It is indeed by co-processing the research object that it will be possible to achieve this objective, by adapting or developing robust validation instruments. In the integrative approach (boundary object) that should be put in place, several principles are normally at work:

– the meeting of scientific and technological intelligence by bringing together experts from different backgrounds (even eccentric/divergent? users), in order to produce unexpected intellectual connections capable of generating new ideas and confronting theories with reality. An improbable idea *a priori* only becomes reasonable after it has emerged from the collective consciousness;

– inspiring trust: creativity in a group tends to be perceived negatively or even tacitly muzzled, as potentially disturbing. The collective exerts a coercive force that forces each member to rally to the "majority" opinion. Once the talents have been gathered, it is important to "free the voice" of everyone within the collective;

– the size of the teams is then the essential counterpart of individual development. An organization that favors small think tanks and action groups should foster a closeness of minds, learning about the culture of others, avoiding clans, and ensuring consistency of information, provided that a real "laborious" activity is accepted by all. The small size of the teams should also discourage absenteeism;

– with the flexible organizational framework in place, creativity should be able to emerge from an environment that cultivates a certain lightness and is free of hierarchical issues. The creativity sought is ultimately only the collateral effect of an informal time of in-depth reflection and cross-fertilization that should naturally become the place for collective production that is both scientific and technological;

– the presence of an arbitrator (who must advocate for free access and altruism) to facilitate creativity/collective monitoring sessions. Creativity is not synonymous with the anarchic emergence of thought; it depends on a flexible and rigorous reminder of the framing;

– according to Michèle Freud (2015), creativity requires a good dose of perseverance. Too often, at the first difficulty, at the first failure, especially when the results are not up to their expectations, some give up. However, for creativity to be fruitful, it requires real commitment to achieve its objectives. It is through performance, the construction of an idea (or its consolidation) that we can improve the intuition of our own possibilities. Creative people are very often also perseverant people, who seek to study in-depth to validate their ideas. Driven by their curiosity, their desire to understand, they can become absorbed in their task and devote significant energy to it, mobilizing most of their intellectual, emotional and even social resources. They do not willingly give up and refuse to “let go”. Creative people, even if some of them have also experienced failures, learn from it and persevere. It is by understanding the causes of their provisional failures that they succeed in correcting their mistakes and making progress;

– the classical multidisciplinary approach starts from an object:

- it consists of involving several specialists in the presentation of a subject without there being any confusion between the disciplines and it is up to the person who has requested qualified expertise to make the synthesis. It is up to them to find their interest, to get a general idea or to take a decision, with all the elements in hand, in a specific framework of interdisciplinary scientific democracy,

- it is, rather, that which is required for research on a complex type of object that needs to be approached from several points of view by specialists from different backgrounds,

- the initial specifications must be in the form of a definition of the function or role to be played by the project group, rather than in the precise form of a “product” to be provided. “The main part of the definition of the result to be achieved lies as much in the production methods as in the final product, and the specifications” (Albaladejo, Hubert and Roche 2009).

How does one come to include research requiring new instrumentation in an interdisciplinary perspective? In several writings on interdisciplinarity, the idea that it is the complexity of certain objects of study (Boiffin 2004; Deffontaines and Hubert 2004) that calls for interdisciplinary practice is recurrent. Indeed, the nature of these objects is conceived as a dynamic system, “irreducible to a single dimension” (Klein 2004). The accumulation of knowledge and the intersection of views and the interactions between phenomena undeniably characterize research objects: complexity has become an intrinsic value of knowledge and research in general (Bühlera *et al.* 2006).

The *ENS de Lyon* has set up an interdisciplinary junior laboratory (Durrive *et al.* 2012). The authors of the article shared their experience of working on a boundary object to break out of disciplinary frameworks and, in particular, the pitfalls to avoid, under penalty of failure:

– do not directly match the object with non-shared concepts;

– do not believe that goodwill is sufficient to make approaches, methodologies, concepts, or paradigms commensurable;

– have a reflexive perspective to prevent everyone from engaging in their own practice;

– avoid generalist points of view that can be understood by each member of the group, by trying to get out of their discipline, there is a risk of them getting deeper into it.

To move forward, the authors operated in several stages:

– definition of the concept related to the boundary object, by trying to make it operational in its disciplinary practice;

– use of an explanatory diagram (flowchart, for example) in which everyone is invited to express aloud what they understand, what seems intelligible to them (making unspoken words appear). The use of this "tool" allows the understanding of one's bias towards their own knowledge (the use of "conceptual black boxes") through the interaction with "lay" scientists from other disciplines; each member cannot mobilize the common references of their discipline and must open the black boxes; the presence of other representatives in the interdisciplinary space imposes a requirement of common understanding (see Figure 1.13);

– discuss the importance of a particular discipline in dealing specifically with the boundary object and how it makes it potentially intelligible;

– return to one's practice, avoiding "by-passing" others to engage in one's own research activity (self-understanding) and external criticism (passing from "I" to "we" to reach a conceptual connivance);

– in exchanges, if everyone is led to express themselves in their scientific culture by trying to avoid finding themselves in an "a-disciplinary no-man's land", it is important to share their points of view (this cross-referencing the one relation to the other, comes close to defining the object of interdisciplinary research) and to accept that ignorance is not a defect;

– to move forward, it is necessary to accept a back and forth between the different proposals and explanatory theories, on the one hand, and remarks and heuristic intuitions on the other (going back to the complex problem from the disciplinary reduction).

In this construction operation, it is advisable to try to limit, as much as possible, the use of operations that increase the risk of losing control of the theorization process that serves as a guideline for research oriented towards an applicative purpose. However, the social communications that are at the root of interactions necessarily mobilize common sense. Knowing that it is impossible to totally "purify" the rational dimension of the project – cognitive management – of its largely implicit emotional and social components, and, more fundamentally, the symbolic dimension of any human process, it may be useful to limit and control the share of impurity, by means of all the technical devices allowing us to reduce the loss of distance to the object during interactions... It is therefore a paradoxical injunction.

Sociability naturally plays that a prominent role in the exploration of cross-reflective conditions; there is a need to know each other, to have common references, to rely on strong shared implicit values (Le Marec and Faury 2012). This situation of interdisciplinary project management, which has been experienced over a period of about two years, requires that, in order to achieve a possible objective of theorizing a complex problem, the necessary time and a proactive attitude be devoted to it. This necessary condition does not say whether there will be enough time to achieve the objective, whether the disciplines present are sufficient in number (hence the need for openness) or whether the problem has a solution. But it is this experimentation that must be attempted. Who will take the risk of trying, if the probability of failure is not zero?

Following Béchillon (1997), interdisciplinarity would be defined as “an articulation of knowledge that leads to successive approaches, as in a dialogue, to partial reorganizations of the theoretical fields involved”. In many situations, as in the case covered in this section, interdisciplinarity is essential for the development of knowledge and should make it possible to provide answers to possible applicabilities of the concepts developed (Bonaccorsi 2007, 2010). In a recent article, Louvel (2015) explored the effects of interdisciplinarity on boundary objects (Trumpet and Vinck 2009), using nanomedicine as an example. Normally, it is a question of analyzing how exchanges between biology and medicine, on the one hand, and chemistry, physics, and engineering, on the other hand, are developed in the most balanced way possible.

It is conceivable that there is the attractiveness of a new field, on the one hand, because of obvious and spectacular results, and, on the other hand, through the use of public opinion and technostructure, to promise even more, and find significant funding to develop scientific research at the interface between different disciplines. What Séverine Louvel’s article (2015) shows, for the nanomedicine component alone, is that the scientific pressures of the disciplines called upon in interdisciplinary action are not balanced, either for France or for most other developed countries (with differences, linked to culture and local organizations). So, what about the integration of technologists in an operation where their place is important? Will they be lateralized?

Process engineering, which integrates the biological, physical, chemical, mathematical and engineering sciences, as well as engineering principles and technological foundations, to apply new concepts that will one day create robust methods for the transformation of matter and energy (with behavioral and health and well-being aspects) aims to "manufacture" objects and products that are useful to society. In this future, highly new approach, where more than two disciplines must work together, we should, at least partly, move away from Vinck's (2000) vision of interdisciplinarity, which involves the import of instrumental technologies and concepts from "hard" sciences into process engineering, while specialists in this field characterize the effects in the role of data providers (a form of domination relationship, in a way?). Perhaps we should consider an educational world involved in a post-disciplinary approach? If the transfer of know-how is necessary because it introduces elements of quantification into a field that is not fully defined, the contribution of these skills through the rationality associated with them can lead to forms of profound mutilation, by reducing the scientific project (or simply by ranking disciplinary knowledge). Figure 1.17 represents a number of criteria (some of which are uncertain) that need to be mastered in order to innovate and that need to be estimated.

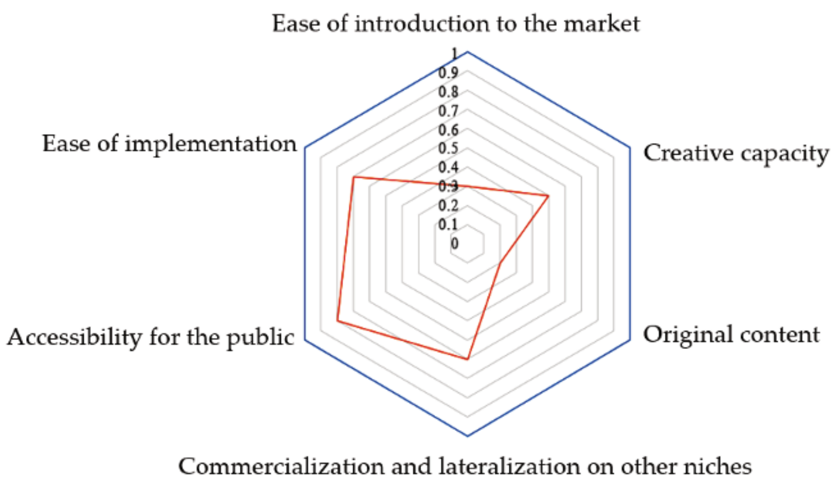

Figure 1.17. *Steps for innovation. For a color version of this figure, see www.iste.co.uk/schaer/process3.zip*

Bühlera *et al.* (2006) remind us, however, that "for most institutions, interdisciplinarity is only conceivable if it does not challenge the foundations of the disciplines, better, if it reinforces the thematic frameworks in place: '[the] practice of transdisciplinarity requires, on the contrary, the constant strengthening of the "hard core" [of the different disciplines]' (CNRS 2002). Evaluating authorities will more readily admit the incursion, into a related discipline, of a young researcher who is easily identifiable within their discipline than that of a young researcher who is in a new and/or marginal field in their own specialized field. In the first case, they will be congratulated and congratulated for their curiosity, even their risk-taking, and their approximations, since they have proven their worth in this field. In the second case, we will be suspicious and mock their pretentious incarnations, perhaps we will sense ‘intellectual instability’; it is certain that it would have been better if they had stuck to the achievements of their discipline”. What about a strong consultation with the technical services?

For the actors of the dominant “colonizing” disciplines of a “boundary object” type subject to act with motivation, they should have integrated, into their deep self, the reasons for acting in the name of a common benefit and not be afraid of disruption (especially if it is exogenous). Hence, in biotechnologies, biological systems must be analyzed like conventional machines! Especially since, for many biologists and life scientists, the label of “hard” sciences seems to constitute, with an implicit hierarchy, a real attractor, by the apparent rigor it can bring (Louvel 2015; André 2017a).

An interdisciplinary project results from the action of the following elements to varying degrees (see Touraine 1978):

– the highlighting of disciplinary affiliation, its interest, and reinforcement;

– the need for a mutual conviction of symmetrical coupling: mutual learning and sharing of knowledge and views;

– the integration of personal interests into the operation, which is conceived as an opportunity;

– participation with a vision of knowledge sharing to advance knowledge with “we” and less “I” for a successful operation (Habermas 1986).

However, as has already been pointed out, the scientific development of frontier domains open to creativity (Buys and Mulder 2014) and to the exploration of a goal of complexity poses considerable epistemological problems that do not yet seem to have concerned many researchers, perhaps not the leadership or the principals interested in the most immediate possible results? So, as long as we are satisfied with a “second-hand” search with purchased equipment (i.e. equipment previously purchased by others who may have made the first publication), the technical services will make the adaptations requested by scientists in a relationship of a certain vassalization.

As we can understand, the authors’ point of view focuses on co-processing research project teams, integrating theory, instrumentation, and experimentation (a desired combination of science and technology). In this essential context, if we want to get out of the accumulation of knowledge and proof of publishable concepts, we must accept the risk and help to integrate knowledge and professions that are still too disjointed today. This does not mean that the metal lathe operator will have to theorize, but that he has his place in a global process, which must win a project group on the innovation front from the corps of the different scientific professions involved. It is not enough to understand it, but to take the risk of putting it into practice. The example of chemical and process engineering could be used as a demonstration, but it is certainly not unique. In any case, ideas of responsible slow science could be examined with interest, in that they allow less standardized ways of operating research (Stengers 2013).

1.10.2. *How to do or not to do?*

Scientific advances in national and international programs are now the responsibility of major laboratories and international teams, and the independent researcher no longer has much of a place in them. However, there are niches on breakthrough subjects, which are certainly not well perceived by the principals because they disrupt the course of things, the planned, and then, do not fit into the boxes provided for this purpose (Vian 1967).

Anyone who dares to question the procedures accepted by the majority of the scientific community risks being considered as a deviant, or non-compliant (the "must avoid the proliferation of ideas" recommendation from the CNRS National Committee for an old researcher from this great organization, now risks their work not being considered at all), but distinguished. It will be considered uncontrollable until the day when a happy idea passes into the economic field (André 2017a). However, it is often by formulating different questions that new avenues of research are opened up for us.

There must be a greater willingness to support ways of solving this problem, considered as a real brake on innovation of scientific origin, which cannot, for the innovator, be an obligation of patience. Additive manufacturing is now more than accepted after 32 years, a period that corresponds to approximately one generation. Intellectual agility may be a skill that can be worked on. It requires both plasticity and an appetite to leave its "comfort zone" (or the possibility of using additional hours that will occupy the temporal space). But, to their misfortune, the "system" still remains subject to the influence of their reptilian brain, the one that seeks to limit risk-taking by adding, day after day, procedures, organizational charts, committees, and ever longer decision-making circuits. Organizational sedimentation with "fractal percolation" may inhibit any initiative.

If the original researcher proposes an innovative device and faces such difficulties from the system, a promising solution could come from the call for participatory funding. This "ubiquitous" phenomenon is already reshaping the world of innovation. This was the case for the bioprinting company "Poietis" managed by Fabien Guillemot[3] in Bordeaux, which also brings scientists and society closer together. Maybe we could think about it for PE?

Everything leads us to support scientific creativity, but this is not urgent because the indicators rethink and quantify the methods of the past, and because we can take refuge in other well-rated (or well-funded) priorities. The space of "possibilities", the philosophy of "what if", "and why not" clashes with local cultures, hidden hierarchies and organizational routines, non-aggression, tacit rules, and evaluation procedures. How often are time constraints, short term, production imperatives (files responding to calls for funding, contracts, conferences, publications, etc.), and hierarchical imperatives (when they exist), priority management thwarting newly converted idea carriers (when there are any)? The "what if" is opposed to the polite but crippling "yes but" and the spirit of conviviality made of tolerance (or simple disinterest) and possible reciprocity is undermined.

Creativity and organization (real, often different from the one displayed) do not always go hand in hand. Organizing a human group means setting up a certain number of means, rules, procedures, standards, or values aimed at ensuring the effective cooperation of its members. It is, in a way, an attempt to channel individual actions, to reduce uncertainty and unpredictability in order to shape collectives, in order to achieve the desired operational efficiency and performance. However, creativity and innovation promote deviance, disruption and, as a result, upset the established order. It is therefore a very difficult art.

NOTE.– For Bernard Stigler (2019): "Disruption is therefore, first of all, an almost inconceivable acceleration of the speed of circulation and information processing."

The extent of anxiety, for those who are aware of this situation, has an effect on their avoidance strategies, which are largely unconscious or not expressed, but subliminal. From there to asking the question of whether the fear of being spotted one day (because the mode of control will have (finally) changed) is a reason to block our imagination and take risks is only a single step. But perhaps the researcher was recruited for his ability to produce well, but not to think too much about the divergence? So, we encourage behaviors of helplessness and self-reflection. We remain childishly afraid of the gendarme and slow down in front of the radar.

3 Available at: https://www.poietis.com/fr/index.php.

In order to try to go beyond these egotistical and childish attitudes, we need to rediscover a taste for scientific discussion, for culture in all its forms, for imagination, for effort and for the desire for personal action (not through an intermediary) with real risk-taking. To do this, it is necessary to recreate conscious desire, the collective imagination, because the energy for the desired is much greater than that of anxiety or, ultimately, cowardice. By working in an open system, thermodynamics then makes it possible to create organizational creativity.

However, it should be kept in mind that, if the researcher proposes a conceptual disruption (or an improvement of an existing theory), challenging the current paradigm, accepted "comfortably" by their scientific community, then few solutions will be available to them. Already, they will have no reason, their culture having conditioned them, to immediately believe in the legitimacy of their research. Moreover, the greater their disciplinary deepening, representing their monoculture, the more likely they are to have difficulties believing in it and being financed (see the example of Henri Poincaré in relation to Albert Einstein). Further, today they risk facing difficulty in publishing their articles in scientific journals through validated referrals, as they do not fit well into the current paradigms (the box syndrome of the archaeologist, Boris Vian (1967))! Do you have to be ignorant to dare? If so, how can we be scientifically credible and advance PE?

Eurostat (2019) has just published a report on the quantitative representation of PhD students at the EU level. Figure 1.18 shows that training through research in the engineering sciences represents only a small percentage of postgraduate students, reflecting students' small appetite for this scientific field, which is, nevertheless, able to find employment opportunities for them. It should be examined how to improve this general situation and, more particularly, that of PE, to participate in an industrial deployment of France in the transformation of matter and energy.

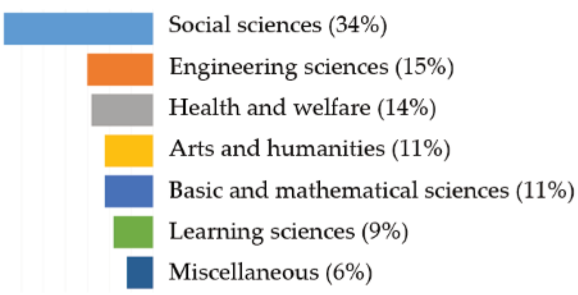

Figure 1.18. *Distribution of postgraduate students by major fields of science*

Research and "Matthew effect"

Scientific production is unevenly distributed among the population of researchers and teacher-researchers, that is, a small proportion publishes a very large number of articles while the rest publishes only few. In general, if, for a given period, a histogram of the number of persons N, having made p publications, is produced, a fairly representative correlation of the facts corresponds to an empirical law of the form:

$$N(p) = K.\ \exp(-\alpha.p)$$

where K is a discipline-dependent constant and α is an invariant.

These radical differences in the productivity of the scientific research community could have several origins:

– differences in talent between individuals;

– the possibilities given to some to lateralize their activities: research administration, teaching and additional hours, etc.;

– differentiated treatment by the system of how science works: the most reputable researchers (for a variety of reasons) at a given time benefit from more advantageous research conditions.

These differences generate a cumulative process that affects competition between scientists, in the sense that the researchers who have been the most "productive" will be able to benefit from conditions that promote greater productivity. The founder of the sociology of science, R.K. Merton (1968), first described the processes of cumulative advantage in science, which he gathered under the common name of the Matthew effect. He refers to Saint Matthew because of a passage in his Gospel where it is stated: "For to him who has will more be given, and he will have abundance; but from him who has not, even what he has will be taken away."

Academic hierarchies and major research organizations make recruitment decisions based on a comparison of candidates' scientific production profiles, based on peer selection methods, associated with yesterday's conformity of thought where the slightest risk is prohibited. However, apart from partial information, committees acting for future employers do not always have in-depth access corresponding to the real quality of the applicant. Several coupled reasons are attached to this situation:

– a lack of time to judge the merits and use of quantitative analyses;

– a lack of critical thinking on the part of the evaluators, or even unhealthy cronies;

– difficulty in judging;

– fear of taking risks.

Employers have a given job (for a long period of time) with fixed attributes that they are satisfied with filling as best as they can. Over time, these attributes (the associated levels of pay and productivity) are heterogeneous (although they tend to get closer with age). More specifically, new hires are competing for positions as "junior" researchers, then as "senior" researchers who are characterized by different levels of remuneration and associated productivity (apart from bonuses and overtime). The agent that has been most productive in the first step is selected by the organization offering the job with the greatest expected productive utility. However, the latter increases the chances of obtaining a position that offers a better salary. A dynamic bias favors, during the second competition, the researchers who were the most productive during the first: we then speak of a cumulative advantage or the Matthew effect.

Box 1.11. *Matthew effect*

1.11. Activities initiated from the "base"

> The problem of Value must always hold the pivotal position, as the chief tool of analysis in any pure theory that works with a rational schema. (Schumpeter 2006)

> The first spontaneously evolved form of wealth consists of an overplus or excess of products, i.e. of the portion of products which are not directly required as use-values, or else of the possession of products whose use-value lies outside the range of mere necessity. (Marx 1957)

1.11.1. *Framing elements*

In 2016, with Laurent Falk and Jean-Claude André, Marine Horckmans carried out qualified work to recall the more in-depth work of Bruno Latour (1995). In André (2017b, 2017c, 2017d), a synthesis of this work was presented, to illustrate the difficulty of training researchers from a large CNRS laboratory associated with a university, in disruptive pathways, requiring risk-taking. Given the theme of creativity and innovation, some of the conclusions of this research action, carried out largely and successfully and efficiently by Marine Horckmans, are summarized below. Most of this work involves a survey of the staff of this unit by direct interviews.

The elements related to the changes mentioned in the previous paragraphs have advocated for an internal analysis of the factors supporting this need for evolution that could emerge to remain in international scientific competition. But to participate in a form of transgression corresponding to the processes of change, it seems necessary to “convert” part of the staff, to train them in the process (towards the creation of “temporary micro-solidarities”?). To this temporality allowing prototyping, some others must be associated, that of the majority of the population concerned by the novelty, that of the “followers”, which will allow the stabilization of the process (normalization) and that of the “refractories” becoming, according to Alter (2002), “non-standard”, unable to participate in the famework of the movement resulting from the scientific activity in the necessary performance of the research unit. Arguments about potential risks that are not analyzed or perceived by the researchers involved in the action can naturally support rejection positions for change. There is therefore the possibility of creating controversy, increased tension and self-reflection, which are difficult to manage, especially in an increasingly complex space.

The principle of training other partners, by the one who has authority in the movement, was analyzed in another framework by Fivaz (1989) who makes a link between emotion and entropy, by transferring this concept of thermodynamics to humakind. According to this author, this link is defined by the German term *Schadenfreude* and by a sign characterizing the mental system: if the entropy flow is outwardly oriented, the emotion is positive. The mind is sensitive to the flow of entropy, related to the possibility of adaptation to the new, and well-being situations may arise when the entropy extracted from the mental system is at its maximum. In this context, the key actor (the scientific project manager for interdisciplinary work) builds a detailed image of the evolution of his environment, coherent and rational (order), taking into account the real and the possible (knowledge). This image must be able to be used to draw verifiable conclusions (stabilization of the projection). Part of this entropy flow can be captured by receptive partners allowing the success of the project. If one of the criteria is not met by at least one of the partners (project understanding, insufficient technical competence, relationship problems, etc.), there is negative entropy. Disadaptation creates a gap between the norm and the maximum entropy, thus limiting the chances of success of the change.

In this operation, Marine Horckmans served as Maxwell’s demon, to appreciate the forms of social bonds that are formed in unity and their possible “exploitation” for new purposes required by the evolution of the world around us. This factual analysis can be used to take into account expressed knowledge or information (which is no longer subliminal or hidden) to develop better social links within PMs for purposes that should be discussed and shared internally. This dimension involves adding ethical and social skills to the scientific and technical expertise of researchers and teacher-researchers, which implies a capacity for empathy with other members of the laboratory who feel concerned by its future. It is indeed essential that the respective points of view of the research community and the hierarchy agree for action on a certain number of axes. This is an ethical necessity of a necessary debate that must consider every member of the unit as an alter ego, because everyone has a share of “truth”. It is in this spirit that this ephemeral interaction takes place in an attempt to examine the potential for the emergence of a new identity in PE, a source of scientific competition, and enhanced outreach (see Figure 1.19).

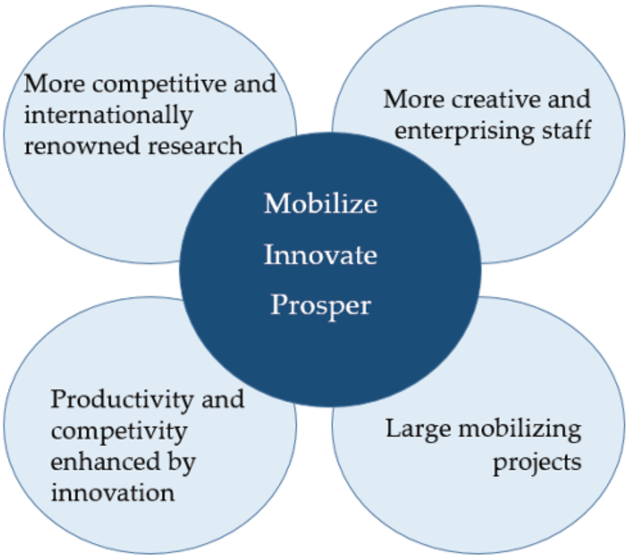

Figure 1.19. *Framing the positioning of the LRGP*

1.11.2. *Main results*

The questionnaire proposed to the staff is summarized in Box 1.12 below:

The researcher on a daily basis

1) Why did you come here instead of elsewhere?

2) Why the public?/The private?

3) Why a thesis? (CIFRE?)

4) Why teach?

5) Why France?

6) What is your subject? What is PE for you? What is your position in what you consider to be “orthodox” PE?

7) What is the center of the target?

8) How does your research relate to this target?

9) What are you turning to? (Outside, center?)

10) Have you changed? How?

11) Is there unity in the lab, visions of this center?

12) What brings the groups together? (Points in common)

13) What makes the difference between groups?

14) What are your internal interactions with the different components (axes)? Are they decisive for your research?

15) What has changed in the last 10/20 years? (Has the target changed? The position of the P/R lab at the target?)

The main challenges of 2030 (2060)

[Presentation of a table with the different scenarios, discussion about the different parameters and their influence, positive or negative]

1) Concerning the columns (the 4 scenarios): in which case would your research be the most relevant/solicited? In which case would it be on the margin/inhibited? Would you pursue your research in a different way if one of the scenarios took place?

2) Does the ethics/responsibility impose constraints/will it impose them *a priori*? (Do not develop).

Towards more "innovative" research

1) Can PE be a leader in creation and innovation in the field of material and energy transformation (creation of new concepts (which ones?); industrial applications, etc.) or is it in a position to follow scientific and technological innovations from other disciplines? Do you think that PE is "only" an application science? Is PE a discipline in itself (autonomous) or a living and fruitful example of an interdisciplinary field → is someone working in PE inclined to open up to other disciplines?

2) Your personal journey: more linear or more changes? Does it satisfy you or do you want to change/would you like to do something else? Why don't you change (what would you need to move towards your dream, what are your dreams in relation to your career)?

Transition: What would you think of the possibility of allocating a space of freedom to risky projects, a space shared by several researchers (e.g. 20% of working time) so that they "have fun" or commit to "crazier", "riskier" projects (in the sense that the result would not necessarily lead to something or that it is an unexplored field), projects which are more personal, time allocated to several members of the laboratory synchronously so that there can be an interdisciplinarity, a crossover of views on common projects?

16) If we put this idea into practice, would you have any plans in mind? What is preventing you from carrying out these projects at the moment?

17) What would you consider to be the main difficulties in setting up this type of activity (material, human, time management, money, etc.)? If a barrier is mentioned, admit that it can be overcome: what would the next limit be? What would an unconstrained search be like? (a) Money: it is possible, with an idea and a modest budget, to at least test its feasibility (provided that one succeeds in convincing others of its interest), the next step being the prototype, the model (requires more money) (see section on financing of development) (b) – i) If an innovation budget were imposed, what value would it represent? – ii) Who cares about money? Time: trying to understand where this "lack of time" comes from: is the researcher also a teacher? Does he prefer to focus on publishing? etc. (c) – i) How do you allocate your working time (teaching, bibliography, manipulations, simulation, administrative procedures, etc.)? How important is it to publish? (no obligation to achieve a result) – 1. What is the distribution of time in % between the different activities? – 2. From 1 to 5, how important is each activity? (for you, for the lab, etc.) – ii) The Germans do theses in 5 years. Discuss the advantages/disadvantages.

18) How to facilitate communication between researchers during the brainstorming and/or idea implementation phases?

19) Do you think you are able to act as an interface between disciplines, through your openness to other subjects?

20) If an idea came out of brainstorming, would you be willing to get involved? Up to what stage? Would you agree to participate in the decisions? Would you be willing to sacrifice some of your current research for this project?

21) Do you have any suggestions for how best to organize this activity? Sharing of experience: system already in place in another laboratory? (a) – Want to supervise, organize, exchange (open science)? (b) – Who would participate? How can we encourage researchers who do not know each other/work in a different way to focus on the same topics? (c) – Other proposals.

Conclusion

Scattered questions, outside the theme, but which seemed important.

1) What should be done to make PE an even more recognized structure (such as MIT) in its field: "professionalism", communication, representation of members internationally (ambassadors, organizations), creativity, influence, relationship with socio-economy, others, etc.

2) What is scientific excellence (qualitative criteria)? How is it measured (quantitative tools)?

3) The management of research is associated with the search for funding: does it contribute to the orientation of your work or do you keep a good control of your own research dynamics?

4) Are you looking for change or are you more comfortable in a stable, predictable, well-defined environment (who are the implementing and decision-making forces)?

Box 1.12. *Issues addressed*

1.11.2.1. *General vision*

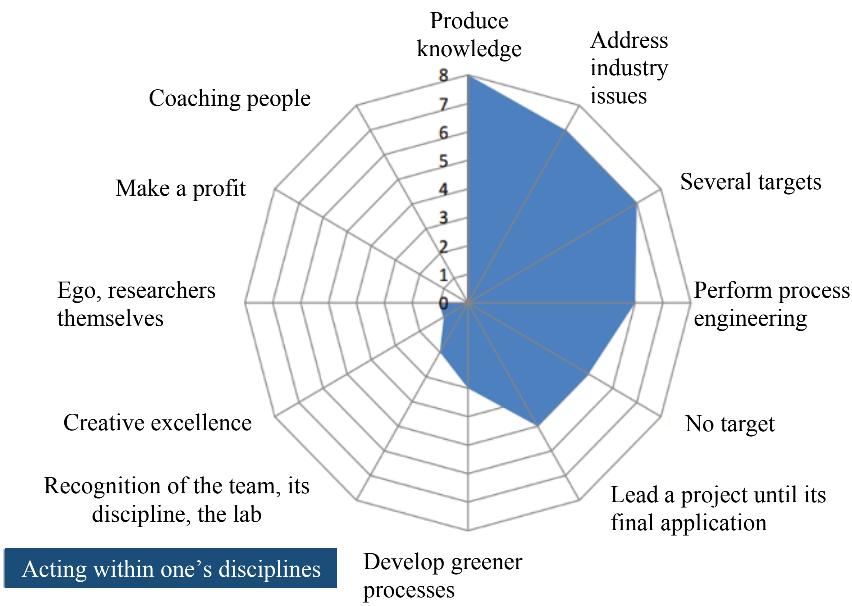

Figure 1.20. *Key targets in researchers' orientations*

When asked about their vision of their research, the interview results presented in Figure 1.20 show a strong appetite for knowledge creation, all in a serene setting (the work discipline of the research unit was hidden). Scientists have perceived the demands of industrialists as a "threat": that of no longer doing "disinterested", detached, "pure" science, the preference to make a science "that works" rather than trying to understand it fundamentally. Some researchers have reportedly been "victims" of exploitation by industrialists by offering services at derisory prices. Some teams feel a little behind in what they perceive of what the rest of the laboratory is doing, but their daily activity does not allow them to make a connection: with insufficient resources, they do not choose the direction of their research.

It is this dependence on funding that sometimes governs the researcher's evolution in relation to the target: it depends on the proportion of industrial contracts (diverging from a hypothetical objective common to the laboratory). This strong dependence on calls for projects can prevent a long-term vision. In order to assess the independence, or even the "compartmentalization", of the teams constituting the laboratory, it is necessary to know the relationships between the axes, the teams and, more precisely, the permanent members, among themselves.

Several sometimes paradoxical, trends emerged from the interviews:

– no member of the laboratory knows what is happening in all the other buildings/teams;

– very few interactions outside work (joint projects);

– some teams closed in on themselves;

– a stated desire to open up more to the other components of the unit.

This is a young structure that originates from the merger of former research groups, some believe that internal exchanges will increase in the coming years.

1.11.2.2. *Support for creativity*

> How can there be any plenty where every man will excuse himself from labour? for as the hope of gain doth not excite him, so the confidence that he has in other men's industry may make him slothful. (More 2005)

The question asked was as follows:

> What would you think of the possibility of allocating a space of freedom to risky projects, a space common to several researchers? (e.g. 20% of working time) so that they 'have fun' or commit to "crazier", "riskier" projects (in the sense that the result would not necessarily lead to something or that it is an unexplored field), projects which are more personal, time allocated to several members of the laboratory synchronously so that there can be an interdisciplinarity, a crossover of views on common projects.

This leads to the results of PE share presented in Figure 1.21:

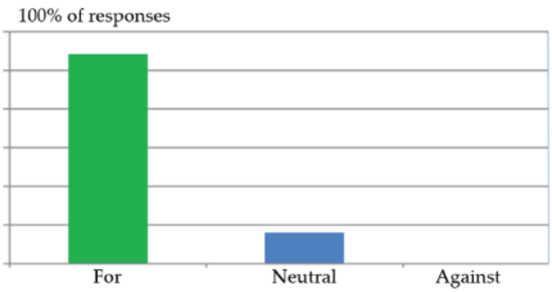

Figure 1.21. *Agreement for support for creativity*

The interviewees were rather interested in the idea of working on an innovative, cross-disciplinary project. This is, in fact, a way of trying to decipher the “mysteries” of new integrative themes that, if successful, give research teams real international legitimacy, rather than solving problems and seizing opportunities. It is necessary to go a little further, by no longer relying on traditional inertial foundations (because they have proved their worth) and by proposing that we leave the following conservative spiral: rather than producing knowledge adapted to the situations as they emerge, we adapt it to existing or planned knowledge? However, a third of the tribe has announced its refusal to contribute to this. About 10% offered to contribute to short-term projects, to work on only part of the project, or more. Nearly half (“followers”) announced that they would be willing to engage in possible operations and 15% even offered to participate in its organization and decision-making if the project was convenient for them. These figures are encouraging (knowing that, with declaratory procedures, the difference between saying and doing must always be taken into consideration, and that it will be possible to attract a few researchers from the “seconded” category (see Figure 1.22)).

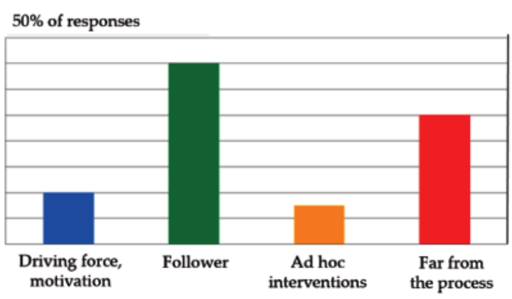

Figure 1.22. *Investment (estimate) in an innovative project that breaks with the existing one*

The question of the budget was raised and the histogram in Figure 1.23 shows the different proposals:

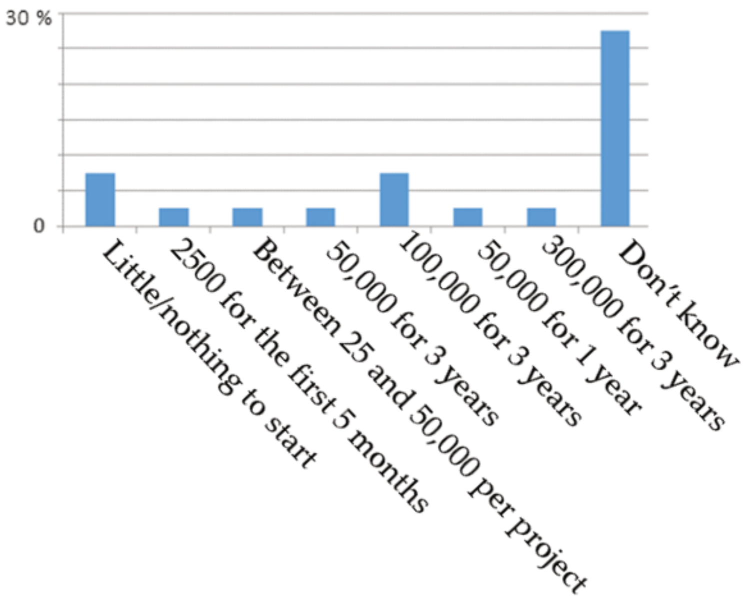

Figure 1.23. *Estimate of the cost of the creative/innovative project (excerpt from interviews)*

The average budget is around €70,000 (but with a wide disparity in responses). Interviewees explained that the cost of the project depended on the area in which it was located. Some researchers also believe that a PhD student should be hired for a high-risk project, etc., representing a minimum investment of €100,000.

However, 10% of respondents pointed out that in order to create a prospective think tank, a scientific initiative for debate (perhaps the first stage of the project), the necessary equipment represents a very low investment. You just have to agree to spend some time.

Fears: regardless of this aspect, some people have concerns about this type of cross-disciplinary action (see Figure 1.24).

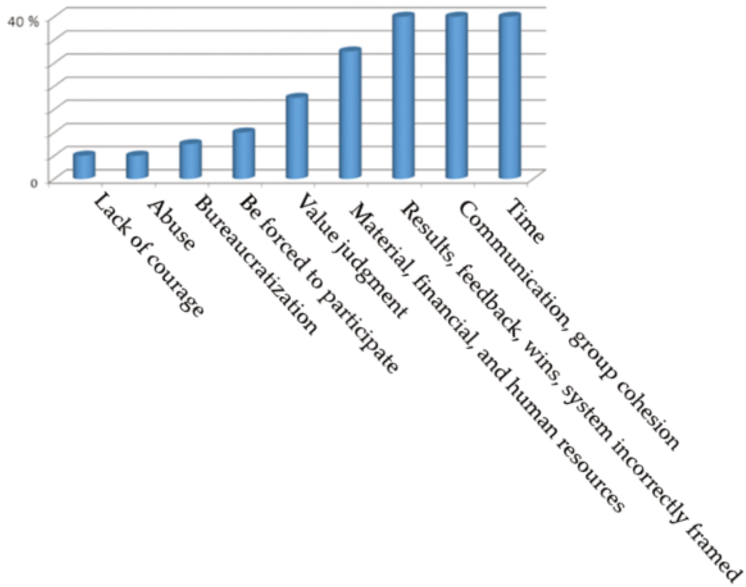

Figure 1.24. *List of fears regarding the "innovation/creativity" project versus number of people involved*

1.11.2.3. *Time to devote to potential disruptions*

> Rational knowledge and rational activities certainly constitute the major part of scientific research, but are not all there is to it. The rational part of research would, in fact, be useless if it were not complemented by the intuition that gives scientists new insights and makes them creative. These insights tend to come suddenly and, characteristically, not when sitting at a desk working out the equations, but when relaxing, in the bath, during a walk in the woods, on the beach, etc. During these periods of relaxation after concentrated intellectual activity, the intuitive mind seems to take over and can produce the sudden clarifying insights which give so much joy and delight to scientific research. (Capra 1975)

Lack of time is the most frequently cited reason for the inability (potential or actual, partial, or total) of a member of the unit to get involved in a project on a new boundary object. During the interviews, the development of the subject was the subject of further study. Figure 1.25 gives a declarative indication of the average time use of respondents (apparently incompressible). On average, this schedule would fall into three main categories: teaching – research – administrative tasks:

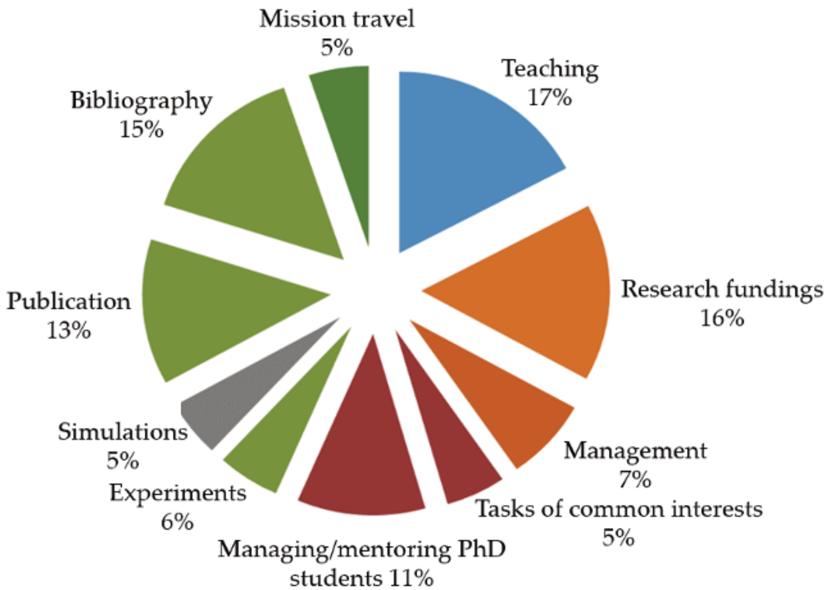

Figure 1.25. *Distribution of activities as a percentage of total working time (researchers, teacher-researchers and PhD students combined). For a color version of this figure, see www.iste.co.uk/schaer/process3.zip*

On average, the activity is divided into about one-third research, one-third teaching, and one-third various administrative tasks (including project development). The teacher-researchers interviewed are the most constrained by the criterion of time optimization, because the activities related to training represent time that they cannot value in terms of scientific production (in the same way that they value their research by publishing, for example). This is why they must make the *best* use of their research time. A researcher who does not teach in parallel (or who does little teaching, like a CNRS researcher) should potentially be in a better position to sacrifice part of his research to open up to others (a hypothesis confirmed during the interviews).

There has been some evolution over the past 20 years. The project set-up (ANR, H2020 in particular) has become, even if the ratio (chances of obtaining funding/time spent writing the project) is low, the most time-consuming activity for researchers. Some argue that ANR projects will soon be neglected because of their low probability of success, a thesis supported by the fact that some researchers have already abandoned the idea of obtaining funding through this means. The interviews showed that they would be reluctant to participate in an innovative cross-disciplinary project if it were to be developed during overtime and/or at weekends.

Abuse, predation – group cohesion

Some people express reservations due to the risk of abuse: fear of having their ideas stolen, of dealing with profiteers, of appropriating other people's ideas. How can we ensure team spirit so that members play the game? It may also be that during the implementation of the project, the direction initially taken may favor one discipline over another (specialization/strategy; creation of a hierarchy (see previous items in this chapter). For some, while we are in an exploratory phase, we should think about measuring, at the different stages of the project, that the initial specifications are always followed. For example, establishing a strict check every 18 months to ensure that the subject is still in compliance with the initial specifications (does it include the different disciplines present in the unit?) to avoid deviating onto a personal subject. The different tensions that exist in any structure could also compromise the confident atmosphere of a possible "creativity" cell. Communication difficulties may stem from the inability of some people to popularize their work, to be understood by specialists in other disciplines, and from the barrier of the vernacular language of certain disciplines. The desire for openness is basically about the *status quo*.

Open Science

Recently, there have been significant upheavals in the scientific community, particularly in the way knowledge is produced and disseminated. The movements of Open Science and Open Data in favor of free access to publications and research materials, the multiplication of platforms for networking researchers, the growing number of initiatives, such as participatory sciences or citizen sciences, based on the massive use of collaborative platforms and the development of new spaces for scientific communication with increasingly diverse audiences are actively participating in the redefinition of the scientific uses of the contemporary web (Millerand 2015). However, it must always be remembered that "a popularized technology is a better accepted technology" (Blanchard 2018). These innovations are accompanied by speeches highlighting a number of evolutions – even transformations – of scientific activity crystallized today around buzzwords such as "science 2.0". This openness does not represent a significant element in the responses and comments of the interviewees.

Going a little further

Doesn't this fear reflect a lack of conviviality in the laboratory? It is unthinkable, in a structure the size of a laboratory of several hundred people, to deny the existence of internal conflicts (some which were clearly stated during the interviews). We can't get along with everyone. In addition, abuses of property rights (signing publications to which one has not contributed, appropriating an idea) may have already occurred, if the fear of this happening again is present? Out of a desire to protect themselves, interactions cool down (see the increasing evolution of individualism). Rather than bonding, won't teams tend to withdraw into themselves (recreation rooms dispatched with, etc.)? This is far from the Fab Lab spirit described in André (2017b, 2017c, 2017d).

But "you have to overcome your fears". What seems to be implied in many responses is the courage to embark on a risky project, the courage to step outside your comfort zone, the courage to be confronted with different points of view. At the same time, there seems to be a strong desire to impose a project "leader", sometimes materialized by the project itself (the desire for the subject to be exciting, catchy, attractive): a figure is therefore needed to motivate researchers, to make them want to work on the project. Then, there is an expression of a desire to sanctuarize the project: the support/protection of the management. To have a foot on the ground, a sufficiently large safety zone, without which one does not dare to go out, to invest oneself. The campaign to motivate the "troops", if this type of operation is implemented, should nevertheless take care not to devalue existing projects, not to put the innovation project on a pedestal (see above). It is therefore a paradoxical injunction at all levels.

Other comments

– *Abusive bureaucracy*: the interviews highlight the fact that a good innovative project should take place in a balance between space of freedom and framing. But most researchers did not develop the idea further. When the possible initiative of a "creativity cell" was mentioned, some people imagined a poorly defined debate, an atmosphere too "good-natured", a project not taken seriously, that was informal, lacking in perspective, debates of "balanced" ideas without them having been matured beforehand. While, in reality, the organization of such a project is based on a work of maturation, negotiations, alliances, in meetings such as brainstorming, war-rooms, and deepening knowledge.

– *Forced involvement*: obviously, in order to carry out a transverse project, researchers must be given the choice of whether or not to participate in it.

– *Judgment*: the risk of making a judgment on the researcher who has chosen to join (or not) the project in breach: the risk of frustration, of devaluation of their disciplinary activities.

– *Return*: if someone participates, even in a limited way, in a transversal project, it will be necessary to ensure their return to their team, to keep them informed of the progress of the project. Do not keep anyone away.

Some researchers think that it is useless to want to be seen to be doing, that it is not necessary to do anything except to continue to do one's work properly and honestly: recognition will then come naturally.

1.11.3. *"Scientific excellence"*

> The advance of exceptional beings is due to a vocation for disinhibition that is only made possible by an active contempt for the containment power constituted by morality and origin. (Sloterdijk 2011)

It was a matter of examining whether the opinions were part of the ethics of scientific practice, formulated decades ago by Robert Merton (1942 and 1968), which is associated with an open discipline such as that practiced in engineering sciences in the unit. Merton defined scientific ethos based on a series of standards, methodologies, and ethics that guide the behavior of scientists. In particular, he distinguished four ethical standards that constitute, in a way, the "scientific spirit" (Saint-Martin 2013):

– universalism (as opposed to individualism), whereby the same rules apply to all and, therefore, scientific value must be assessed on the basis of universal criteria;

– communalism (as opposed to secrecy), considering knowledge as collective goods that must be disseminated in society;

– disinterest as an attitude aimed at advancing knowledge for its own sake and requiring verification processes;

– organized skepticism, requiring the systematic evaluation of scientific productions and scientists themselves.

These "ideal" norms have been widely criticized, not as effective norms guiding scientists, but rather as "rhetorical resources" acting as an ideology. These ideals, in particular, the ideal of communalism, are not fully reflected, if only because of the strong links that exist between researchers and socio-economic groups. Above all, we find reflected the principle of knowledge as a common good, reformulated by the publications and, to a lesser extent, the requirement for verification and evaluation, conducted by "peers" or external evaluation bodies.

1.11.3.1. *Quantitative evaluation criteria*

Spontaneously, it is often the H-Factors (Hirsch 2005) that are mentioned first. However, they are severely criticized, without questioning the very idea of measuring excellence. Because of these evaluation systems, which are based on measurable criteria, some scientists do not dare to take risks, to open up: they do what they know how to do, and limit themselves to projects that are sure to succeed and for which they have funding.

1.11.3.2. *Qualitative criteria*

How does the researcher bring "new" knowledge? What is new about it? The researcher must have a historical vision of their subject, in order to know what their work brings, to highlight the interest of their work, and to take the time to think about what they do. “In some fields, innovation is so rare that bringing in one is excellence” (excerpt from an interview in Horcksmans 2016). In others, achieving a result with a significantly lower margin of uncertainty than previous work can also be excellent.

> Someone who is globally recognized by their peers or scientific community. The best are those who are “not seen”: humble, accessible to all (even students), at the disposal of others. A person who is able to understand complex phenomena and make them intelligible to the community. Others think that excellence is something intuitive, you “feel” if the person is good or not in what they do, at a conference or by learning about the innovative work they do. (excerpts from interviews)

1.11.4. *Funding and research orientation*

Some scientists in the laboratory consider that, given the number of industrial requests, conducting their research means choosing, from among the proposals, what they want to do. This allows them, among other things, to open their minds, by discovering new problems that are partially external to them, by facing challenges, but also to become anchored in reality (research close to the final application). The profitability of a project (financial resources, but also human resources, with the creation of one or more thesis offers) will be decisive, much more so than the ethical aspect, the risk or the anchoring in the team’s theme.

A researcher rarely refuses a project on which they can have PhD students work. This represents publications, results, pure research and financial support. In short, “promising PhD students” is a good way to “impose” a contract on a researcher. The underlying idea expressed is that if a PhD student is working on the project, the researcher considers that they can devote more time to their own research (without directly benefiting industry). Many researchers would like to do more basic science without the need to seek credits. While money does not influence the work of some members of the unit, it is nevertheless the driving force behind their dynamics (with the risk of confusing goals and means).

However, some simply refuse to set up ANR projects, finding the situation of carrying out projects resulting from industrial contracts more “comfortable”: many requests, fewer administrative constraints, neither the State nor the laboratory take a lot of money from the contracts, no files to fill in to justify the use of the money, etc. Moreover, it is not necessarily fundamental research that drives the application, with many cases proving that the opposite is possible.

Finally, some researchers are not at all concerned with fundraising, either because they rely on their colleagues to secure contracts and distribute some of the funds raised (division of labor), or because their field requires very few resources (computer work in particular).

1.11.5. *Foresight, opportunities for the PE research unit*

Respondents were asked to complete a table with several scenarios. The first part of Table 1.2 is divided into four parts:

– *the fundamental science on which the person works*: which are the disciplines that the person best masters, for which are they recognized? In most of their work, what knowledge do they mobilize in the most depth?

– *the link between teaching and research*: if the person is a teacher-researcher, do they change their course/supervised work according to the discoveries made in their field of expertise? Do they only teach the basics, the fundamentals (fixed course), or do they make students work on problems encountered recently?

– *international openness*: does the person work with external laboratories? On European projects? Others?

– *multidisciplinary openness*: is the researcher a specialist in their field without taking an interest in other disciplines or, on the contrary, do they have difficulty defining which are their "core" disciplines because of a significant multidisciplinary overlap? Where does it fall between these two extremes?

In the second part of the table, a non-exhaustive list of societal issues was drawn up, the last box of which, entitled "other", allows respondents to add what may be missing. The first column concerns the current status of research activities. In which category does the researcher fall? With a weighting from 1 to 4, 1 meaning that the researcher had been involved in some projects in this field ("small" projects, simple intervention, work indirectly impacting the field) and 4 meaning that the person is highly solicited on this theme, that it is their main research work. In the second column, the interlocutor was asked to imagine what their position might be in the next 5 to 10 years. Will they stay on the same issues, invest in a new field, be more on one subject while neglecting another?

In the third column, the aim was to imagine the impact that a binding policy, that of an imposed ecology, would have on their research work. On the basis of the responses, it was possible to estimate the researcher's dependence on the guidelines defined by the company. What do they imagine by "ecology"? For some, we are already in this scenario: "there would be no impact on the research themes that are already working in this perspective. In addition, projects that are described as 'green' are more likely to be selected for public finance, this will be part of the words to be used when setting up a project." For others, this would have a positive impact by boosting the financing of industrialists who have to comply with more regulations, etc. Finally, some considered an extreme ecological scenario, a "return to nature", which would completely annihilate research activities.

	Current status	Current system scenario	Ecological society	Landlocked society	Willingness
Information society (Internet of Things, home automation)	8	11	5	5	8
Reserves (resources)	45	44	48	39	25
Sustainable development, environment, recycling	60	62	43	35	46
Health	30	32	8	12	17
Silver economy (aging population)	3	2	6	4	7
Agri-food industry	14	12	10	7	7
Technological innovations	43	31	20	16	23
Tertiary	3	0	0	0	0
Population ↗ Cities ↗	8	8	1	0	3
Formulation	6	7	4	4	4
Defense	6	0	0	0	0
Maintenance products	1	1	0	0	0
Ethics	5	6	5	6	3
IT security	4	4	4	4	0
Cosmetics	1	0	0	0	0
Process safety	2	2	0	2	2

Table 1.2. *Vision of the future in their research associated with the opinions of laboratory members according to different scenarios (very low: orange; low: yellow; low to high: light to dark green). For a color version of this table, see www.iste.co.uk/schaer/process3.zip*

In the fourth column, we referred to a "landlocked" society, a society whose borders are closed, limiting imports/exports and trade with foreign countries. For some teams, this scenario is seen as a “disaster scenario” because they exchange a lot with external laboratories, or because their research work is essentially dedicated to international applications (subsidiaries of French companies, etc.). For others, this would have no impact, either because their research is done only in France, or because they believe that science has no borders, and that it would be impossible to stop the flow of knowledge and information.

In the fifth and final column, entitled “willingness”, researchers are invited to discuss what they would like to do (in their career, in general), and the direction they want to take in their research or their dreams (in relation to their career).

Regardless of the proposed scenario, there is no significant change (at most by a factor of 2 for appreciative measures) in the external effect on scientific activities. “Many of those who call themselves sociologists or economists are social engineers whose function is to provide revenue to the leaders of private companies and administrations. They offer a rationalization of the practical or semi-skilled knowledge that members of the ruling class have of the social world. Today’s governments need a science capable of rationalizing, in both senses, domination, capable of both strengthening the mechanisms that ensure it and legitimizing it” (Bourdieu 1984). From the results of the interviews, it is clear that what can be taken as provocation is beyond the scope of the mission. What appears to be the case is that the resolution of social problems and the sharing of interests cannot be reduced to the mere question of the skills of researchers or to the technical and professional expertise possessed by a few. Rather, it is a societal issue, whose treatment requires the formation of a collective expertise developed in the context of a democratic debate (which is therefore beyond the scope of this book).

In other words, the question of the ability to promote scientific anticipation of usefulness is a matter of the internal resolution of local governance problems (influenced by the global), based on collective skills. From this perspective, social engineering must probably integrate collective, experimental logics into its project and methods, and thus contribute to generating appropriate, even innovative responses. How, then, is PE to evolve?

1.11.6. *Collective projects? Risky projects?*

Everything, basically, is a matter of beliefs, in the future, because no major clouds darken the sky, in leaders, who assume scientific and administrative responsibility. So why try to practice activities that involve divergent thinking (when you have not entered a laboratory on this criterion), when there is no obligation to change? But are the time bases of the resources adapted to maintaining the scientific and technological leadership of a research unit? That’s the dilemma! To whom should I give credit for these changes? The risk has apparently not been assessed, which does not allow an urgency to emerge in the necessary changes and their anticipation.

"Creative or innovative periods are precisely those in which, under the influence of various circumstances, people are brought closer together, where meetings and assemblies are more frequent, relationships more frequent, exchanges of ideas more active" (Durkheim 1967). Obviously, the interviews did not reveal any favored encounters that would allow for constructive debate. This does not mean, however, that it would not take place, but it is difficult in the context of ambient and traditional inertia in units with a recognized quality in their work to recognize the potentially emerging forces allowing evolutions, evolutions that should fit into the collective ideal. Orléan (2011) writes on this subject: "this transformation is not the product of an intellectual adherence resulting from a rational analysis of the situation, but rather that of a setting in motion of individual desire by a power greater than the individual." The organizational problem would consist in seeking, through different forms of perceived, present or future external constraints, as they are understood and shared, the different ways of resourcing that correspond to them.

These different "manifestations" of external tensions must therefore be shared in order to create a feeling of common action and a sharing of a confident feeling on the part of the members of the scientific community of the research unit. The intelligible representations by all staff imply a minimum desire for sharing between its members so that they can interact; one of the possible ways would be to define an original common, or partially common, scientific project. This "material" project would not be there to reveal the "mental" state to which members are associated, but to a way of bringing energies together, to do. To win better together, this would be an externalization in the movement to create a link, to participate in the evolution of the image, reinforced because all the partners have contributed to its creation (Durkheim 2003). This pooling would then have, in a rational anticipation in an uncertain environment, a renewed attractiveness and a reinforced power of integration, allowing a shared risk-taking.

Those who have ideas to make a difference, and there must be many of them, are divided into two categories (Philippe 2012):

– those who do not dare (for different reasons); they understand the issues and the importance of new ideas, but they do not want to take risks and may be afraid of "displeasing"; having never been "beyond the mirror", they have never failed and may feel free from blame;

– those who dare to move forward by "disturbing" conformisms of all kinds, organizations and sometimes "procedures". If they are not supported in their action (in a framework to be determined), they raise fears, misunderstanding, criticism, and rejection (especially if conformism is directed towards research funders).

It is therefore difficult for researchers selected on the basis of scientific excellence and productivity to become, without support, disruptive elements, capable of taking risks, and making the community take risks. It will therefore only be possible to overcome this type of impasse by pooling the risk.

It is true that on open subjects, the debate between the proponents of bottom-up, useful continuity and those of integrative reflection (top-down) of risk-taking, may appear in an unstable heuristic approach as a discussion without robust foundations because it is impossible to decide and move forward. The latter must find meaning in a heuristic approach. Debating, however, is an attempt to get out of certain paralyzing stereotypes, application desirabilities, competitions, emotions, and the search for recognition, even “grabbing fairs”, as far as one wishes.

The problematic horizon of this operation extends well beyond this contact with the social field of a recognized laboratory. We can see the importance that the capacity discourse has taken on to shape science policies of “excellence” based on social and developmental relationships at the individual, local, national, and international levels. This work reports on forms of human incapacities in an attempt to reflectively accompany any attempt at assistance, resourcing, competitive training (but also their limits), and to cultivate vigilance in order to unmask injustices such as the opportunistic union between a possible managerial ideology disconnected from the “field” and the enhancement of everyone’s capacities.

What may have been felt during this work was the need to explore the mobilization capacities of “troops” in relation to “incapacities to act organized”, by placing them in the wake of reflections on the continuity between action “within” the organization and action “outside” the organization – the latter very often already being organized and powerful (ANR, EU, CNRS, etc.). It is an in-depth exploration of the degrees of formalization involved in organized action that gives access to the capacities of this action, as well as its incapacities and thus an additional dimension of scientific anthropology. This work to be carried out should allow for a conceptual clarification of the notion of incapacity to shift the lines: first, it would involve making a phenomenological series of distinctions between correlative incapacity, relative incapacity, and absolute incapacity, the latter being the only sign towards the notion of vulnerability for the future of unity as an organized and competitive structure; second, it would involve unfolding the strictly social dimension of “incapacity” through a reflection on inter-research and institutional mediation (Fonds Ricœur 2014).

Basically, what was expected was the beginning of a debate on creativity and active monitoring in PE, making it possible to play on reasoning by analogy (see Table 1.3 which presents some comments concerning the role of actors in these processes).

Agree to dive into an unknown subject and continue, even if insecurity sometimes destabilizes.	Agree not to master all the content in the eyes of others (but with limits in depth).
When exploring the theme, leave questions such as: “and my program?”, “and my discipline?”, “and me, in this operation?”.	Try to explore a subject that is constructed with a systemic perspective; keep the objective in mind.
Be wary of fallout from the beaten track (disciplinary content that could be “hung up”), which can become ruts when they are “dumped” in a research project.	In negotiating the time that will be devoted to the project, do not let yourself be confined by the time division between disciplines; be able to imagine the life of the project.
Be open to the unexpected and be ready to engage in learning according to the needs revealed by the previous day or the requests of possible partners.	Measure the interventions like a monitor of new dimensions to avoid them becoming constraints, whilst not answering a question related to the subject.
For a future team to be enriched by the presence of several disciplines, each of them must be sufficiently aware of what they bring to the table.	Learn to share knowledge and accept that researchers implement sequences that are not specific to their disciplines, in order to better manage the project; be open to others.
Apply the following rule: practice the meta-disciplinary methodological cross-fertilization.	At any time during the design of the project, ask yourself if the specific perspective, originality, and subsidiarity that you think you are carrying are present.

Table 1.3. *To achieve active monitoring*

In this necessary quest for knowledge, there is no need to pit bottom-up researchers against top-down researchers. Rather, we should bring them closer together; the adventure needs all talents and it is not after advocating openness and resourcing (interdisciplinary, but not only) that it seems wise to engage in a quarrel between approaches that must intertwine to win. Otherwise, it would be mutilation. Perhaps we should remember Immanuel Kant’s famous proposal on the obligation to “treat humanity […] never merely as a means to an end, but always at the same time as an end.” (Kant 2002)

To conclude this section, is Servent (2011) not at least a little right when he writes: “It is understandable that France has always preferred a precise preparation of operations based on its past experiences – and strict compliance with the resulting structured hierarchical instructions – to taking into account changes and new realities, thus at the expense of innovation.” Also, should we not remember Edgar Pisani who wrote in 1956: “the mission administration is light, it has a taste for doing, it is realistic, it moves, it goes towards the event; it is involved in life, it does not wait for the initiative, it solicits it; it must be able to create the legal persons necessary for the creation of its companies; it is dynamic and involves risks, while its older sister must be content to be cautious and requires the elimination of all risks. This one is anonymous, it is discreet by definition even. The officials who constitute it are interchangeable. The other needs to bring about membership; submission is not enough. It is based on the movement of a person's or team's thought. The management administration is the judge; the mission administration is the actor. The first is Cartesian, the other is concrete"? Will we be able to be concrete and unsubmissive? (see also Pezziardi and Verdier 2017).

1.11.7. *Difficulties in the functioning of research*

> Saint Augustine had inscribed curiosity in the 'catalogue of vices' and heresies on the grounds that people's interest in the world must be limited to their utility for salvation. Enjoyment must only be attached to the relationship one has with God. (Blumenberg 1999)

> As soon as capitalist societies suffer from the dominant tropism of profit and socialist societies remain dependent on bureaucracy, one could have guessed that the French – allergic to any option – would cumulate the two flaws. That's what they do. (Elgozy 1970)

> With low tech, we know how to predict the return on investment. We do not invest if the start-up does not have positive growth, a product and customers. But even with a really great deep tech, we get a ticket to the roller coaster. It is often necessary to invest without clients. As it is a breakthrough innovation, the start-up will have to create a new market to survive, which is very difficult. (Le Drogo, quoted by Rolland 2017).

> The size of consumer populations passionate about technological innovation seems to be shrinking and consumers no longer seem to want to make the necessary efforts to appropriate them for use. (Maillard 2017)

> Changing tools is not only adopting a new work instrument, but also often disrupting an entire system, an entire work rhythm; we therefore have a better understanding of certain collective or individual resistance. (Haudricourt and Bruhnes-Delamarrre 1955)

Many barriers to innovation have already been identified (Iddriss 2017): the inability to unlearn outdated mental models, a successful dominant design, a risk-averse business and academic climate, poor management of the innovation process, lack of adequate monitoring skills, and the inability to develop a mandatory internal and external infrastructure. Frishammar *et al.* (2012) focused their analysis on the capacity for process innovation. Their review proposed strategy, collaboration, and culture as the main dimensions of innovation capacity. For disruptions, Slater *et al.* (2014) have developed a radical success model for product innovation. Their review revealed that senior management, organizational culture, organizational architecture, the radical innovation product development process, and product launch strategy were the main dimensions of innovation capacity. So not everything comes from the ground up.

"Technologies function politically and culturally as social structures by exerting physical coercion, encouraging subconscious conformity, establishing opportunities and constraints for action and self-realization, promoting the evolution of infrastructures, affecting non-users, shaping communication, psychological development and culture in general, constituting the essence of the world in which life takes place" (Sclove 2003). However, everyone knows that social structures have a certain momentum; it is also the price one pays for a certain level of stability. It is therefore a question of trying to work on behavioral induction strategies – going with certain digital technologies to the point of building a "voluntary servitude" to make the "manipulated" subject desire, which we have, in fact, decided in their place. But, if this situation is conceivable for a direct relationship between subject and object, persuasion is not possible to support the genius of processes, always hidden inside commercial devices.

Innovation is not a defined process where the path and outcome are known in advance. We know where we are starting from but not where we are coming from. Innovation is above all an attitude, more than an ability. There is no doubt that invention and discovery are unpredictable, non-linear, and unexpected phenomena; one step forward, three steps back. This does not mean, however, that innovation is the sole result of chance. On the contrary, if flashes of genius have a role to play, innovation is much more the product of the determination and obstinacy shown in pursuing a mission than that of a chance encounter with a muse at the turn of a flowery path. As Thomas Edison recalled, "genius is 1% inspiration and 99% perspiration." Indeed, it is the efforts and perseverance shown to accomplish a mission or achieve a goal that create the right environment for "enlightenment", not to mention all the previous and subsequent stages that have been ignored, that ultimately make it possible to convert these sometimes brilliant ideas into sometimes revolutionary innovations.

The road is, in the industry, full of pitfalls, the proof is that less than 12% of the drugs studied get approved. This result explains why few new processes or products are emerging and why drug costs are high. "A new technology is always evaluated using performance criteria specific to the existing technology, which it is intended to replace," says Tellier (2003). The economic world has its own rules. "This is why, in the face of these accumulated uncertainties, some prefer conservative retreats in which values are more binary, clear oppositions, sufficient means of control to constrain people and ensure the sustainability of systems that wish to be sustainable, even if they carry promises of a future for the earth and humanity that are probably not very exciting" (Marsan 2018).

However, in the university sector, with success rates for ANR or H2020 proposals, only about 12% of applications are accepted with numerous administrative constraints. This means that the rapporteurs, for obvious reasons of financial scarcity, do not accept (either) risk-taking and support non-disruptive operations that we are sure will succeed, because we are in continuity (creativity should not be assessed only in reference to the past). This shortcoming generated by the domination of "New Public Management" supports the reassuring continuity and very little research on boundary objects involving, only in the scientific field, flexible and interdisciplinary forms of organization, which are certainly more risky, but are the bearers of only a successful creativity.

We are kind of in a rain dance paradigm as we go deeper (for good reasons at the beginning) into the method, without knowing if it will rain (after all). This difficulty is therefore only imperfectly taken into account by the academic system (unlike what industry does for its economic survival). To return to the example chosen (by design), it is possible to look at the remaining 88% – projects that do not make it to the final stage. They are also part of the history of innovation because the road to failure is often paved with intermediate successes, some of which can be applied, and because any "failure" provides information that leads to functioning on other bases to lead to other tangible or intangible products/processes. However, failure is not allowed in academic research... which, moreover, has a staff funded for life (which therefore has little interest in being known for providing a "suitable" career).

In this frozen, sterilized setting where the industrialist is left to deal with one or more researchers in the public domain on a disciplinary aspect of a larger whole, this leads to a partial vassalization of academic research and, what is more serious, the knowledge produced locally is not exploited locally unless the industrialist is present on the spot. What then do we do when one is located in an area that is partly affected from an industrial activities point of view?

What should be attempted is a willingness to question the scientific practice exemplifying the use of interdisciplinarity and the associated methodological choices, the need for dialog between people concerned by a given field. There are probably as many philosophies as there are people trying to think, which is not based on the principles of "one thought", inertia of different origins and inclusion in the consensus induced by paradigms (whose interest in terms of effectiveness must not be rejected). If specialization has played a crucial role in the progress of science, does it not lead to a certain fragility? So, returning to the foundations can be an important cultural asset to participate responsibly in the robust construction of our futures, near and far, in a world led at all levels to quantitative, even binary reductionism, especially when social and economic demands are clearly strong.

To achieve these ambitious objectives, as may be the case in new areas, it is necessary to change the method, to accept exchange, failure, and questioning because the required interdisciplinarity is profound, complex and therefore difficult. As long as it does not voluntarily seek to confront "recalcitrant" problems, the domain will remain alive, as long as it maintains an "acceptable" contact with the anticipation of society's needs (through different channels), which raises the delicate question of the voluntary departure from the habits perpetuated by the "system", its social organization, and its ends. The question of an unanticipated post-mortem survival towards the opening of new fields of research is, however, raised in a world that overly supports risk-taking, creativity, and ruptures *a posteriori*, but which recovers them with ease.

However, what we can expect in research is risk-taking in disruptive terms and not a presentation of good, comfortably-installed professionals who meet all the funder's criteria for incremental approaches (no risk-taking in particular, it is enough to be "good"). By satisfying the criteria, we can still share some money with "milestones" set at each the millimeter. Everyone is happy, except for the creative researchers and their possible jobs. Nevertheless, the remark recalls some real difficulties with interdisciplinary approaches.

How to get out of the incantatory discourse on interdisciplinarity when the following exist:

– difficult peer recognition for scientists working in an interdisciplinary setting with career problems;

– a difficulty in integrating the various disciplinary elements into a summarized version;

– doubt as to how to know the practical methods of the other disciplines necessary for action; doubt as to how to understand each other;

– the "trial and error" approach implies a dynamic knowledge of the different actors and does not fit well into action and funding programs;

– the creation of new disciplines by bi-disciplinary fusion (e.g. biophysics) can restructure actions within a recognized framework (scientific journals, learned societies, candidate selection sections, etc.).

From an epistemological point of view, the creation of new knowledge does not normally follow a linear process. This makes it difficult to group knowledge from different disciplines that also have their own distinct jargon, paradigms, methodologies, and ways of working.

Box 1.13. *New considerations regarding interdisciplinarity*

In recent years, this situation has become more critical, as in a Malthusian context – the population of researchers varies exponentially while the resource varies linearly (if it is even stable). How to get out of the game in a system that creates hungry people? Either by doing inexpensive computer research or by accepting the rule of the game – do as you did before. With a system that finances "from above", there is no longer any real transfer of responsibility for research and, finally, there is an inability to propose changes in human activity that allow for serene debate, to avoid, by reinventing our relational modes, forms of resignation. The resumption of its anticipatory role (but no more) of research would undoubtedly avoid simplistic discourses on the powerlessness of national (local?) society to emerge from the crisis, because we remain within the same habits of not thinking. As stagecoach drivers did not invent the aircraft, projection on the future, which is a real bolt, cannot be made from extrapolations from the past or by a simple programming of the future. One of the solutions presupposes being able to distance oneself from the upstream and downstream in order to try to propose ways of strengthening the links between science and society from the bottom up. The link with policy then should not concern the optimal way of responsible research activity at all levels, but the flexible framework of the movement in which society must integrate to redirect growth and/or employment. It is therefore up to the authorities to express themselves and support the necessary changes by taking risks.

1.11.8. *Concluding elements*

> No consumer today has even an approximate knowledge of the production technique of the goods they use every day and most of the time they do not even know how they are made or by which industry they are produced. (Weber 1965)

Interdisciplinarity has gained momentum within universities when it has been more or less forced to solve problems. In particular, the State has undertaken to remind researchers that their work must be useful and have practical benefits in these cases. At the start of this injunction, which has become urgent over the past 30 years, the analysis of the rapid developments in science and technology, which is on the way to becoming the main productive force of society (Habermas 1973), is being developed from the prism of science for the economy. Interdisciplinarity is an oil stain (see Laflamme 2011).

Although the notion of change is already old, it is regarded as an ideology today, strongly linked to the context of immediacy, creation, and networking on which the knowledge economy is based. The idea of permanent change seems to have become a new paradigm, also synonymous with immediacy and instability. But, at the same time, Alexandre (2011) writes: “in industrial matters, the illusion that managers of diligence will invent railways leads to the concentration of technological aid on old industrial groups with strong lobbying skills, failing to understand the trends of the future.” How can we be creative in this setting, which is part of the ANR or H2020/Horizon Europe programs, or even the National Research Strategy?

How, moreover, with funding leaving little room for individual initiative, can we get out of the game? What the authors were able to observe was the development of modeling (confirmed by the survey presented in this chapter). He joins Ganascia’s (2000) reflection, which states: “Beyond this dematerialization of media, scientific practices are changing in depth. Researchers leave the bench to sit in front of a computer screen. And with these evolutions, the epistemological status of the experience changes radically.” Thus, by seeking to resist a constraint, that of producing as much as possible, researchers lose contact and confrontation with matter and consequently, the possibility of validating an idea in depth, which limits the development of industrial activities based on ideas.

NOTE.– It would be interesting to consider the essential role of experimentation in PE science. Indeed, until recently, experimentation has been given a central epistemological function because it was conceived as a standard of scientificity and a methodological ideal. It is essential in the processes of verification or the corroboration-refutation of assumptions.

Finally, to add a layer and to justify, at least in part, this approach, a society can only develop in relation to its history and traditions (a long time for Europe, more recent for the United States, more fractured for Asia), because its know-how is an element of its economic heritage. Having products in line with a company, its positioning, and its culture, is a necessity for a coherent strategy, because successful companies build their history without real chance and with continuity. When developing a company strategy, it is important to think about the products it sells and the markets in which they are sold: it is the overall coherence that is essential for success. And creation must act as the cement between the past and the present, between history and the future. This is the very definition of modernity: knowing how to identify with the thought of our time. This is the classic field of incremental innovation, with little or no “disruptive” innovation. According to Marchesnay (2013), “Herber Marcuse recalled that the great strength of organizations is their inertia. This is all the more significant because it is based on a broad and hyperopic vision and because it comes up against vested interests.”

But the world is changing and will change again because in the East, ways of thinking are changing; know-how exists, both ancestral and very high-tech. In Asia, as in the United States, execution and copying are current business models but they will soon be outdated, because the integration of new products in real time into industrial processes is very rapid (as in the case of rapid prototyping and additive machine manufacturers who are outside a French (ETI), American or Eastern industrial company). The obvious evolution is the implementation of new technologies such as 3D printing in local products with high added value, with an internationally recognized creativity likely to seduce the Western world, including France. How can we stay in the competition? The business strategist, the university researcher, in their mission and with their means, after having been in turn a moderate anticipator, an industrialist, a salesperson, a marketer, or financier, will have to integrate all these notions to become a "creator of new disruptive trends". But this presupposes in France many changes in cultures and behaviors.

Moreover, and this is not new, trainers (see Chapter 2), as their names indicate, are responsible for shaping young people, leading, according to Vincenti (1990), to a number of difficulties, particularly with regard to the training of engineers, with difficulties of:

– asking the right questions on a new subject and keeping as much as possible the methods and technologies that were at the origin of their training (classical conservatism);

– a vision of technological challenges and qualitative modeling of emerging situations (while they are well-versed in quantitative processing methods, knowledge required by the hierarchy);

– generation of ideas to consider original solutions, etc.

Researchers, for various reasons, are largely ignorant of technologies (the disciplinary approach is generally valued), do not have a global vision and have difficulty thinking from the general to the study of subsystems (and then back to the general). Increasingly, New System Management, due to cultural changes, is leading to a refocusing of activities on core knowledge (with a monodisciplinary orientation, avoiding investing in bibliographic analysis beyond its discipline), which increasingly leads to "single solution" brainstorming. It is true that more and more time is running out and that the framework imposed in the calls for proposals must be respected. In short, creativity is an operation that occurs "despite" the challenges.

But when the idea takes shape in terms of proof of concept, not everything immediately succeeds. According to Silverzahn (2016), it is when the hierarchy realizes its existence and, even worse, becomes aware of its interest, that it decides to support it, even push it to succeed on a large scale. But, as a price for its support, the general management will ask, and it is understandable, that the project be "well managed". "By good management, general management actually means above all that order prevails. It must be said that, born underground, the project has often seen its promoters resort to DIY and execution: start small, use available resources, work in co-creation, etc. All this is not very sexy, not very salesperson-esque, not very Blue Ocean Strategy and it's too small; how are we going to have a real impact on the turnover with this DIY? No, you have to think big! But above all, it is necessary to move from DIY to 'real' management. We need to better control our costs."

> Exit therefore the do-it-yourselfers and set up a real management. In the logic of rationalization, management will consist in cutting down everything that makes the innovative project unique. You have to connect to the company's computer system and stop using these open platforms [...]. It is necessary to build on the functions of the organization and reduce the autonomy of the project. We need to align the innovative offer with the existing one, to be more coherent. You have to know where you're going. We have to do like the others, we have to simplify. The project, or rather its breakthrough, dies by the famous Chinese torture of a thousand cuts (*Lingchi*), which consists in successively cutting and removing parts of the condemned individual before, at last, their head is cut off. In the end, dozens of small modifications, all with good reasons and that are perfectly defensible, reshape the project to fit into the organization's mould [...]. But these changes transform the breakthrough project into a continuous innovation project, i.e. an extension of the current range (the same thing for the better) or more specifically, of the current business model [...]: instead of adapting the organization to innovation, innovation is adapted to the existing organization by trying to force it within the existing framework, which is necessarily intended to distort it. (Silverzahn 2016)

The question is how to transform a perceived or anticipated "social interpellation", whether or not requested by society, into an object of scientific research. On boundary objects such as those associated with process engineering, a reflection for action by the authorities that govern us seems necessary if we do not want to miss scientific and technological operations with application completion.

With an angelic vision, one might think that a research unit goes beyond an average summary of the functioning of society. Media discoveries are expected, innovative activity in the world is incessant with a rational confrontation with reality, the proactive attitude is permanent, etc. However, what we see for a large part is that the complexity of the world is, within previously supported paradigms, reduced to incremental progress with inbred peer validations.

Broadly speaking, good laboratories are attentive to the "social demand" (and the significant funding that goes with it) and transpose what appears to be a need for scientific orientations that are generally monodisciplinary (but not always) and that, by creating legitimacy, can ensure continuity in research. Creators, disrupting the organization, cannot normally fit into this scheme. It is their success that will (perhaps) lead to new scientific orientations stabilized for a while, so Kuhn is not yet dead!

It has been 75 years since Auguste Lumière published his book *Les Fossoyeurs du progrès : les mandarins contre les pionniers de la science* (meaning The Gravediggers of Progress: Mandarins Versus Pioneers of Science). According to Duvivier (2016), this book paints a dark picture of the situation generally experienced by an innovator when they present a new idea or theory, different from the current paradigm. "How many of them have not pretended to be madmen, for the enlightened? Indifference, mockery and virulent attacks drowning their ideas in oblivion for many years and pushing them into poverty, indifference, isolation and sometimes, even suicide […]. This phenomenon affects all fields, from chemistry to medicine and from the little-known researcher to the Nobel Prize winner." Conservatism and perpetuated habits must never be forgotten.

What is expected is a process of interunderstanding to engage in a maturation of an issue. It is also to express collectively a passion for the new, nourished by the tension between promises and possible scientific(s): how then to organize the unpredictable, propose a confident, mobile, and polymorphic environment? How can we encourage risk-taking to support an innovation dynamic? How to learn by transposing ideas and by reasoning by analogy? How to combine intuition and rational analysis? How can we arrive from the "contemplation" of the unknown to the emergence of a common thread through the acceptance of uncertainty and the possibility of failure? Etc.

It is not necessary for a group engaged in exploring a boundary object with risk-taking to have a leader who, to develop its own idea, needs a collective on which it will impose a vision so that they bring their disciplinary skills to the project. The latter must be self-constructed through an in-depth exchange between partners. Where no disciplinary scientific talent dominates, an interdisciplinary group is, by construction, vulnerable and therefore, to win, it must cross the boundaries of specialized knowledge. This implies that we accept to question ourselves among all the members of the group, that we are able to encourage ourselves in a difficult process, to associate points of view, in short, to share moments of doubt and pleasure (see Edwards 2011).

But, the comments adapted to this one laboratory that we have called PE, may not be adapted to the functioning of all the other research units in Old Europe.

Pierre Simon de Laplace stated at the beginning of the 19th Century that most of the laws of astronomy were known and that astronomers would only have to add a few decimal places to the data already acquired through improved instruments. Similarly, Lord Kelvin announced the end of the history of physics. Then came the experience of Michelson and Morley in the 1880s on the speed of light, which introduced major challenges. The road would later be rebuilt by Einstein.

This little reminder serves me as a small reflection on a very standardized research, engulfed in the belief in its comfortable and almost immortal paradigms (i.e. before his retirement). However, deep down, around us, do we not see the emergence of several revolutions, whether it is artificial intelligence, biotechnologies, perhaps nanotechnologies, non-linear systems, etc.? However, in our fields related to the transformation of matter and energy, do we not apply in a very important way forecasting approaches that are an art where the future is determined by continuity, just with possible changes in rhythm? There is no break and the operation is reassuring because predictable satisfies both the academic world and the principals because we work within a framework of (total) risk control.

In this context, it is not traditional to ask "legitimate" questions whose answers are not programmable in the quality scientific activity, but that are ultimately routine in our knowledge and its deepening. What I miss is that we don't try to think about it, to formulate reorientations, an expansion of our mental space, the search for our blind cognitive tasks, etc. It is this questioning that can lead to a scientific debate on what is not known (agnotology) and how to overcome this ignorance to create opportunities for tomorrow.

As examples (small, open-ended exercise) that could be the subject of reflective debate, can we not invest in PE issues such as: "creating order from disorder"; "microscopic causes of macroscopic events"; "noise, determinism, and complexity"; "informed matter"; "self-adaptive molecular-based reactor"; "killing death"; "changing the shape of a reactor in real time"; "tele-transporting matter"; "self-organization of matter"; "cybernetics and process engineering"; "responsibility for competence"; "replacement of rare and expensive materials"; "substitution of polymers, metals and ceramics"; "new catalysts"; etc. This non-hierarchical list should be much longer if more than two people are involved in the exercise.

In practice, it would be good if this creative dynamic were to be associated in a complementary way with the consolidation of new spaces of possibilities, the training of others and, finally, the transformation of our implicit rules of functioning (ensuring that the ecologies of change are harmoniously intertwined between continuity and disruption). It is quite obvious that it is not a question of abolishing the current processes of the day-to-day operation of research, but of supporting them collectively on the basis of a reflexive capacity that is too little exploited, in order to set up new spaces of opportunity and new priorities defined responsibly together in a framework of internal serenity.

Box 1.14. *Asking your own questions*

1.12. Conclusion

> An entrepreneur is not only someone who runs a business; they are above all a person who constantly needs to change things and redo them in another way, to break down doors. (Lambert 2017)

> Everything that science can provide to humans, politics owes to them. A true statesman, an ideal ruler, will see themselves as the scrupulous manager of knowledge. They will feel guilty by omission every time they leave the public good behind the truth. (Rostand, 1959)

The interdisciplinarity of the vision of the distant and the goals introduces a major character, that of decision and therefore of responsibility, because there are important choices to be made for the future of society. This scientific policy results in a possible loss of freedom for the researcher who may feel disengaged "from their own way of searching" (Testart 2003). However, according to Jonas (1999), "the postulate of freedom of research was based on the possibility of distinguishing between knowing and doing, between acquiring and using truth, between pure and applied knowledge, in short between theory and practice."

In an attempt to convince oneself of the need for a strategic approach, based on prospective approaches (Jonas 1998), it may be interesting to examine, in the West, the development of the tertiary sector in favor of tangible or intangible production: productivity in 50 years has increased significantly by a factor of 10 thanks to automation, collective production processes, and new technologies. The population has increased slightly (about 20%) and working time has decreased significantly (-15%). Apart from the production of superfluous or disposable goods (increasingly outsourced), can we not think that the uncontrolled complexity of production systems is one of the origins of the development of the tertiary sector? In this context, would the definition of new processes not have benefited from a more cooperative approach? What subsidiary role should process engineering play: organizing interdisciplinarity and project management, carrying out, in consultation with partners, prospective approaches, and/or promoting invention?

In recent decades, there has been a shift strongly felt by the social body towards a reduction of the national production of goods in favor of services, which corresponds to a civilizational revolution that is reflected in a certain stagnation of competitiveness (often defined in terms of the increase in the average income of citizens). We must remember that, in the production economy, innovation was threefold:

– progress in the mastery of new materials and energy;

– processes allowing “efficient” production;

– products allowing mass production at the lowest cost.

Clearly, when process engineering emerged in France at the beginning of the *Trente Glorieuses* (1945–1975 - the French economic boom after World War 2), the objectives were largely focused on aspects of optimization in the broad sense, which made it possible to satisfy many of society’s quantitative needs (following the shortage of goods after WWII). Today, thanks to technological advances (IT, automation, electronics, etc.), production is carried out at a lower cost and in a more flexible way, in a context where speed is a priority (the ability to prioritize and respond to change in order to best adapt to a turbulent environment (Deloitte Digital 2015)). Thus, we are witnessing a new phenomenon, that of the decrease in the cost of production (reinforced by globalization) and the increase in the cost of design. As Michèle Debonneuil (2007) points out: “There is a shift in value added, i.e. the creation of wealth, within the ‘supply chain’: from factories to laboratories and test centers; from production to distributors and communication companies.”

But at the same time, according to Forgues *et al.* (2009), industry would have difficulty moving from sequential to integrated design, or even relying on complexity because of the contradictory business context created by transactional procurement methods. Even if the technological system is a fabric of inventions (at least incremental) and social organizations that allows the industrialization of these products, objects, and processes, technical activity is only one element of a heterogeneous complex of practices, knowledge, organizations, machines, etc. (Granger 2002; Davallon 2004). The development of the concept of CSR (corporate social responsibility – ISO 26000) where any group or member of the stakeholders (or the stakeholders themselves), can affect or be affected by the achievement of the company’s objectives and by taking risks (Coquand 2018).

The strategic vision and/or the notion of objective are often linked to the search for an expected financial profit in the short or medium term. They assume that each element of the action leads to results to satisfy demand. These developments can only occur with a global vision of causes and effects, also taking into consideration the ordinary and current aspects of social control. If unacceptable consequences for society occur, there is a need for compensation (“polluter pays” stereotype, when the payer exists) and therefore additional costs, delays, or even the prohibition of a product (asbestos, for example). With the use of delay lobbying methods (Héry 2008), which would be commonplace, it is still difficult to reduce the tension between those who produce the risk and those who suffer for it, knowing that the latter obviously do not have the same weapons to defend themselves as the developers (Fourastié 1966).

"The difficulty of disruptive innovation comes from the fact that an established company is a victim of a conflict between its historical activity and its future activity. If it focuses too much on the future, it jeopardizes its current activity. If, on the contrary, it devotes too many resources to defending its current activity, it takes the risk of missing the future opportunity" (Silverzahn 2017a). On this basis, which is certainly at least partly reasonable in the short term, it seems difficult to take the step forward. So, the priority is to focus on the data that Deloitte (2017) believes is at the heart of the strategy of many companies. This data, search engines, and other digital technologies contribute to the understanding of their performance, the needs of their customers, or even their strategic challenges in a certain continuity (incremental innovation) (see also Swiss Confederation 2017; OECD 2017). It is therefore not surprising that more than two-thirds of companies (in the broad sense) consider sales growth to be one of the most important performance factors (PwC 2017). Figure 1.26, taken from this report, illustrates that in the short term, it is this aspect that is targeted.

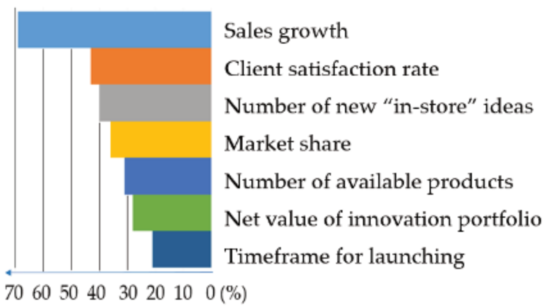

Figure 1.26. *Innovation measurement parameters in the companies surveyed by the PwC survey (2017)*

However, it is true that companies have experienced the effects of quality approaches, standardization (ISO, CEN, etc.) designed to eliminate risks, and standardization to improve economic performance in the short term. With current threats (see Chapter 2 on foresight), these dynamic companies should be expected to seek new markets based on real technological breakthroughs. "We are under the impression that, after having put everyone in prison preventively, we condemned former prisoners to become useless observers of new generations who seek their salvation in creation" (Maillard 2017). But the short term and traditional conservatism reign too powerfully in control. "Changing tools is not only adopting a new working instrument, but also often disrupting an entire system, an entire work rhythm; we therefore have a better understanding of certain collective or individual resistance" (Haudricourt and Bruhnes-Delamarre 1955). The invention of physical or virtual tools will in turn force the operator to evolve and undergo new systems in which they have not participated (hence the question of reinventing people as envisaged with philosophy) Besnier (2011).

Bernard Descomps wrote in 1989 (quoted by Germinet and Harissendy 2003) the following, adapted to a lack of ingenuity and the ability to anticipate questions: “Our country has a habit of identifying an engineer as someone who has worked a great deal in mathematics or physics, and has sufficiently cultivated abstraction before becoming more and more interested in technology. As a result, every 20 or 30 years, we discover that young engineers are not adapted to the techniques and we create a new school.” Though, in fact, in this infernal conservative spiral, we are not closing any of them.

However, this type of operation, apparently far from disruptive aspects, but close to artificial intelligence, spreads applications which, as will be shown in the following, have an indirect impact on the processes themselves (standardization for example). The current 4.0 reflection is in fact based on the in-depth modification of human relationships due to digital technology (Audéoud 2017). With masterable technologies, we know how to predict the return on investment, which induces confidence on the part of all stakeholders. But, at the same time, Citton (2014) considers that serendipity will disappear when we are invaded by search engines that will provide us with a standardized solution. It is therefore difficult to embark on what can be considered utopian, at least for the time being. Skinner (1974) takes this further by writing: “By triumphing in the struggle for freedom and in the search for happiness, the West has lost its taste for action.”

“Companies must realize that opening innovation centres is not enough for them to become innovative overnight. For real and sustainable transformation, companies must develop a culture that encourages employees, through financial or non-financial rewards, to test and commercialize their ideas. Innovation departments can play an important role in this process, working with different teams to develop original ideas and connect with the ecosystem of partners and suppliers. That said, it should be noted that success depends first and foremost on promoting innovation and creativity at the company level” (Lanny Cohen, cited by Gapgemini 2017). But only 17%, according to this report, of companies have developed this effort ranging from creativity to innovation, but most are concerned with producing demand by forcing customers’ attention.

Another path, which is increasingly interesting for large groups, is to follow the emergence of start-ups that are engaging in a new market in an original way (with the difficulty of initial financing, however), even if it means buying them back when they have shown the way. “Deep-tech nuggets focus on disruptive innovation. Most often born in a laboratory, the result of the latest scientific advances, which are very difficult to reproduce, are the subject of technology transfer to tackle the major challenges of the 21st Century in all fields: energy, environment, aeronautics, health, industry, mobility, agriculture, finance, telecoms, transport” (Roland 2017).

However, process engineers, at least in the national territory, are very rarely enterprising, if only in relation to the decent salaries they have in large groups and more modest risk-taking (see Vecteurs économie et innovation 2017).

In this apparent continuity, Figure 1.27 recalls that the technological innovation process as a whole is only one element of a complex relationship between production and society. Indeed, the way in which innovation develops within the company and the choices of its orientations depend strongly on the societal context in which the company is anchored.

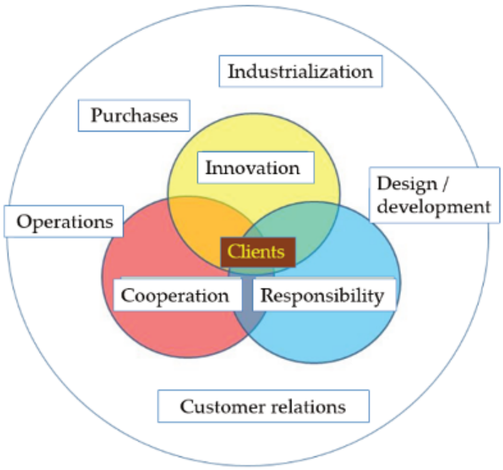

Figure 1.27. *Integration of the technological innovation process into its societal framework*

Companies are constantly adapting their innovative behavior to emerging social norms and the industrial environment (Buenstorf 2000; Pyka and Windrum 2003). The creation of new products obviously depends on the company's receipt of new products (unless they are hidden, as is often the case in PE). Innovation also plays a role in the environmental context, as its results can have a positive or negative impact on the environment and on society, thus contributing to opportunities to address issues associated with major challenges (Owen *et al*. 2013).

For reasons of trust and quality assurance, the manufacturer via the seller must provide a product that meets the specifications at an agreed price. The seller, who has a recognized process for liaising with the buyer, does not generally have to look for a solution that better meets the expected results. On these bases, the decision-making power on revisited designs is transferred to the customer and users (technology pull and not push!). Change, especially with many uncertainties related to complexity, can only occur in traditional (understandable) conservatism when breaks occur. "The technical ideology will legitimize the new technical system. This is becoming more and more rigid, alternative solutions are being abandoned and we are witnessing what economic historians call technological locking" (Flichy 2001). It is therefore necessary to share different "manifestations" of external tensions to force the creation of a divergent will to act and a shared sense of common purpose on the part of members of the scientific community to force change. But when this one is inevitable? Others (EY 2017) consider that the industry of the future must be thought of in terms of performance and not technology, with, according to WTO/ILO (2017), the development of skills for industrial operators. The debate therefore remains open.

However, in the sense of Godet (1991), it is a question of rehabilitating desire as a productive force for the future. In a world subject to ever-increasing constraints, it is perhaps time to get involved in an approach to complexity, which for Foucart (2011), moves the discipline away from a deterministic and mechanical perspective and requires mastering interdependencies. He writes: "It is more in collusion with a probabilistic perspective that also includes sequence breaks. These are based on events that are not very predictable." There is therefore "work to be done" if new forms of thought and action are to emerge. It is from this observation that we must consider our ability to create and theorize in order to better build new processes. This consideration concerns not only the fast-moving digital world, but also the various fields irrigated by chemical engineering. But, as Maurin (2015) reminds us, "a holder of more uncertain and fragile statuses, the contemporary individual is exposed as never before to the need to do like others, to the need to follow others, so as not to find themselves even further away from them." Conformity is at the heart of everything.

Thus, in the actions likely to be carried out, as of now, digital technologies, miniaturization, artificial intelligence, deep learning, the preservation of natural resources, substitution, global warming, social responsibility, etc. will be involved in the reflections, all in a changing political and social context (see Chapter 2 on foresight, (Le Méhauté *et al.* 2007; Economist Intelligence Unit 2011; Académie des sciences 2017; Audéoud 2017; Perrin 2017, MOWATT Center 2017), etc.). Moreover, the Academy of Sciences (2017a) proposes actions for sustainable technologies that could redirect production and consumption towards the preservation of natural resources, the mitigation of climate change, and the improvement of environmental quality. Clearly, there is a place for process engineering in this scheme (although for DGE (2012) and PIPAME (2014), the low level of investment in the field of material processing in France is worrying, with a low turnover growth, with a loss of diversity (and perhaps greater vulnerability). This conservatism would not only have disadvantages because the know-how accumulated in "top-of-the-range" products, reflecting old specializations, still makes it possible to maintain a credible positioning (Cohen 2006).

Basically, everything is a matter of beliefs in the future, because no major clouds obscure the sky above us on a daily basis, because the "process engineering" field enjoys satisfactory quality and attractiveness, in academic and industrial leaders who assume scientific and administrative responsibility. So why try to practice activities that are part of change (why not maintain the status quo in the absence of crises?):

– Based on divergent thinking and creativity (whereas one has not entered a laboratory on this criterion), as long as there is no obligation to change. In any case, strategic choices are, on average, confused with those of other stakeholders in national or international scientific research or are perceived as such. Thus, this character, which is not specific to these organizations alone, leads to a certain form of followerism, even positive forms of conservatism-evolutionism; we just have to seek excellence (which is not so bad!). When there is really "scientific novelty", it is almost always the result of a bottom-up approach that is not sufficiently well-perceived by the whole system, because it breaks with the flow of things (and is therefore badly or not supported).

– Involves an analysis of the changes that will affect us to better anticipate them. "By daring to imagine the future, people are balanced between pleasure and thrill. As science and technology take significant steps forward, people immediately erect barriers for fear of being overtaken" (de Riedmatten 2005). Is it then useful to carry out a "compliant" prospective? Thus, one of the difficulties lies in the definition of credible scenarios that take into account the potential for progress transformed into research axes, because of the difficulty of the exercise, amplified by the lengthening of the chains of interdependencies between new knowledge and uses, hence the need for a better "progressive awareness that we are linked to more and more individuals, more and more distant from us" (Elias 1995). According to Godet (2003), this difficulty to be overcome is due to another cause: "If we overestimate the changes, it is also because we underestimate the inertia. [...] It is the same impulses of power, love and hatred that animate people today as those of ancient Greece."

But are the time bases of resourcing adapted to maintaining the scientific and technological leadership of process engineering in a world undergoing profound change? That's the dilemma! To whom should we give credit for these changes we may experience? The risk of a delay has apparently not been assessed, which does not make it possible to show urgency in the necessary changes and their anticipation.

So, if we want to avoid the idea of agreeing with Lewis Carroll (2010) who wrote: "In the kingdom of the Red Queen, all subjects must run as fast as possible to stay there. As Alice points out, perplexed and stunned, this is a very tiring way to get nowhere!" It is therefore not a question of changing for the sake of change, but of embarking on new paths, probably strewn with obstacles. However, it is a question of legitimacy. "Uncertainty and bifurcation transform the present time into a time of creation" (Prigogine 1996). "He followed his idea, it was a fixed idea and he was surprised not to move forward" (Prévert, quoted by Manoury 2009). So, let's create, and try to get out of Quinn's (1980) reflection: "much of the planning [...] looks like a rain dance; [...] most instructions and advice [...] are aimed at improving the dance, not the weather."

> The ability to innovate requires discernment, the ability to take a new direction that will be successful (strategic vision). To achieve this objective, it requires curiosity, the motivation to engage in the unknown, courage and the use of a certain weakness in the ways in which innovation is prevented, if not support for entrepreneurial opportunities, to advance. (Phelps 2017)

Specific texts are devoted to the education, culture, innovation, process-engineering-oriented creativity component (see, for example, Potier *et al.* 2015; Teles dos Santos *et al.* 2018). However, it will probably be necessary to go a little further than Figure 1.28, published by the *Société française du génie des procédés*[4] (2017), which remains in the great tradition of conventional process engineering by expanding, as Mihelcic *et al.* (2003) already pointed out, but more clearly, the mission of "process" engineers: to design and monitor the implementation of new equipment or adapt existing tools, within plants and production units, by addressing issues of safety, efficiency, and performance.

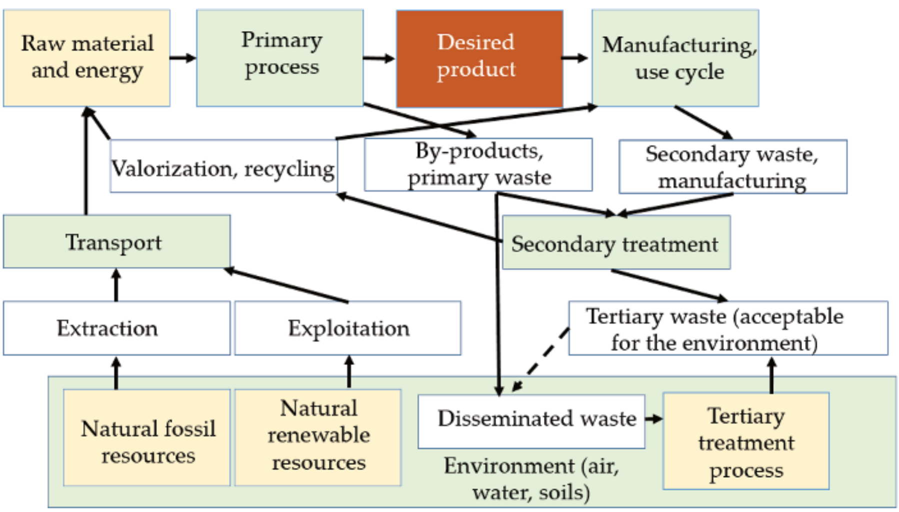

Figure 1.28. *Areas of action for process engineering in the future. For a color version of this figure, see www.iste.co.uk/schaer/process3.zip*

4 French society of process engineers.

In practice, the development of multidisciplinary integration technologies requires, for example, the initial combination of technical skills in materials and polymer engineering, chemistry, biochemistry, engineering, and protein within process platforms. Then, in the medium term, the integration of teams of researchers from these disciplines (preferably, but not exclusively, at the local level to avoid the heavy constraints linked to major geographical movements) would make it possible to implement genuine innovative projects in a favorable environment where specific skills and equipment would be available. The community of innovators would thus have acquired a more relevant and broader scientific culture in these fields to develop new ambitious and credible projects.

This presentation is not only limited to organizations that have already proven their worth, but also takes into consideration the need to work on ways to truly pool interests and objectives that have yet to be created, particularly on new subjects (requiring speed, flexibility, and relying on serious strategic intelligence). The implementation of demonstrators (in the context of student or young researcher projects) requires specific support (interdisciplinary project management to be considered with industrialists, etc.) combined with appropriate scientific, technological, and organizational assessment methods (to overcome reductive rating methods). This policy is partly that put forward by project hotels in technological universities in other major developed countries and remains relevant for multiplinary projects around basic facilities, instrumentation, or characterization techniques present in a school combining quality research laboratories (Weaver and Muci-Küchler 2008). But other avenues need to be explored.

France and the European Union have the capacity to master know-how, to be able to combine products and materials in a modern way, and engineers must play a leading role. Following the example of what is done in digital technology, the business manager, after having been an industrial engineer, a salesperson, a marketer, or financier, will have to integrate all these notions to become a "trend creator" based on incrementality. But it is the new one that will open up industrial and financial opportunities for them. On this desired basis, where knowledge and imagination coexist, should we, following the example of Einstein, who wrote "imagination is more important than knowledge", be satisfied with an innate capacity for some, with a fantasy base oriented towards satisfying societal needs, without delving deeper into certain disciplinary fields? Divergent thinking must help us to search in several directions, to search for as many possible answers as possible (which can then be filtered through knowledge of reality and what is possible), to search for new and unexpected solutions, which are sometimes risky. Indeed, reality has many points of view, without being sure that there is only one optimal way to achieve the new objective. Learning processes are therefore far from linear and the roots that generate knowledge are multiple and deserve to be demonstrated on specific cases and taught.

> When trying to generate new ideas during a workshop, work session or longer project, we often distinguish two phases: a 'divergent thinking' phase in which we try to produce as many ideas as possible in an unbridled way (e.g. by brainstorming) and a 'convergent thinking' phase in which ideas are sorted, classified and selected. (IDD 2017)

To paraphrase Prigogine and Stengers (1988), could we not write that process engineering is not a stabilized science whose behaviors and access to knowledge are known? The discipline must no longer be alien to phenomena that come out of its "toolbox", which leads to new interpretations and invents a future for it (as such and not in its applications within boundary objects that would use classical methodologies). Otherwise, is there not a risk of being subjected to Vinck's (2000) stark opinion concerning engineering sciences: "several disciplines [...] are currently out of order, not academically where some excel, but in terms of what has nourished their foundations and made them relevant". Then, with a little creativity? While knowing that "thinking against the flow" is a high-risk exercise (Sevilla, 2000).

Thus, seeking and/or learning not only implies acquiring skills that correspond to the core of the PE. It is also thanks to the possibilities of digital technologies to be able to appropriate the environment in which PE is necessary, the transformations that it knows today and/or will know in the future. "It means developing transversal skills that are essential for long-term practice and innovation. It means being able to look for ways to think about complexity in several disciplines" (Living Lab Sofa 2019).

> Ever tried. Ever failed. No matter. Try again. Fail again. Fail better. (Beckett 1982)

> I have not the slightest doubt that the present detective-mindedness of the lords of scientific administration is one of the chief reasons for the barrenness of so much present scientific work. (Wiener 1989)

> What is caressed is not touched, properly speaking. It is not the softness or warmth of the hand given in contact that the caress seeks. The seeking of the caress constitutes its essence by the fact that the caress does not know what is seeks. (Levinas 1987)

> Knowledge is always incomplete and temporary. In the absence of a belief that is unanimously shared, explicitly and whose content is

considered true, efforts are made to maintain the credibility that is satisfied with the plausible. (Perrot *et al.* 1992)

Every work has its own dream, every material worked on brings its own intimate reveries... We do nothing good reluctantly, that is, against our dreams. The dreamlike nature of work is the very condition of the worker's mental integrity. Ah! A time when each profession will have its own dreamer is coming, its dream guide where each manufacture will have its own poetic office... Without the reveries of will, will is not really a human force, it is brutality. (Bachelard 1948)

To understand and not to suffer the effect of the habits imposed by long traditions, thought must strive to go beyond its customary way of seeing and try to conceive the thousand other possible points of view that represent the immense variety. (Minazzoli 1996)

But we must distinguish between a meeting resulting from a modification of ideas and a meeting resulting from a material modification. We have seen that, in the first case, the result of the meeting corresponds to the addition, in the cognitive apparatus, of a reduced image of the observations. But what happens in the second case – that of artifact creation and material innovation? The ‘substantiation’ or ‘objectification’ of an idea introduces new dimensions, not necessarily preconceived and not necessarily perceived at the time of the operation. The effects are necessarily unexpected. After a certain period of time, new phenomena emerge, which require new processes of the appropriation of nature. This cycle cannot be broken by humans. It is a unidirectional development, which leads – because of its consequences – to a loss of people’s control over their relationship with their environment. The more a person transforms that which surrounds them, the less they will understand the consequences. Thus, they will never be able to restore the natural state of their environment. Innovation forces people to innovate more. (Van der Leuw 1994)

The imagination is related to the world, ideology to social forces. (Legros *et al.* 2006)

There is flexibility in how people design, interpret, and use technology, but that this flexibility is a function of the material components comprising the artefact, the institutional context in which a technology is developed and used, and the power, knowledge, and interests of human actors (developers, users, and managers. Time too.) (Orlikowski 1992)

No doubt, most scientists and decision-makers themselves had never totally subscribed to the illusion of perfect knowledge and total certainty. Yet, while the dominant paradigm was one of unlimited scientific progress and continuing economic growth, the majority of them felt it legitimate to assume that science was the only source of acceptable knowledge for decision-making. (De Marchi and Funtowicz 2009)

The future of a science depends on the way it first dissects its object. (Bergson 2014)

We dance faster and faster just to stay in place. (Conrad 1999)

Scientists know how to train young people in narrowly focused work, but how do we teach people to sew together established specialties that perhaps should never have been separated? (Hardin 2018)

Disobeying can be a victory over oneself, a victory against generalized conformism and the inertia of the world? (Gros 2017)

Where the inorganized is available in abundance, the organization is weak. (Jüngers 2018)

Our science is dominated by the fundamental concept of exchange. (Friedman 2018)

1.13. References

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