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Is 4D Printing Disruptive or Incremental, or a Bit of Both?

> The fall of France is not a new theme, but it is a reality on many levels, and the most diverse explanations abound. (Silverzahn 2021)

> Richelieu […] said he recognized from experience that, all other things being equal, rebels are always half as strong as the defenders of official power. (Weil 2021)

1.1. Introduction

A certain malaise is developing, despite the prevailing discourse on the decline of France in terms of technological development and scientific relevance. Because of a lack of will, a lack of vision of the future and therefore a lack of risk-taking, 3D printing has not been French. Moreover, as Philippe Silverzahn (2021) points out, “our country and its industry are absent in almost any of the major current technological races, whether in Bio-Tech, artificial intelligence, robotics, digital, or energy”. For all that, the government is not stingy when it comes to launching proposals, rather than catching up, within well-funded projects such as the “*Programmes d’investissements d’avenir*” (see, e.g. Alcimed (2021)). As a reminder, they were set up by the State to finance innovative and promising investments on the national territory, in order to allow France to increase its growth and employment potential. Thus, for innovation, for this bibliographic source, the national criteria for innovation are as follows:

“Let’s make no mistake about it, even if some projects will be financed at fairly low TRLs, the priority is on applications with high market potential and leverage effect to boost French competitiveness”, with the following criteria:

– Can the project differentiate itself from ongoing translational research projects in the field worldwide? How does it add value?

– Is the preliminary data on which the project is based sufficiently robust?

– Can they justify an ambitious translational research project?

> When the State, in recent years, became aware of the delay accumulated by our country, it could only rely on the administrative system as it is, i.e., a system that continues to give priority to the control of the form rather than to the relevance of the action. (Crozier and Tillette 2000)

DEFINITION.– *Translational research*: initially, this transfer-oriented research was situated between basic, in-depth research in biology (e.g. understanding the mechanisms behind the development of a cancer) and application-oriented research aimed at evaluating the effectiveness and tolerance of new treatments in humans. By extension, it is a transfer science exploring TRLs 3–4.

DEFINITION.– *TRL* "*Technology Readiness Level*": this English-language concept is translated by a scale called TRL, which evaluates the level of maturity of an activity aimed at technological applications. It starts at 1 for basic research and reaches 9 for applications.

In the undoubtedly naive minds of many researchers (including our own), entrepreneurship and innovation contribute significantly to the success of firms and the economic growth of nations (Schumpeter 1942; Drucker 2007). Companies create value, directly and indirectly, for themselves and their customers. Entrepreneurship and innovation are often linked directly or indirectly to the notions of creativity and design. Starting from the needs expressed or the offers resulting from research, the design processes define, step by step, the artifact which must eventually meet the objectives retained (needs and constraints) by successive decisions with increasingly detailed approaches (and therefore increasingly irreversible in the limited duration of the action). It may therefore be useful to take stock of what has already been achieved and to examine future courses of action.

In the underlying race of the current major calls for tenders, in an attempt to catch up with the leading pack (which invests much more in research than our country in many scientific fields), we are exploiting the paths defined elsewhere and by others, hence this blind following. In 1984, for 3D printing (André et al. 1984), the financing supporting an economic development could have been modest, because it was merely a slightly sophisticated form of tinkering; the emergence of a child of the additive manufacturing technologies. However, 4D printing concerns a much higher field of complexity and risk-taking. This is one of the major issues of the messages we wish to convey in this book.

So, a nagging question preoccupies the authors: Is 4D manufacturing translational research (therefore incremental) or, on the contrary, despite its filiation, a breakthrough technology? In the first case, this would mean that the paradigms and methods would be stabilized and that we would participate after other foreign research groups in this follow-up of good scientific quality, because we would have already paved the low TRLs. Then, for example, work in 4D printing could be included in calls for tenders for research support accepted by the system. On the other hand, if lakes of uncertainty exist with methodologies yet to be invented, even if we have a certain vision of the future and certain means of achieving it, it is this vision of incompleteness that risks being favored by a country that exploits too much a bias of preference not to do, because it avoids the responsibility of political or non-political contributors.

On the other hand, in the context of university education, and especially in the context of the Grandes Ecoles d'Ingénieurs, mastery of the future, apart from the basic theoretical teachings, is important for two reasons. First, for future tasks over decades, useful skills for the future must be planned and taught. Second, teacher-researchers need to select the most promising pedagogies, tools and technologies to apply in their teaching work. The problem is that there is no robust method for assessing the importance of alternatives – how important will a technology like 4D printing really be in the near and especially long-term future? A useful question to answer would be: "What should every teacher-researcher know about the coming technological changes and how do we prepare for them? In these changes, where would 4D printing fit in?" (Jaakkola et al. 2017).

Moreover, according to Bessen et al. (2020), the decline in disruptive innovations since 2000 is linked to a factor related to the ability of already well-equipped companies to invest massively in intangible assets. They invest in their proprietary software, mega-data and information technology (IT) capabilities, which in the short term can enable competitive advantages, at relatively low cost (marginal cost). Again, the risk is minimized. In both extreme situations, it seems difficult to bring about innovations or breakthrough technologies. However, it is commonly known that information at all levels is expressed on the accessibility of innovations that will radically change the way consumers, industry or companies operate. This means that only startups and SMEs should be in charge of this uncertain future if they hope one day to compete with large companies (like GAFAM).

On the basis of the comments presented in the introduction to this chapter, we propose to take a look at this position, which will be further developed in the other chapters of the book. This reflection makes it possible to appreciate the position of

4D printing in this setting where, for the truly new, risk-taking is left to fragile structures and practically personal initiatives. So, in these conditions, the place of science and technoscience can be strongly questioned: How then to show that it can play a proactive role by developing new processes, illustrating the possibility of a convergence between the expression of an applicative need (more or less formulated) and scientific production. This phase of emergence of new processes, as long as it is understood by the hierarchy, and supported as such, is a possibility to envisage applications that were inconceivable less than 10 years ago, while knowing that these trends can still evolve strongly. This is what is at stake in this chapter, which voluntarily separates intelligent and/or stimulable materials from the 4D printing that uses them.

1.2. Prospective approach

> Learning to admit and exploit the seemingly incongruous means practicing new ways of perceiving and ordering experience that will allow one to maintain an inclusive peripheral vision through an essentially plastic attitude of mind. (Gordon 1965)

It is possible, before embarking on new research, not only to make a bibliography on a subject; especially since, when it is emerging, the number of publications to be read can be relatively modest (and also, it avoids wasting time). Science fiction can be another way; finally, a third way is a foresight, which is not always adapted to the sudden emergence of events or innovations. And yet…

> As anticipation adapted to an unpredictable future, studies on the future remain essential to the organization of the future passage to action: without anticipation, no objective; without objective, no coordination of actions; without coordination of actions today, no human, material, legal means [...] to be mobilized tomorrow to implement a strategy, be it military or corporate. (Roubelat 2017)

But, if this situation is well conceived by the company that needs a certain continuity to function, even if adaptability, flexibility and an ever-increasing capacity to adapt are demanded, what happens when a disruptive innovation that is not foreseen, not easily assimilated, not perceived as relevant by decision-makers (see Kodak syndrome) occurs? This question highlights a real difficulty in a world constrained by major trends and subject to unbridled competition (McKay and McKiernan 2010).

In a prospective approach where it is the uncertain that is explored, generally over longer periods than those associated with European or national plans, there is the possibility of being a little original, without any major constraint apart from motivation and conviction, which makes it possible, faced with multiple and undetermined futures, to question the comfort of the mind, to try to awaken consciences that have fallen asleep on false or old certainties. It is then a question of conceiving possible desired futures and supporting the real means to try to achieve them (Ackoff 1973); it is indeed an approach to the future that is not based solely on the extrapolation of past trends, leading to the highlighting of certain breaks to be made.

Absolute discontinuities occur without having been preceded by warning signs, and this is the whole debate on weak signals, which bring together creativity focused on an object (but in all its richness of possibilities) and foresight (insofar as they have been anticipated! The transistor and its digital sequels are good examples of non-anticipation). But as Fernand Braudel (1993) pointed out: "any effort against the current is doomed in advance"… Some prospective analyses come from strong independent personalities, such as D. Bell (1999), A. Toffler (1991) and P.F. Drucker (2007), who can, thanks to their discriminating power, issue divergent and original opinions, as is the practice in creativity (no need to seek a consensus). The interest of these personalities is that they force us to think about the future differently: Prigogine and Stengers (1979) introduced the notion of order by fluctuation, showing that weak fluctuations can orient systems by bifurcation toward one branch of evolution or another. This highlighting of weak signals can then force original conclusive propositions through in-depth investigation of the issues. Obviously, in this world where economic competition defines the (current) destiny of a consumer society, it is the technological destiny that is the object of attention of many futurists. All highly developed countries agree on the decisive importance of knowledge and industrial innovation as factors of independence and economic competitiveness. But do they not take insufficient account of technological breakthroughs because they are averaged in groups of processes or because of a lack of discrimination (see section 1.1)?

> Creativity is the impulse that invites thinking something new, something amazing, something of value. (Du Sautoy 2020)

> Every inventor, every scientist, has been so because they have known and been able to open themselves up to a field far from their own, from which they have drawn inspiration. They have erased the unfortunate divisions. (Dagognet 1989)

But, if it is not necessary to go too far into this subject, it may be useful to remember the history of 3D printing. Before 1984, there were scientific attempts reported in André (2017a), but there was no foresight about the emergence of this technology (apart from some comics from André Franquin in the "small formats" (Franquin (1973) or d'Hergé …). For 4D printing, Sculpteo (2020) considers that this technology could be used, giving a few examples, ranging from self-assembly of elements to self-repair, then to uses in extreme conditions, finally in medicine and fashion. For his part, Moigne (2020) talks about applications in soft robotics and actuation, citing Barnes et al. (2020). The manufacture of flexible robots that would swim like jellyfish or the transport and delivery of drugs are thus envisaged. This position is supported by Staedter (2019) and Future Bridge (2020). Finally, Tibbits' (2014) prediction of combining 3D printing and programmable matter is a breakthrough that has not really been anticipated outside of science fiction movies like Terminator 2.

Vision, discovery, learning and advancement are among the fundamental missions of the academic body involved in research; they are mutually reinforcing. The transfer of knowledge to those in society who can use it for the general good contributes to each of these missions. These transfers of knowledge and learning take place through scientific publications, student training, conferences, cooperative ventures, etc. Not everything is accessible, and when it is, it may be with delay, as in the case of innovations protected by patent (intellectual property or IP) and by the granting of licenses to private companies. These means of knowledge sharing that have contributed to the history of science–society relations can be exploited to access information on the 4D subject. This is how an analysis of the bibliography was carried out and collected in Table 1.1, which shows the elements expressed for the near future (indeed, it was not possible to have long-term visions in the documents examined). In these future visions, Figure 1.1 from Ergene and Yalçın (2019) gives indications of the cause (stimulus)–consequence relationships.

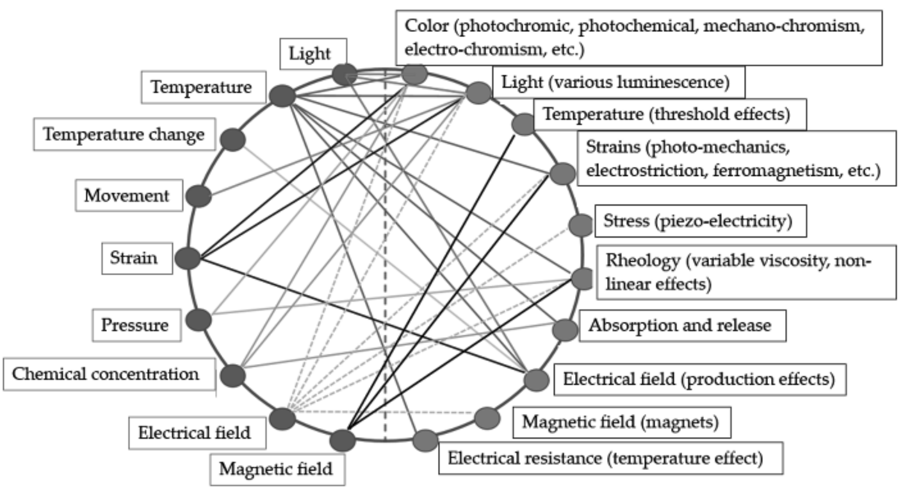

Figure 1.1. *Examples of cause-effect relationships in 4D printing. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

> Every profession makes progress, but progresses according to its own routine, tracing its own furrow […]. The furrow prevents wandering through the landscape and abstracting something, to which no attention is paid anymore […]. The rest of life is treated superficially, with the imperfect categories of a thought that derives from the profession. (Whitehead 1994)

Application	Comments	References
Biomedical		
4D bio-printing	Different biological tissues and organs	Wan et al. 2020; Lui et al. 2019
4D stents	4D structures of adaptive materials introduced into blood vessels (biocompatibility)	Duerig et al. 1999; Wei et al. 2017; Xue et al. 2019; Cohn et al., 2020; Siddharth et al. 2020; Yang et al. 2020
Implants	Shape memory alloys	Elahinia et al. 2012
Personal protections	3D elastomers	Kumar and Pumera 2021
Bio-printing	Adaptive scaffolds (biocompatibility); roadmap	Miao et al. 2016; André 2017c; Sun et al. 2020
Vascular repair	Use of adaptive materials to assist in the repair of blood vessels (biocompatibility)	Kuang et al. 2018
Intelligent sutures	Imitation of tendon mechanics	Ma et al. 2021
Dispensing of drugs	Timely delivery of orally administered drugs to the right place (biocompatibility)	Novakovic et al. 2018; Lamichhane et al. 2019; Lui et al. 2019; Melocchi et al. 2019; Shie et al. 2019; Municoy et al. 2020; Li 2016; Inphonlek et al. 2020; Jia et al. 2021
Medical treatment	Swimming robot	Wang et al. 2020b
Drugs	Nanoscopic materials sensitive to an electromagnetic potential (e.g. local hyperthermia)	Li and Su 2018; Kirillova and Ionov 2019; Lui et al. 2019; Bajpai et al. 2020
Odontology	Consideration of tissue displacement in dental repair	Hamza 2018
Orthopedics	Organic stimulable materials	Semba et al. 2020
Energy and processes		
Storage	Loading by thermomechanical means	Roudbarian et al. 2019
Production	Piezoelectricity; thermoelectricity	Cholleti 2018; Chen et al. 2020; Rösch et al. 2021

Solar	Solar concentrators	Svetozarevic et al. 2016; Momeni and Ni 2018
Micro-fluidics	Adaptive systems	Robertson et al. 2016; Cesewski et al. 2018; Apsite et al. 2020
Microparticles	Deformation induced by nanoparticles	Sun et al. 2012
Metamaterials	Design	Fraternali et al. 2019
Adaptive optics	Integrated and self-adapting optics	Jeong et al. 2020; Apsite et al. 2020
Electrochemical reactor	Several materials including metals	Arenas et al. 2017
Catalysis	Metamaterials and composites	Ludwig et al. 2018; Papetti et al. 2018
Atomic scale		
Manufacturing	Displacement of atoms	IBM 2012
Nano-machines		
Nano-machines	Molecules transformable by the influence of stimulation; catenanes	Sauvage 2003; Lemouchi 2010; Medina-Sanchez et al. 2018; Bandari et al. 2020; Novotný et al. 2020
Nano and micromotors	Idem	Ning et al. 2018; Wang and Pumera 2020
Transportation		
Adaptive structures	Spoilers in adaptive aerodynamics; speed-dependent deformations (but according to Audi’s Wiese et al. (2020), this demand does not appear)	Sellitto and Riccio 2019; Das and Dujana 2020; Siddharth et al. 2020
Morphing	Adaptive systems	Daynes and Weaver 2013; Papoutsis-Kiachagias et al. 2019; Chillara and Tapino 2020; Le Good et al. 2021
Tyres	Wheel-tread torque	Michelin 2016; Monino 2017
Avionics	Active elements	Daynes and Weaver 2013; Su et al. 2018b
Mechanical insulation	Auxiliary/meta-material structures Damping/meta-materials	Liu et al. 2020b; Xue et al. 2020 ; Clough et al. 2019

Architecture		
Design and construction	Adaptive structures	Thomas et al. 2014
Structures	Adaptive structures	Beites 2013; Grassi et al. 2020
Esthetic facades	Reconfigurable shapes adapted to heat and/or light	Abdel-Rahman and Tafrihi 2018; Morteza Hosseini et al. 2019
Robotics, sensors and actuators		
Automation	Association of active elements	Shen et al. 2019; Decroly et al. 2020
Self-organization	Self-organization of robots	Ren et al. 2020
Origami and mobile kirigami	Development of active 3D structures from a flat base on which active materials are printed	Ge et al. 2014; Modes and Warner 2016; Liu et al. 2018b; Apsite et al. 2020; Liu et al. 2020a; Shen et al. 2020a; Alderete et al. 2021; Lin et al. 2021
Flexible robotics	Replacement of structures and joints by deformable elements (actuators)	Gul et al. 2018; Schaffner et al. 2018; Zolfagharian et al. 2019, 2020; Duriez 2020; Scalet 2020; Shen et al. 2020b; Zhu et al. 2020; Schara et al. 2021; Tyagi et al. 2021
Micro-robots	Co-bots, bio-bots; self-organization	Blackiston et al. 2021; André 2017c
Swimming robots	Submillimeter scale displacements	Bumjin 2018; Ceylan et al. 2019; Wu et al. 2021
Mechanical closures	Realization of a 4D object under mechanical tension	Su et al. 2018a
Deformable structures	Temperature and humidity deformable shapes; shape memory systems	André 2017c; Mouzakis 2018; Lopez-Valdeolivas et al. 2018; Wang et al. 2018c; Zhang and Xiao 2018
Sensors	Strain-dependent strength; mechanical effects	Surjadi et al. 2019; Garces and Ayranci 2020; Verpaalen et al. 2020
Engines	Activated deformable shapes	Peng et al. 2020; Rubio et al. 2021
Clamps and actuators	Deformation of a 4D object serving as an actuator thanks to an external stimulation	Miriyev et al. 2017; Chen and Shea 2018; Liu et al. 2018a; Yuan et al. 2018; Akbari et al. 2019; Lui et al. 2019; Schreiber et al. 2019; Liu et al. 2020b; Milana et al. 2020; Shao et al. 2020; Ze et al. 2020

Bilames	Stimulation-induced changes	Hagaman et al. 2018
Bistables	Shape memory alloys	Rostaing 2004; Jeong et al. 2019; Jiang et al. 2019; Boni and Royer-Carfagni 2021
Shape memories	Alloys and polymers	Nicolas et al. 2000; Wagg et al. 2007; Ould Moussa 2011; Simoneau 2013; Yao et al. 2021
Optics	Various elements	Willis et al. 2012
Magnetism	Insulating coupling, magnetic materials	Huber et al. 2016
Bio-mimicry	Active auxetic structure	Lee et al. 2020; Wang et al. 2020c
Color change	Transformation induced by an electromagnetic field or light or temperature	Rai et al. 2017; Salmon et al. 2019
"Programmed" self-organization	Robotic voxel assemblies; catomes	Moskvitch 2015; Rus and Tolley 2015; Poty et al. 2017; Su et al. 2020
Fashion and clothing		
Smart clothing and textiles	Adaptive clothing (changing colors, permeability, size, etc.)	Chan Vili 2007; Hu and Lu 2014; Rayate and Jaemi 2018; Zhang et al. 2018b; Ren et al. 2019; Yu et al. 2020; Biswas et al. 2021; Koch et al. 2021; Miao et al. 2021
Military applications	Camouflage (color change)	Puren 2013; Wang et al. 2019a
Color change	Color changes with deformation	Vatankhah-Varnosfaderani et al. 2018
Shoes	Adaptive materials	Konakovic et al. 2016; Rastogi and Kandasubramanian 2019
Jewelery	Mobile jewelry	Zarek et al. 2016b
Electronics		
4D and structural electronics	Integration of electronics into objects (4D) including actuators; flexible printed electronics	Espalin et al. 2014; McDonald et al. 2014; Lee et al. 2017b; Oh et al. 2018; Lu et al. 2018; Liten-CEA 2019; Wang et al. 2019b
Printed electronics	Printing with conductive inks (including those containing nanoparticles)	Zarek et al. 2016a; Kwon et al. 2020; Deng et al. 2017; Lou et al. 2017; Jasiuk et al. 2018
Switch	Photo-activation	Gu et al. 2018
Circuitry	Photo-deposition	Tabridzi et al. 2017

Transducer	Several successive operations	Cesewski et al. 2018
Biochemical analysis	Miniaturization, integration, automation and parallelization of biochemical processes	Zhang et al. 2018a
Wave absorption	4D acoustic wave absorption structure	Le et al. 2020
Digital		
Synapses	Adaptive materials	Park et al. 2020
Memories	Idem	Zhang et al. 2019
NAND gates	Idem	Zhang et al. 2019
Information storage	Three-dimensional microscopic indentation layers	De Angelis 2019
Space		
Antennas, solar collectors, etc.	Spatial structures that can be deployed	Mitchell et al. 2018; Ntouanoglou et al. 2018; Tofail et al. 2018; Melli et al. 2020
Various		
Food	Pasta	Tao et al. 2021
Self-repair	Poly-methyl siloxane elastomers	Idumah et al. 2020; Liu et al. 2020c
3D animation	3D TV; 3/4D cinema	Patel et al. 2017
Waterproofing	Functionalization of textiles	Puren 2013; Yu et al. 2018
Packaging	Smart packaging	Kuang et al. 2019
Alphabet	Letters of the alphabet made in 4D printing	Hoa and Rosca 2020
6D printing	The consumer will use his sixth sense; the data will be transferred to the 6D printing interface	Moonmoon 2019; Simeral et al. 2021
	Other view	Georgantzinos et al. 2021

Table 1.1. *Examples of application targets*

The partitioning in this table is relatively artificial; thus, in Figure 1.2, we have represented, for a garment, a concept of energy production and storage in association with other sought-after qualities which will promote the attractiveness of a device. There can be several 4D operations in the same object.

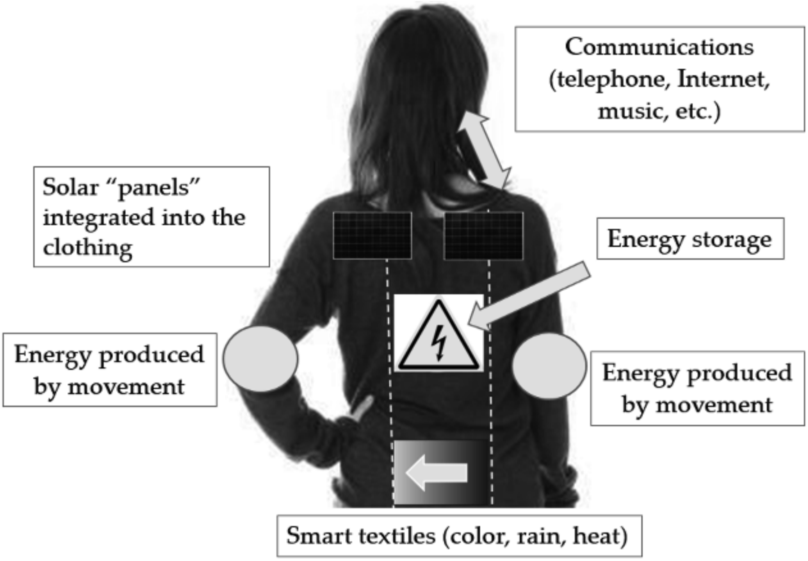

Figure 1.2. *Integrations enabled by 4D printing; the example of smart clothing. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

DEFINITION.– *Structural electronics*: generic technologies for integrating electronics into the heart of objects, that is by combining electronic functions with the structure of the parts themselves.

For Melli et al. (2020), 4D printing is a revolutionary invention; it is expected to have a significant impact, provided the challenges it faces are overcome, on the fabrication of dynamic structures for various applications. This assumes, at a minimum, that the varieties of tunable, 4D-printable smart materials increase in number and performance. Thus, 4D printing remains for the moment at a proof-of-concept stage that has yet to show its capacity to pre-program the material, which must react appropriately to various stimuli localized in time and space. An axis emerges in 4D actions, that of space, because it is quickly conceivable to realize simple adaptive structures allowing weight savings (as a reminder, each kg launched from the Earth costs, according to Mitchell et al. (2018), about 10,000 €). For these same authors, a step should be taken when it will be possible to have large printers combining additive manufacturing and robotics, with multi-material printing. However, in this picture, these ideas and concepts remain in line with what can be envisaged; there are few "revolutionary" contributions (apart from the idea of 6D printing). Has science reached the peak of wisdom or does it no longer know how to question itself?

This situation is recent, and one of the origins can be defined, in agreement with Gordon (2016), by these sentences from Cowen (2011):

> We can't figure out why we can't do it anymore. All these problems have a single, but unnoticed, cause: we have lived for at least three hundred years on fruit that was just waiting to be picked […]. But in the last forty years, these fruits have become scarce, and we have acted as if they were still there. We didn't want to recognize that we had reached a technological plateau and that the tree was much barer than we wanted to admit.

So, as soon as a guideline seems to bring scientific and/or technical progress, we pursue the action via incremental research (as is the case today with 3D printing) by seeking to win without making a clear break. But this quest obviously has its limits.

For Vinsel (2020), to complement Cowen's analysis, interest in technological innovation (and its benefits) is overestimated (see also Vinsel and Russel (2020)). He concludes that "this situation invites us to work on technological situations that are not real and are not even realistic projections of where science and technology are going" (Guillaud 2021). This is somewhat what was observed in the case of nanotechnologies, where considerable promises were made more than 20 years ago, with a rather mediocre application result (Frochot et al. 2020). Will the same be true for 4D printing?

1.3. A tectonics of paradigms

Figure 1.3, which is a bit provocative, reminds us of the old Christopher Columbus syndrome: when he left, he did not know where he was going; when he arrived, he did not know where he was and all the while, he did not do it with his own money!

> But another world exists. Today, at the micro and nano scales, an unprecedented revolution is underway. It is the ability to program biological and physical materials to change shape, change properties, and even perform computation in a non-silicon based material. (Tibbits 2013)

The *technology-push* model has long been dominant and is still applied (Badillo 2013). It has inspired the development of technologies such as 3D printing. It is a linear model with an innovation that is the result of science and technology. This "*top-down*" innovation respects the "E-C-R" (emission, communication, reception) communication model inspired by Shannon's work and is situated in a

Schumpeterian logic (Schumpeter 1942, 1952; Von Hippel 2013), that of the innovating entrepreneur (the emitter). In this simple situation, users are considered, to a first approximation, as passive receivers. Schmookler (1966) introduced the concept of "*demand-pull*" or "*market-pull*" involving the user. Rothwell and Zegveld (1982) then combined these two models with feedback effects. "The innovation process can be thought of as a set of communication paths through which knowledge is transferred" (Trott 2008). More recent models, such as network models or open models of innovation, are based on a systems approach to innovation (Chesbrough 2003; Chesbrough et al. 2006). While the situation is relatively clear for 3D printing, we discuss below the situation for 4D printing and its possible applications.

Figure 1.3. *Peter Breughel's The Blind Leading the Blind. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

1.3.1. *3D printing*

> Collective intelligence is an open approach based on the freedom to belong to a process. Because they find benefit in collaborating, individuals voluntarily and autonomously engage in a community bound in time and space. The structure thus developed is perfectly horizontal, without any hierarchy. (Novel and Riot 2013)

The concept of 3D printing was demonstrated and operationalized in 1984 (André et al. 1984) by a patent concerning stereolithography consisting of the spatially resolved polymerization of a light-sensitive resin. The coordinates of the object to be produced were stored in a computer which controlled galvanometric mirrors to transform a liquid into a solid by polymerization of a fluid layer, voxel by voxel, hence the concept of additive manufacturing. Adding a second layer, then a third, and so on, would in principle create the desired prototype part, which finally had to be extracted (and washed) from the non-photo-transformed fluid (André 2020). The other manufacturing principles are based on the same foundation of additivity, but as shown in Figure 1.4 and Table 1.2 the processes differ essentially in the nature and modes of adhesion of the material to the object under construction (André 2017a; Kalyan et al. 2021). The rule of the game is indeed to have either localized energy or a localized positioning of material or both.

When Dagognet (1989) wrote: "Didn't the clothiers catch a glimpse of the future digitalized image, since they worked on the one hand in a binary mode (a presence or absence) and with the help of a few strands, dyed in different ways?", did he not introduce this mechanization as an eminent ancestor of additive manufacturing? Digital additive manufacturing techniques that exploit elementary volumes called voxels (and not strands) are now well known to have many advantages (and naturally limitations expressed in André (2017a)). Recently, a new technology called volumetric 3D printing has been developed (Amra et al. 2017; The Chinese University of Hong Kong 2019; De Beer et al. 2019; Loterie et al. 2020; Mayer et al. 2020; Regehly et al. 2020; Doualle et al. 2021).

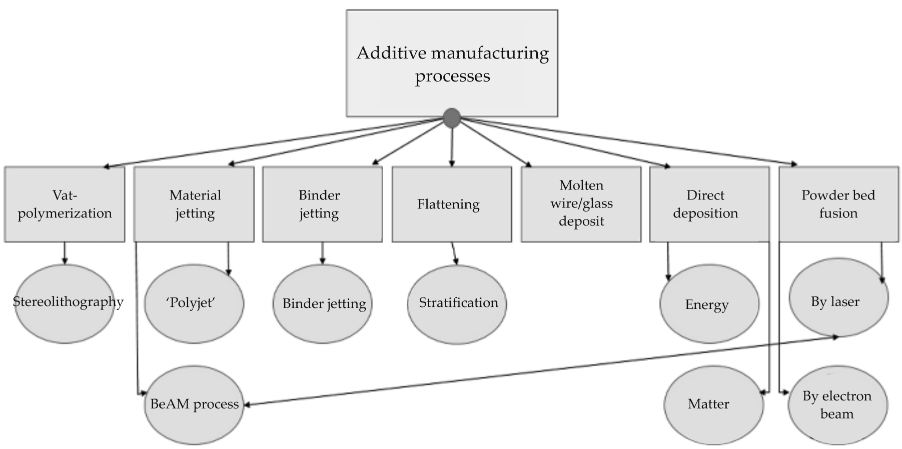

Figure 1.4. *The different additive manufacturing processes*

Theme of the chapter	Process name	Official name	Comments
Stereolithography	SLA	Stereolithography	Light-induced polymerization of charged and unfilled resin Different irradiation systems
Strand fusing	FDM/FFF	Fused Deposition Modeling/Fused Filament Fabrication	Wire fusing: layer by layer deposition of a thin layer of molten wire. The material cools in contact with the air and solidifies From molten polymer to metals and glass
Bonding of sheets or powders	SDL	Selective Deposition Lamination	Sheets with activatable adhesive; uses inkjet system (photosensitive or UV-reactive material)
	SC	Strato-Conception	Sheet cutting – "mechanical" assembly; at each layer, a laser or a cutting tool removes the contours of the desired object
	3DP	Three-Dimensional Printing	Powders combined with an adhesive; uses inkjet system (photosensitive or UV-reactive material) or thermal bonding
	BJ	Binder Jetting	Ditto; particles are deposited on the printing plate and bound by the addition of an aggregating liquid, possibly colored
	SUR	Soluble Unsoluble Reaction	Change in solubility of an organic material
Melting/Sintering of powders	SLS	Selective Laser Sintering	Laser-induced sintering of flat surfaces
	SLM	Selective Laser Melting	Laser-induced melting on a flat surface
	EBM	Electron Beam Melting	Electron beam induced fusion
	LMD	Laser Metal Deposition	Simultaneous metal deposition and melting
	CLAD	Direct Additive Laser Construction	Simultaneous supply of material and light energy: material melted during its deposition by a highly directed thermal source
	MPA	Metal Powder Application	Ditto, particle kinetic energy

Table 1.2. *The different additive manufacturing processes with some elements of differentiation*

With a number of manufacturing techniques limited to less than 10, the existence of specialized machines and knowledge on the qualities of 3D parts that can be produced are known. If there was a breakthrough in 1984, in 2021, it was rather in the logic of supply. It is only when new 3D machines covering new energy-material interactions are put on the market that users will make their choice. It is basically a machine like any other to be chosen from a commercial set, with its defects and its qualities. This is in fact what is shown in Figure 1.5, from Gao et al. (2015), concerning 3D methods and associated offers.

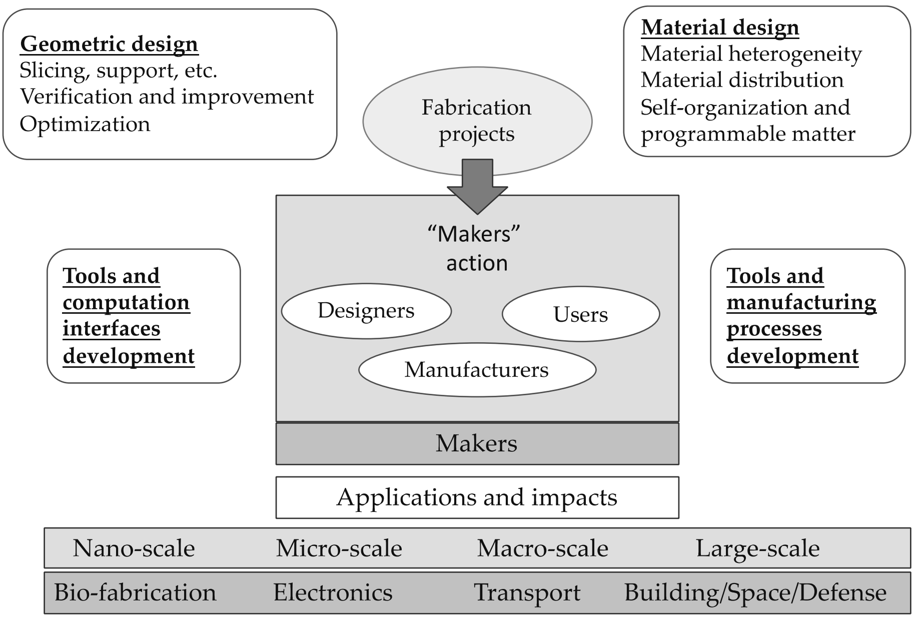

Figure 1.5. *Offerings resulting from the mastery of 3D technologies. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

1.3.2. *4D printing*

No matter how we look at the material world, there are many visible or hidden materials that frame our everyday lives. These can be inert objects as well as living or formerly living objects. We have shown that scientists are developing tools and ideas, some of which are inspired by nature (bio-mimicry), to create materials that have life-like properties; in other words, materials that can feel, move, change shape or function and adapt to their environment to fulfill specific purposes. These are the foundations on which 4D printing is being developed.

1.3.2.1. *Double disruption*

> Technology can be defined "as the set of procedures and means that a society uses to understand the nature and scope of scientific change, technological development and capabilities, and to assess economic utility and feasibility, social value and relevance". (Petrella 1992)

However, as André (2017a) reminds us, 3D technologies are numerous (see section 1.3.1) and meet precise and now well-known criteria. For all that, we can distinguish the fabrication of 4D parts with single materials which correspond to the main applications targeted by scientific publications (homogeneous 4D printing), then hybrid fabrications, using a single machine, with various materials (hybrid 4D printing) and finally heterogeneous processes which use in part 3D manufacturing principles (heterogeneous 4D printing). Figure 1.6 recalls, with different modes of distribution of passive and active materials (Rafiee et al. 2020), these three definitions.

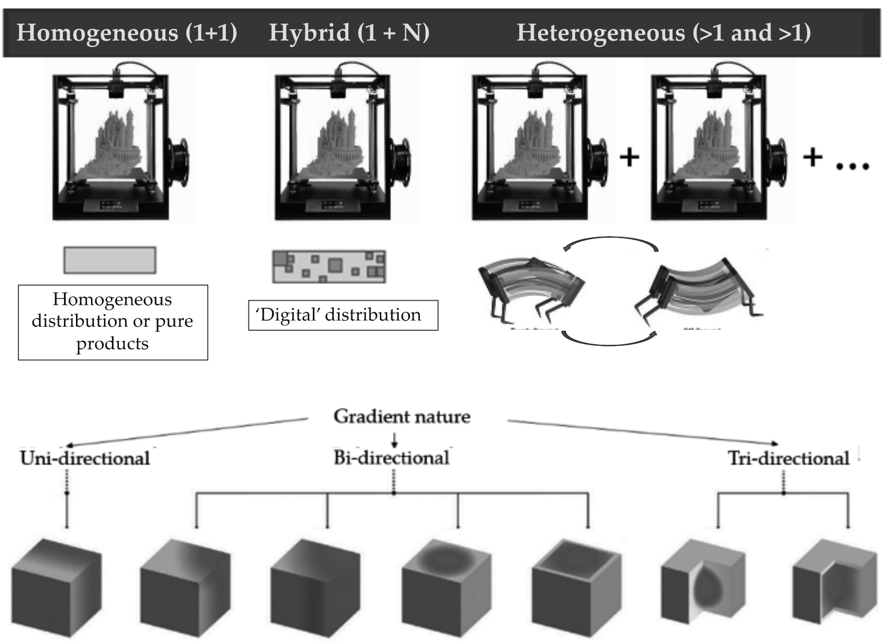

Figure 1.6. *The different forms of 4D printing. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

COMMENT ON FIGURE 1.6.– *The upper part of this figure has already been presented in a previous chapter; this situation repeats itself for a small number of other figures. They have been kept in the chapters where they belong to avoid the reader having to look for the pages where they were introduced for the first time.*

For Magistrelli (2021), heterogeneous manufacturing processes combine additive and subtractive manufacturing processes.

> These are implemented sequentially or incorporated, with proper control of component attachment and orientation. Such a process is used both to improve dimensional accuracy and to speed up the overall manufacturing process. [Heterogeneous] processes can be used to solve complex production problems where a single manufacturing method (subtractive or additive) is not sufficient.

Robots can be used for this combination to produce complex parts. A first combinatorial analysis would show a great diversity of choices: variable voxel sizes, modes of action and stimulation. However, the excess of possibilities risks, by accumulation of possibilities, not to serve the morphic creation and its evolution. A principle of parsimony should probably be used to optimize the realizations of the 4D devices.

Furthermore, 4D printing requires an association with an energy stimulation mode: light, pH, chemistry, humidity, heating, mechanical, pulsed or continuous electric and magnetic fields, global or localized, single or coupled with a time resolution, etc. Thus, with respect to the 10 families of 3D printing technologies, it is possible to consider 10^3 (homogeneous, hybrid and heterogeneous technologies) x 8–10 (stimulation modes) x 2 (continuous or pulsed) x 2 (couplings), that is approximately 10,000 possibilities, which prohibit any operation based on supply logic (unless one restricts oneself to a small niche). 4D printing is already a breakthrough by associating 3D printing with active material, which means that we must not operate on the basis of supply, but on the basis of demand, from needs expressed by possible users, which is a radical change. This context of double scientific and organizational breakthrough is not yet perceptible, but it will have to be taken into consideration if 4D printing is to develop.

1.3.2.2. *Demand-driven management*

> Why is it beautiful? […] Because it is a constrained movement, because the profound movement of dance lies precisely in absolute and ecstatic obedience, in the ideal lack of freedom (Zamiatine 2020).

The public is beginning to be familiar with the development of self-healing materials targeting many applications: asphalt, concrete and self-healing fiber-reinforced polymers. But beyond this sensible notion of rejecting the vision of a throwaway society, there are many spaces that can be covered, from the nanometer to the decameter. Clearly, as the understanding of materials can be animated with the development of shape and stimulus technologies advances, large numbers of applications can emerge in all industrial sectors for the production of consumer goods, as shown in Table 1.1.

Even if it is only to develop activatable materials from an idea, knowledge from different disciplines must be drawn upon. While these fabrication, analysis and testing techniques are based on the already broad fields of materials science and engineering, shaping and stimulating them to become active require input from other scientific fields ranging from synthetic chemistry to physics to engineering and digital sciences. For example, in its report, the Royal Society (2021) imagines building walls that could absorb ambient carbon dioxide and act "as bioreactors, using inputs such as light, water, heat, algae, bacteria, nutrients and gases to generate a range of products such as purified water, energy, oxygen, recoverable biomass and heat". In their report, the authors imagine clothing or bandages that react, for example, to changes in a person's body temperature to detect possible illnesses (Wang et al. 2020a). Robotic-type devices could be developed with elements or organs that could incorporate some degree of adaptation or even swarm intelligence, all using ambient energy (heat, light, mechanical, etc.).

4D structures have the potential to fundamentally change the way material goods are designed. These possibilities in the medium term may envisage the exploitation of molecular nano-machines, for example in medicine, "living robots" that would perform high-risk tasks, from storing and processing data in DNA to creating battery-less devices powered by electromagnetic waves (Royal Society 2021). Eventually, replicas of living cells could combine to form a new evolutionary tree with life forms different from those that have evolved on the Earth so far.

1.3.2.3. *Paradigm shift in design*

> Our time is the time of the dispersion of specialized knowledge and the incoherence of values; at least that is how our time becomes aware of itself. Our culture is that of the malaise of culture. From then on, the task of the philosopher seems clear: to propose a conception of the world in which each discipline finds its place; and to give back to our culture cohesion and confidence in itself. (Lefranc 2016)

The construction of artifacts involves the use of different types of materials. So, the design has a fixed goal of providing a robust result for a device that may be static (a table, a bridge or a house) because it is supposed to keep the same shape during its life. With 4D printing, it is possible to incorporate change into design methods, which will force method designers to propose new ways of making and using. There are probably considerable differences between the realization of an adaptive garment and structural electronics, taken as examples. So, these new approaches to be created should be mainly positive, offering applicators a multitude of new possibilities dedicated to each envisaged use.

In any case, the development of 4D printing requires cooperation between researchers in the fields of process, digital, materials science and engineering, mechanics, etc., combined with those who have ideas. They must work together to exchange data and share, invent approaches and methods that meet a set of specifications. The problems highlighted in these interdisciplinary activities should be taken out of the field of project management for further scientific study and then returned to it. This work, cycling between scientific convergence and advancement at different scales, requires associations between engineering sciences and advanced sciences such as physics, a generally difficult marriage.

1.3.3. *The potential development of 4D innovations*

> The dreamer always has a cloud to transform. The cloud helps us to dream the transformation. (Bachelard 1943)

In fact, current industrial developments consist of producing elements in additive manufacturing and gradually introducing them into the usual manufacturing/production processes. 4D printing is still timid on the industrial level because of its low maturity and the time needed for interdisciplinary research. What is shown in this book, moreover, is the very great complexity of the relationships between a wide variety of scientific and technical actors in the development, integration and proposed use of the artifacts created. As discussed elsewhere (André 2017c), best practices are described by organizational and practical solutions associated with the lifecycle stages of 4D systems:

– development;

– integration and organizational anchoring;

– validation of the use of 4D systems in an operational environment.

However, the specific nature of 4D active objects can give rise to interdisciplinary development and concept testing processes (Proofs-of-Concept or POCs), in which the successive phases of convergence (project management, epistemological approach, development, acquisition, initial knowledge and use) form a spiral development process, as schematically represented in Figure 1.7. During these phases, the development of the concept and the testing of successive versions of the instrumental models serve to improve the 4D system. Similarly, during the use phases, lessons learned may influence the functionality and design of the system through feedback, thus necessitating possible radical or modest modifications. This is an iterative process with risk-taking at every stage that blurs the boundaries between the developer engaged in interdisciplinary activity, the producer of the 4D device and the end-user. The notion of the “client-supplier” relationship can no longer be easily satisfied in a deterministic and causal activity, because all the different stakeholders are involved and interconnected in all the stages of the lifecycle of the realization of a 4D object (apart from simple school cases).

> It should be noted that interdisciplinarity certainly calls for the overcoming of disciplinary boundaries, but that the disciplines still remain at the root of the process that activates its decompartmentalization: interdisciplinarity is cyclically linked to disciplinarity and vice versa, insofar as any interdisciplinary practice is likely to make the disciplines involved evolve, or even transform them from within. (Darbellay 2020)

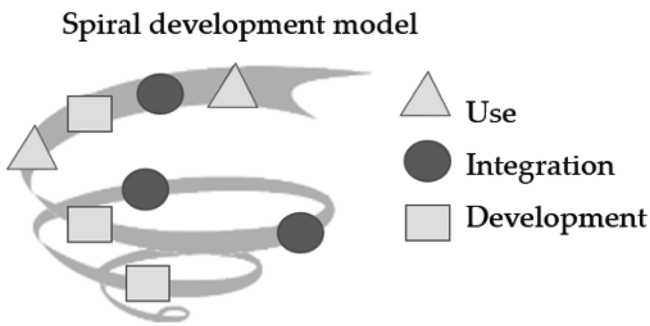

Figure 1.7. *Spiral development process and stages involved in the system design lifecycle. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

Thus, it is necessary to establish adequate cooperation between the relevant stakeholders already in the initial phase of developing an application using 4D principles. This design research requires an interdisciplinary approach with, as far as possible, good cooperation between all stakeholders. It is on this basis of necessary trust that interdisciplinary actors can meet the demand for convergence through the integration of specialized scientific and technological knowledge.

Independently of these central aspects aiming at the realization of POCs, or even more functional mock-ups, a certain number of questions must be asked by the users (who have worked since the beginning in connection with the designers) before arriving at an operational device (The Hague Centre for Strategic Studies 2021):

– Reaction speed: is it compatible with the intended application?

– Mechanical resistance: idem.

– Reliability: is the result in line with the degree of confidence envisaged by the applicant? Are there any fatigue phenomena making the device less accurate or reliable (Mirzaali et al. 2019)?

– Adaptability: are 4D systems adaptive and reconfigurable (scaling, extending, upgrading, etc.) to meet new requirements?

– Flexibility of the device: ease of modification of the 4D system according to the evolution of the R&D project?

– Volume and mass of the stimulation device: is it compatible with the envisaged application (e.g. in a mobile application)?

– Robustness and sensitivity to real-life failures: can the 4D device operate in degraded mode, and with what effects on the application?

– Safety and hygiene risks for humans? If so, is encapsulation possible? Effect of failures?

– Maintenance: is it necessary? At what cost (training of staff, materials, difficulties in extreme environment activities, etc.).

– Price relative to a positive reception by the market.

– Ethical compliance, etc.

This reflection translates for the authors into the following top-down generic propositions:

1) *4D manufacturing in a short-term approach* (<5 years before producing application paths)

It is necessary to return to what is achieved in mechanics by the association of elements from different “classic” additive manufacturing or robotic methods (for mechanical assemblies that can be disassembled, welding, gluing, etc.) with the specific component of the programming of the manufacturing process, which must take into account the materials, their shapes, their stowage and the effects of the stimuli on the desired deformation. It can be envisaged that the assembly and disassembly of the elements are possible to authorize the repair, even the reuse of the elements. Another advantage, cultural this time, must be noted in this preliminary approach, that of a manufacturing mode largely included in the current manufacturing processes, real factor of integration of innovations and novelties.

2) *Incremental approaches*

> Bio-mimicry: "An approach to innovation that involves the transfer and adaptation of principles and strategies developed by living organisms and ecosystems to produce goods and services in a sustainable manner and make human societies compatible with the biosphere." (Benyus 2017)

In the exploratory approach by scientific advancement (>= 5 years before producing application paths), the potential of "bottom-up" manufacturing remains an element of improvement of certain technologies, or even a way to promote new ones, even if "top-down" manufacturing processes should not be put aside in the production of high-tech devices. Cross-fertilization will already be considered. But, this currently rather virgin field of study (which could exploit ideas from bio-mimicry (Mathijsen 2020; Poppinga et al. 2021; Tahouni et al. 2021)) in the field of manufacturing may have great potential for spontaneous (or stimulated) self-assemblies to broaden the accessibility of some technologies and capabilities to new markets (Islam et al. 2021). In particular, work associated with changes in scale, nonlinear dynamical systems, or the study of behaviors can be enriched by cooperation in the following directions:

– Modeling the behavior of active materials under stimulation.

– Moving from nano-/micro- to centimeter-scale studies (with fatigue studies related to self-organizations under stress).

– Applications in centimetric 4D printing (modeling of the desired deformations and programming of the manufacturing of the constituent elements and the active object): actuators, flexible robotics, etc.

– Use of the knowledge acquired for adaptive optics involving active materials.

– Realization of active microsystems of the optode type, the stimulation, advantageously optical, allows modifications of forms (release of chemical or biochemical substances) or of functionalities (lab-on-fiber concept). In addition, the fiber can act as a stimulating energy carrier and as a feedback system. The fabrication of active deposits and their stimulation is a current topic; the stimulation can advantageously exploit two-photon photochemistry technologies.

– If chemists can contribute their knowledge on the materials selection (Pinho et al. 2020), it is essential in the process, whatever the scale, to characterize the materials and their structures (e.g. metamaterials). Thus, the thermoelastic, acoustic and optical properties of heterogeneous materials (metals, liquid, phase change, piezoelectric, gain, self-organized, etc.) should be studied.

– Finally, innovative adaptive materials can find applications in energy (electricity storage, fuel cells in particular), etc.

In an upward approach, this work (not exclusive) should lead to original scientific research, to a better mastery of research on new frontier objects via interdisciplinarity, likely to lead to industrial protection. These options imply creativity and require the management of projects that bring together a number of scientific disciplines and professional skills in an interdisciplinary approach. It allows the creation of skills and the introduction of working methods that will be useful in upstream-downstream activities.

1.3.4. *Note: example of 4D printing in structural electronics (SE)*

> In the field of participatory research, we do not know a priori the state of knowledge at the end of the process, because this will not result exclusively from the explanatory capacity of the research experiments, but also from the interactions between the knowledge of the researchers and the "lay" knowledge of the other actors around a problem with a view to solving it. (Hubert 2005)

Von Neuman was one of the pioneers of computer design based on the presence of several elements: a memory (programs or algorithms and digital data), the calculation unit for processing, the control unit (computer operation) associated with inputs and outputs. Even today, it is thanks to silicon with its extraordinary performance that the digital field is developing. However, already in 2013, Puren wrote that Microsoft had filed a patent that aimed to develop 3D electronic objects by providing "consumables" consisting of electronic components (chips, LEDs, processors, etc.). This promise, which however did not exclude this metalloid, has, to the authors' knowledge, remained just a promise. The aim here is to examine how 4D printing sees its contribution more widely than through the use of classic (and let us say particularly efficient) semiconductors in the general field of electronics. The aim is to develop new active or intelligent media that will be able to receive and process information in a minimum amount of time, leading to a variety of uses that meet human needs.

In Table 1.1, we have cited this theme among others. To try to go further, we thought it would be useful to consider a more in-depth study of this field to show, with a generic example, how it can enrich the innovations resulting from 4D printing (and vice versa). Figure 1.8 shows the performances sought in structural electronics (Saleh 2020). Even if we are still a long way from the collective manufacturing that is used in traditional electronics, this field of possibilities allows great freedom in its principle and, potentially, very numerous applications. It is in continuity with the Internet of Things and robotics in the development of the Industry 4.0 concept.

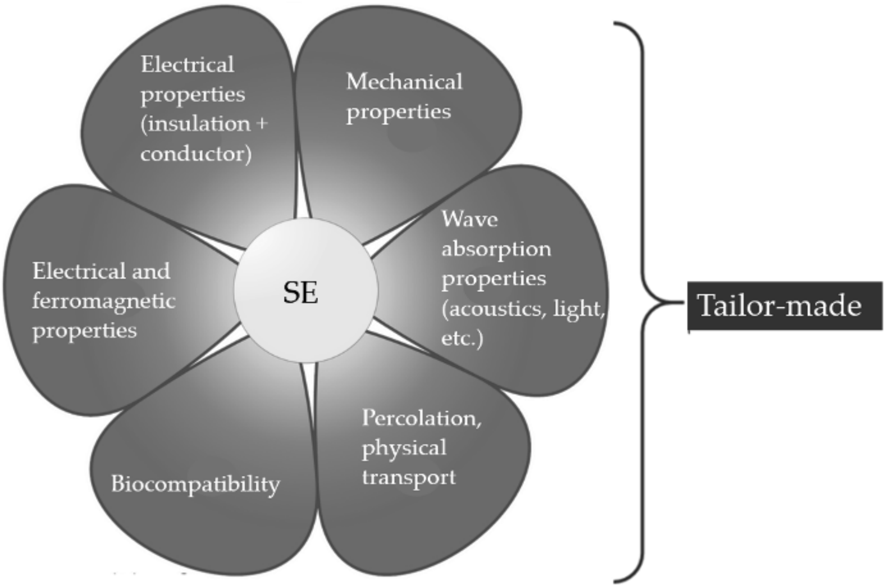

Figure 1.8. *Properties sought in structural electronics (SE). For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

1.3.4.1. *Structural electronics*

> When I opened a Physical Review Letters in 1960, I found a revolutionary idea every time. These days, I come up with two or three a year, in a journal that has become five times as thick. (De Gennes 2020)

As recalled in Table 1.1, structural electronics aims at the integration of electronics in the heart of (4D) objects including actuators; for a significant part it concerns soft, flexible or portable printed electronics, with the objective of an easy link with connected objects (Fresneau 2020). More precisely, structural electronics aims at placing sensors and their amplification circuits as close as possible to objects, whether in industrial equipment, everyday objects or on/within the human body. To further explore future needs in structural electronics, it is desirable to conduct research on the possibility of printing organic transistors on complex substrates to interact with sensor arrays printed on/in the same substrate. In parallel with this energy/information orientation, the integration of devices requires the formulation of materials for the matrices containing the components, the development of printing, shaping and assembly processes using flexible or stretchable substrates of a polymer or textile nature (Liten-CEA 2020). This CEA center (in French: *Commissariat à l'Energie Atomique et aux Energies Alternatives*) has already developed "sensors for physical parameters such as pressure, temperature, elongation and actuators based on organic materials for applications in the automotive, health, intelligent packaging, and building sectors".

In fact, all electronics are concerned with the following angles: energy supply, information intake, information transfer, actuation and possibly information storage. With 4D printing, it could be envisaged to "subvert" the current industrial models by giving a prominent place to imagination, to freedom, if only through the existence of new systems to study, of new forms of integration, and also by allowing a return from the digital to the continuous. On the University of Lorraine website, the theme "*structural electronics*" corresponds to 1,135,000 publications (and to 15,154,000 for the keyword "electronics" alone). Table 1.3 constitutes a magnifying glass effect concerning the themes involved in this recently emerged field (compared to what is presented in Table 1.1).

Structural electronics	**Integration of electronics in the heart of (4D) objects including actuators**	**References**
4D and flexible and structural electronics	Integration; flexible printed electronics	McDonald et al. 2014; Lee et al. 2017b; Lu et al. 2018; Oh et al. 2018; Fernandes et al. 2019; Liten-CEA 2019; Wang et al. 2019b; Agarwala et al. 2020; Kwon et al. 2020; Rodriguez et al. 2021; Wang et al. 2020a
Bioelectronics	Flexible; hybrid biocompatible materials	Herbert et al. 2018; Jung et al. 2019
Electronic skin	Sensor; self-healing; environmental analysis	You et al. 2018; Gu et al. 2019a; Yang et al. 2019
Drivers	Nanoparticles; metallic deposits	Kamyshny and Magdassi 2019; Joshi et al. 2020; Stano et al. 2020; Zhu 2020
Electrodes	Porous polymers/metal nanoparticles	Wang et al. 2019b
Transistors	Material transfer in inorganic materials; organic transistors	Huang et al. 2019; Shi et al. 2020
Switch	Photo-activation	Gu et al. 2018
Electromagnetic shielding	Coupling of carbon nanoparticles and lamellar carbon	Liu et al. 2021
Sensors	Hydrogel base; silicone elastomer and magnetic powder; 3D printing	Ni et al. 2017; Kotikian et al. 2018; Marasso et al. 2018; Kamat et al. 2019; Mirzanejad and Agheli 2019; Zhang et al. 2020

Circuitry	Photo-deposition; electro-deposition	Tabridzi et al. 2017; Chen et al. 2019b
Transducer	Several successive operations	Cesewski et al. 2018
Communication	Chemical route	Chen et al. 2018
Liquid crystal	Liquid crystal elastomers/CNT nanoparticles	Donovan et al. 2019; Kim et al. 2019
Biochemical analysis	Miniaturization; integration; automation and parallel structures of biochemical processes	Zhang et al. 2018a; Muzzafor et al. 2020
Absorber	4D acoustic wave absorption structure	Le et al. 2020
Synapses	Adaptive materials; electrochemistry	Fuller et al. 2017; Sharbati et al. 2018; Park et al. 2020
Diode	µ-fluidic pathway	Lee et al. 2021
Memristor	Adjustable synaptic plasticity; neural networks	Yang et al. 2016
Memories	Adaptive materials	Yu 2018; Zhang et al. 2019
Liquid neurons	Adaptive neural networks	Hasani et al. 2020; Przyczyna et al. 2020
Logic doors	Meso-porous silica; organogels	Bradberry et al. 2015; Zhang et al. 2019
Power generation	Triboelectricity	Di Giacomo et al. 2016; Chen et al. 2019a; Shi and Lee 2019
Energy intake	Use of existing electromagnetic waves	Eid et al. 2021
Energy storage	Super-capacity (nanoparticles); triboelectricity	Maurel 2018; Reyes et al. 2018; Song et al. 2018; Xiong et al. 2018; Chen et al. 2019a; Gu et al. 2019b; Wang et al. 2020b; Wang and Xu 2020
Solar cells	Composites	Burela et al. 2020
Atomic storage	Information about a holmium atom	IBM 2017
Nano motors	Biochemical potential	Abdelmohsen et al. 2016
Micromotors	Various forms of actuation	Medina-Sanchez et al. 2016; Ning et al. 2018; Ren et al. 2020

Table 1.3. *Some themes corresponding to structural electronics*

However, as shown in Figure 1.9, taken from Joshi et al. (2020), the use of charged polymers does not lead to the realization of conductive materials of the same quality as the metals conventionally used in electronics. Progress on this topic is therefore expected before competing with current electronic devices.

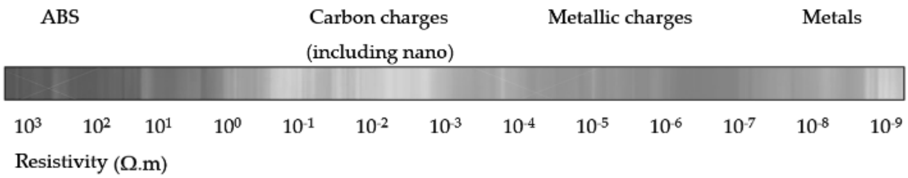

Figure 1.9. *Resistivity of conductive/insulating materials used in 4D printing (illustrating the interest of hybrid manufacturing). For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

As can be seen from Table 1.3, there are a large number of topics that need to be explored to cover the field. This observation highlights the need to work at several scales, to use different types of materials: organic, mineral and semiconductor. Thus, by choosing an element from Table 1.1, we are confronted with the same situation: the existence of a very large number of topics to be dealt with through concepts of physics, chemistry, biology, cleanliness, scale, integration, etc., which are very different from one another. This makes it, a priori, difficult to realistically engage in top-down approaches (e.g. Lee et al. 2017a; Espera et al. 2018; Lu et al. 2018; Fernandes et al. 2019).

According to Wang et al. (2020b, 2020d), flexible electronics is being developed with functional materials, flexible energy devices and versatile sensors, which allow for functionalities such as self-healing, stretching or compression, self-powering, environmental sensing, etc. Some critical issues remain in the development of this particular field of electronics associated with aspects of the integration of flexible electronic systems, power supply, etc. Flexible integrated circuits based on thin film transistors (TFTs) are the focus of wearable electronics for their ability to be fabricated on a variety of flexible substrates, thus creating ultra-thin electronics, with applications in the Internet of Things being targeted. Other activities are in their infancy, such as the exploration of organic field effect transistors or nature-inspired semiconductors (Irimia-Vladu et al. 2010). Multifunctional flexible electronic components such as energy storage devices, sensors and electrical circuits with improved performances continue to be developed, up to the “electronic skin” (e-skin), which should allow applications in artificial intelligence, health monitoring and, more generally, on human-system interactions. However, progress remains to be made in integration, multi-scale approaches, resolution, sensitivity, energy self-powering and more (Chen et al. 2019a; Gu et al. 2019a).

1.3.4.2. *Structural electronics and 3D printing*

> Scaling up is an event regularly encountered by successful startups and it is common that it be also the cause of their failures. (Le Blanc 2017)

Recent developments around new classes of printable materials, such as conductive or semiconducting polymers or those containing metallic nanoparticles, have enabled the emergence of printed electronics (Ganet 2018). Taking advantage of the maturity of conventional printing processes, such as screen printing or inkjet, the realization of new portable and flexible devices has thus been made possible, at least in the form of a POC. Unlike traditional subtractive technologies in microelectronics, 3D and 4D technologies offer new opportunities by enabling the additive production of a structured pattern, reducing the number of manufacturing steps and the amount of materials consumed. Moreover, printing is applicable to flexible or non-planar substrates for the realization of flexible electronic devices or 3D parts.

Following what was presented above, the number of published articles corresponding to the combination of the themes “structural electronics” and “additive manufacturing” is, for the same database, 14,491; it decreases to 2,327 when dealing with *4D printing*. For example, Kuang et al. (2019), in a general article (rather 4D than electronics), report the need to print several types of materials (metals, insulators, composites, inorganic or organic semiconductors) and different resolutions for integrated devices (from µm to mm).

For these authors, high-resolution, high-speed, multi-material 3D printing technologies (yet to be invented) will be needed for the rapid production of materials with complex geometry and devices at multiple scales. Second, new inks (also to be invented) should enable the production of multifunctional materials. They write: “Stimuli-responsive material properties have a profound influence on the method of actuation, robustness of a part, speed of shape change, etc., of 4D printed parts”. This is already an issue of control and improvement of 4D processes in general. But for all that, 4D processes, resulting from 3D, do not have the extraordinary properties of materials used in microelectronics, which are generally very pure and/or with perfectly controlled concentrations of impurities, with precise crystallographic conditions, etc. Major efforts will undoubtedly be required if we want to bring the two fields closer together, since they are currently quite separate, with one culture stemming from learned tinkering and the other from a solid rigor with precise quality approaches (but with very different machine costs).

This “material and process” aspect must be combined with theoretical work and design methodologies to accurately predict and optimize the effects on the 4D printing objective. The modeling of geometries, the determination of interactions at different scales for the states of change of shape and the calculation of energy (from heat, mechanical stress, ultra-sound, light, pneumatics, gravity, electromagnetism, etc.) must be undertaken. For the (very simplified) electronics component, Figure 1.10 shows the question posed by scale changes (even if, in electronic and 4D coupling, the interaction and assembly modes have no reason to respect current manufacturing models).

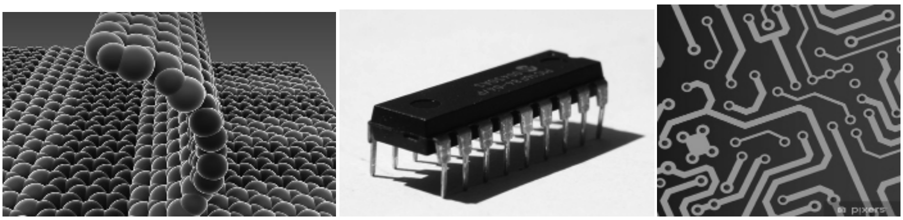

Figure 1.10. *Scaling in electronics. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

However, today with 3D/4D printing, it is not yet possible to play on very important scale changes (from the atom to the printed circuit (or what will take its place)). From this scale, the many obstacles to be overcome really exist but, obviously, depend on the desired objective to reach. As a reminder, it is the size of the voxel that determines the precision. If we want to get closer to the field of microelectronics, we either accept prohibitive manufacturing times or we develop "multi-voxel" manufacturing processes with variable resolutions, or…

> How is it that philosophy had to wait several centuries to ask that we wait a little while for sugar to melt in a glass containing water? How is it that, when such evidence was presented, we did not immediately associate the mixing and fusion of one body in another with time itself? Two flows, however, poured their component together. (Serres 1985)

Thus, by taking an example, barely touched upon for the moment (about 10^{-4} of the scientific contribution to electronics), many specialized issues are expected; however, this approach largely confirms the point made in the previous paragraph: application development is demand-driven. However, a certain number of generic issues concerning 4D printing could advantageously be taken into consideration, such as the multi-material approach, changes in scale, stimulation modes, variable resolutions and modeling (enough to cover several researchers' lives!). However, the promises are numerous: flexible robotics, actuators, medical applications, home automation, transportation, etc. But, to this day, other pending questions limit this intrusion of an original manufacturing mode into the real world:

– choice of processes and associated creativity;

– design;

– optimization of structures;

– materials with important transformations under stimulation;

– stimulation systems (optical, thermal, mechanical, chemical, ultrasonic, electromagnetic, etc.);

– materials with acceptable mechanical qualities (up to 100 MPa);

– shaping of materials: desired anisotropies; local self-organizations;

– metamaterials and Voronoi structures;

– stimulation modes; software, artificial intelligence;

– deformation modeling;

– treatments of the inverse problem;

– robust applications in soft robotics, actuators, prostheses, “smart” drug delivery, transportation, home automation, etc.

The French fragmentation is similar to that observed on a global scale. Although our country lost the battle for leadership in additive manufacturing in 1986, the CNRS (and INRIA) has disciplinary capacities which, when pooled, could help create a strong dynamic in this field. But, when reading the references in Tables 1.1 and 1.3, France does not seem to shine too brightly in those cited!

1.3.5. *Partial conclusion*

> An individual’s compliance with a constraint can also be analyzed as the result of a desire to make their behavior intelligible in the eyes of the group to which they belong, their interlocutors or, more generally, the public in relation to which they act. By conforming to expectations and prescriptions, they make their behavior anticipatable, thus facilitating interaction with other individuals and integration into the group. (Boudon 2003)

What we have shown is a beautiful vision, translated in terms of “reasonably creative” but possible applications. However, the bibliographic approach reveals a very broad spectrum of action with a small number of generic themes to be explored, and this with cultures of sophisticated “bricolage” associated with the origins of 3D printing, the use of materials without major purification, etc. Not only do tectonics of scientific and technological paradigms emerge, but also of cultures, and this with an impressive list of hurdles to be jumped over. Figure 1.11, inspired by Daynes and Weaver (2013), illustrates the difficulties (or hurdles) to be considered in the case of a 4D object composed of passive structures and active structures (without taking into account the stimulation). And these are not the only ones!

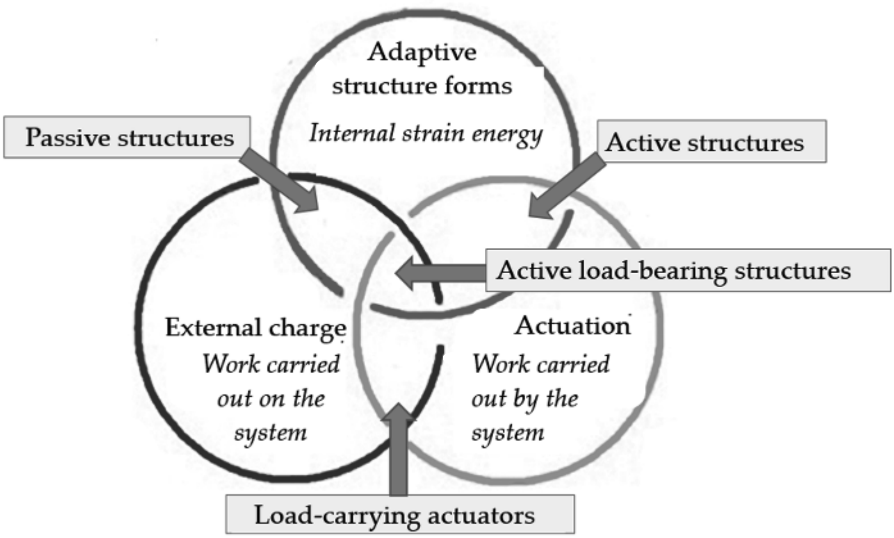

Figure 1.11. *Interdependencies between passive structures and active structures. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

1.3.5.1. *Upstream-downstream co-piloting*

> What is difficult to accept is that no idea is good at first. Our natural tendency is to imagine and judge at the same time when we think, yet we must learn to separate these two times of creative thinking. (De Brabandère 2019)

According to Bouët and Duréault-Thoméré (2011), the increasing complexity of the questions we have to solve between 3D and 4D printing and an application axis, such as structural electronics, imposes the idea that we cannot find the answers and solutions alone. Thanks to our own creativity, each of us contributes of course to the enrichment of this research, in particular on well-identified axes. But, far from being the addition of each of these intelligences, upstream-downstream collective intelligence methods can stimulate the production of ideas, which should then be enriched exponentially, at least initially. They are the foundation of what are called “positive sum economies”.

The proposal to link the concepts of creativity and collective intelligence poses the hypothesis of a possible link between causes and effects. The promoters of collective intelligence and its methods postulate that they are factors of creativity and innovation. Giving birth to a new form of intelligence, which goes beyond individuals and their egos, collective intelligence methods should encourage the letting go of the defense or authorship of ideas. They would offer the possibility to go where no one thought possible by significantly improving the processes of intellectual collaboration. These upstream-downstream co-production approaches would allow for an appropriation of the subject matter and a recognition of the people who facilitate their involvement.

> It is easy to understand that training a human being to compete by making them understand that life is a struggle where only the strongest survive and educating them to cooperate by making them discover that they can be both fully singular and fully connected are two very different options. (Viveret 2012)

They are, however, sensitive to the personalities involved in the process (batch), to a form of learning about friendship and exchange and to their common history and dynamics, and echo a concrete and living reality. But at the same time, subliminal forms of soft coercion (the mission) and awareness (e.g. a facilitator who, in order to move the operation forward, might be tempted to make their contribution a priority) are intertwined. Apart from the work on oneself that could have been carried out by each member of the upstream-downstream group to appropriate the proposals, to make them their own, there is probably no way to go too far in the time allotted (Grojean 2015).

On the other hand, in groups exploring specific topics by associating a theme associated with an applicant and experts from different scientific backgrounds, the operation is generally of the "project" type with interdisciplinary approaches. On the subject of interdisciplinarity, Mahy (2014) writes:

> It is above all a question of sharing a desire, an intention, of wanting to create a solidarity that invites one to adopt a generous and trusting posture and to return to inhabit it when it is momentarily lost from sight, for a moment replaced by the conquering warrior. One can imagine the dynamics of such a group, the maturity it must demonstrate, its relationship to knowledge, to its self-image, and the empathy required to establish and preserve a very special quality of trust…

In short, the die has not yet been cast!

In any case, communities that share the same disciplinary passion are innovative, but tend to close in on themselves. From a scientific point of view, the opportunity of the Convergence Sciences is to develop an interdisciplinary space that is open to society, allowing for a more collective operation of the creation and exploitation of new concepts. In this way, by associating with traditional scientific disciplines on truly open subjects that concern the technological future of the city, discontinuities will emerge that lead to reconfigurations and adaptations. It is these components that must constitute the specificity of interdisciplinarity, aiming at new approaches, other links between researchers and artifacts, between users and production systems. This is why it is necessary to account for the way in which the objects studied by scientists and technicians return to the social world. Thus, techno-scientific disciplines need to be analyzed partly away from their possible relation to scientific "truth" alone, and should be more involved in approaching the horizon of social practices, artifacts and the power relations with which they are associated. This is a set of central questions that strongly links research to the economic, social and political, and puts techno-scientific research in direct contact with society (but this concern is clearly outside the scope of monitoring, foresight and even strategy projects).

> We observe a strong hierarchical prescription of the company, a vertical coordination of its organization. This verticality is characterized by rigid, formalized and hierarchical processes. In contrast, web communities claim a freer, less ordered organization, without formal hierarchy; a more horizontal organization leaving the activity of Internet users free. (Cardon 2005)

1.3.5.2. *Interdisciplinarity*

> Interdisciplinarity leads to marginalization. (Algoud 2014)

Camacho-Hübner (2007) provides an element of definition of interdisciplinary research, he writes:

> Fields which, through mutual contamination, find themselves on an unexplored or even new track, could be considered as belonging to this interdisciplinarity. Nevertheless, it is important to know that the mere bringing together of two or more fields of investigation does not confer on the research in question a true interdisciplinary value. In the same way, any change of direction within the same discipline is not necessarily identified with an interdisciplinary opening, even if this change has been induced directly or indirectly by the appropriation of a research object traditionally belonging to another discipline. (See also Henry (1998), Vinck (2000) and Alvarez-Pereyre (2003))

There is therefore a need to engage in the search for “bifurcations”, for synergies between disciplinary fields (bissociations for A. Koestler), a search that conditions the object of the action and its relations between Science, Technology and Society (Ollivier 2002), “not totally predictable by the knowledge of the prior art”, as is claimed in the patentability of innovative work. Moreover, for Gramaccia (2008), it would aim for “the social integration of knowledge for more social and cultural mediation”. However, if we have to select the few interdisciplinary actors, if we do not try to “recognize” our own deviant “children”, it will never be possible to define the concept of interdisciplinarity more precisely.

Risk-taking, which must be supported by the hierarchy (with, let us remember, “candidates” willing to participate in the experimentation), and which is implied by the fact of not anticipating the common project, should be one of the essential driving forces of collective creativity. New ideas, based on partial knowledge of what is real and what is possible, should be born and take shape in the course of a process that has yet to be built. Going through phases of disorder, accepting detours, not knowing, not judging, not excluding, leaving room for chance and freeing one’s imagination, it is in these conditions, sometimes playful, sometimes insecure, that divergent thinking and creativity should express. Thanks to very diversified methodologies, made up of work processes and situations, collective intelligence should allow for real interdisciplinary innovation.

Researchers are free to choose their subject, but it is necessary to know how to approach and analyze it, and in these conditions of a project coupling upstream and downstream, it is not possible to do just anything because one’s own activity has an effect on that of the other partners. Each member of a group works according to the theoretical presuppositions and methodology offered by each discipline (paradigms), which does not prevent them from questioning and working with other disciplines in a spirit of interdisciplinarity. The work of the group is therefore not the place for the expression of personal opinions.

> It is necessary to begin by ploughing a field, searching the archives, constructing an object of study, structuring a corpus, carrying out an initial classification of observables, then proceeding to a detailed description of what has been collected in the field or constituted into a corpus, or even carrying out experiments, then establishing new classifications according to discriminating criteria (what is similar, what is different), and finally engaging in interpretations. Interpretation is one of the most delicate and distressing moments for a researcher. In a process of constant back and forth between inductive and deductive reasoning, the researcher must engage in internal interpretations, those made within the theoretical framework of the discipline (which can lead to a questioning of the latter), and external

> interpretations in terms of what other disciplines can say on the same subject. (Charaudeau 2021)

> We take the opinions and knowledge of others into account, and then that's it. We must combine them with our own. We are like those who, in need of fire, go to their neighbor's house to get some, and upon finding a large and beautiful one there, stop to warm themselves, without remembering to bring any home. (Montaigne 2020)

Interdisciplinary research, transversal thinking, collective intelligence… these are current trends that challenge traditional conceptual tools, which are robust and validated, but rather conservative and incremental, while drawing attention to the limiting power of methodology. The academic discourse, which aims to broaden the boundaries of intellectual reflection (and this is part of its mission), seems at the same time to set its limits, a process in which a non-stabilized (unnstable?) methodology of discovery inevitably participates. In the age of interdisciplinarity (at least in its political discourse), theory and methodology are facing new challenges for which creativity normally represents the keystone of a collective drive. It is difficult to reason about few cases, but it seems, after an earlier experiment with CNRS-INSIS researchers in 2015, during more than a year of operation, that it is useful to explore (to find answers to) the following general questions: To what extent and under what conditions is methodological innovation in collective intelligence possible in academia today? Can it be envisaged for 4D printing? Today, it is a question of going far beyond the timid roadmap of Utela et al. (2008) by introducing trial and error methods precisely because the logic of supply is no longer credible. Will we be able to change the minds of researchers and especially decision-makers in time for the 4D field to take its rightful place?

> It is necessary to pay attention to what emerges, to what is emerging, but there is no reason to forget resilience […], the weight of rigidities, of friction. It is important to keep the processes of hybridization, crossbreeding and irreduction in mind, 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)

1.4. 4D printing: breakthrough or increment?

As has already been pointed out, entrepreneurship and innovation contribute significantly to the success of firms and the economic growth of nations (Schumpeter 1942, 1952; Drucker 2006). Firms have a mission to create value, directly and indirectly, for themselves and their customers. Entrepreneurship and innovation are often linked directly or indirectly to the notions of imagination, creativity and industrial design. Starting from the needs expressed or the offers resulting from research, the design processes define, step by step, the artifact that must eventually meet the objectives selected (needs and usage requirements) by successive choices with increasingly detailed approaches (and therefore increasingly irreversible in the limited duration of the action). It may therefore be useful to take stock of what has already been achieved and to examine future courses of action, as has already been undertaken.

For professionals in the field, what has been envisioned is that 4D printing can fundamentally change the design and manufacture of objects through combination/association with other digital capabilities (Internet of Things, artificial intelligence and robotics). By making shapes evolve through various stimuli, many applications are targeted. For example, Airbus would develop programmable carbon fibers as fuel savers and ambient air purifiers (Rander 2020). For Garcia (2020), robotics is today limited by the “hard” materials used; “soft” robotics should solve this problem by using some stimulable soft materials. Similarly, in the textile industry, 4D printing would make it possible to manufacture clothing that adapts to the shape and movement of the body. For example, cited by Garcia (2020), the U.S. military is reportedly testing clothing that can change its color depending on the environment or regulate people’s perspiration based on the outside temperature. According to Market Analysis Report (2017), in China, the main efforts are in military, space, aerospace, automotive, “smart” textiles and health applications. According to Market Intellica (2019), four approximate quarters outline the 4D landscape: space, aerospace, automotive and miscellaneous. The growing need for soft or flexible objects in various applications, such as folding packaging, adaptive footwear, controlled origami-robots, adaptable wind turbines, etc., has supported the emergence of 4D printing through the use of different materials that form material anisotropy and allow the object to modify the 3D structure by bending, elongating, twisting and corrugating along its axes (Future Bridge 2020). More generally, functional developments are expected from 4D printing. In fact, apart from simple examples, it is more about promises than concrete, demonstrable achievements.

However, as the extensive bibliography has shown, in this phase of the emergence of new processes that make it possible to envisage applications that were inconceivable less than 10 years ago, these trends can/should still evolve considerably. In fact, this is the whole point of the separation of intelligent and/or stimulable materials from the 3D or 4D printing that uses them in this chapter, which aims to estimate how we can respond through research to the legitimate expectations of the socio-economic world.

> Shoppers […] form a mass […]. Each of us is “gregarious” to the exact extent that our social attitude is, in any domain, determined by the influence of a mass. (Pech 2017)

1.4.1. *Creativity and 4D printing*

To express creativity, we can talk about intuition, attitudes, sensitivity, divergent and playful spirits, etc. Basically, this consists of putting names to complex concepts, without the hope that this is enough to describe them. Creativity is not easily “caught”, but some of its manifestations can be understood, and there may even be methods of learning about creativity. To begin with, one of these seems easy to implement, and that is to make known phenomena unusual by calling them into question, by inverting them, by transforming causes into consequences, in short, to enter into the bissociation dear to Arthur Koestler (1976). If these processes of inversion do not systematically lead to new ideas, questioning can lead to a renewal of ways of thinking and acting (this can sometimes be observed in a focus group involving a “false” naive person or in certain role-playing games, which makes it possible to shift the objective by lateralization). This position may be held in particular by those who consider that experts are the least likely to discover a new idea, but there are other conservatisms at work and this assertion cannot be demonstrated. We must then move on to invention and its aftermath.

The word “creativity” is related to the word “creation” which implies that something new is put in place. According to the classical view of creativity based on Guilford’s dichotomous divergence/convergence principle (1956, 1959), the creative process starts with the recognition of a problem. From there, a process of divergence begins (“*think different*”), and finally ends, through convergence, in a new solution to the problem. Creativity can be defined as the ability to achieve an original (new) and contextually appropriate result, with a performative dimension in the creative process (Ingold 2010). Creativity is based on personality, attitude, culture, development and motivation that can have an impact on the creative process, creative potential and creative ability. But the existence of these factors does not guarantee creativity (Eisenberger and Aselage 2009; Hennessy and Amabile 2010; Runco et al. 2010; Runco and Jaeger 2012; Simonton 2012; Runco 2015; Corazza 2016). Creativity can be seen not only as a quality coming from atypical individuals, but also as a useful skill in everyday life (use of imagination, original choices, resourcefulness, etc.). Moreover, the knowledge society that brings people, communities, creative processes and knowledge domains together to interact in new societal contexts imposes enhanced innovation and agility (associated idea of open innovation according to Trabucchi et al. (2018), Von Hippel et al. (2011) and Bogers et al. (2018)).

Box 1.1. *Creativity*

1.4.1.1. *Creativity and complexity*

> Either the researcher treats the object in a partial manner, ignoring or concealing all the links that inevitably exist between this partial view and the global biases that they cannot fail to have on the object. Or, they put their global biases at the heart of the scientific questioning: not as interesting elements to look at, but as the motors of a dynamic which then takes the inevitable desire for unity as a steppingstone towards what becomes a requirement for unity. (Alvarez-Pereyre 2003)

Complexity is a situation with a variety of elements of different forms and natures in dynamic interaction. Innovation moves the complexity of a situation by artificially modifying a relationship between interacting elements (it imposes an original path between elements in the form of an imposed convergence). When it is disruptive, with characteristics of interaction between multiple actors, uncertainty, unpredictability, co-evolution of the project and its context, etc., it is then part of a complexity issue. Some believe that it requires an evolving strategy to emerge (inventing while walking). It is this vision (André 2017c) that we wish to question, based on disruptive innovations involving the convergence of disjointed disciplines (see Figure 1.12).

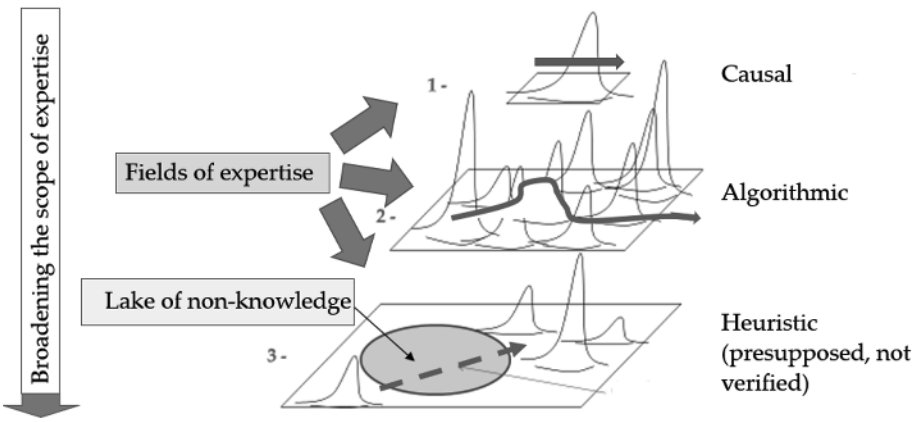

Figure 1.12. *Fields of expertise (the approximate Gaussian lines represent the scientific achievements from previous research work; depending on the form of expertise, the field is covered (causal, algorithmic) or partially covered (heuristic)). For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

The heuristic approach can be defined as an empirical, approximate, intuitive, but fast and daring method to find a possible solution to a question for which all knowledge is not stabilized, and consequently to have a field of expertise, partially deductive, and perhaps to accelerate the resolution of the problem for which one (among others) possible solution is brought to light. No idea is born "good": it represents only a new hypothesis, which may, perhaps, become so.

1.4.1.2. *Estimating creativity*

In an in-depth peer review conducted for the principal actors, is the proposal from one researcher or a small group of researchers an appreciation of understood preferences or of the satisfaction of material constraints? Do these views provide conflicting or complementary perspectives? And so on. These are questions to be asked. But one must avoid a total "creativity" operation on the part of one's own evaluation and that of the responsible decision-maker, which would risk "nipping in the bud" any initiative. It would be better to do nothing, or to do as before!

To keep things simple, six criteria have been selected and presented in Figure 1.13, criteria of opportunity relative to the spirit of a disruptive project, and also of feasibility.

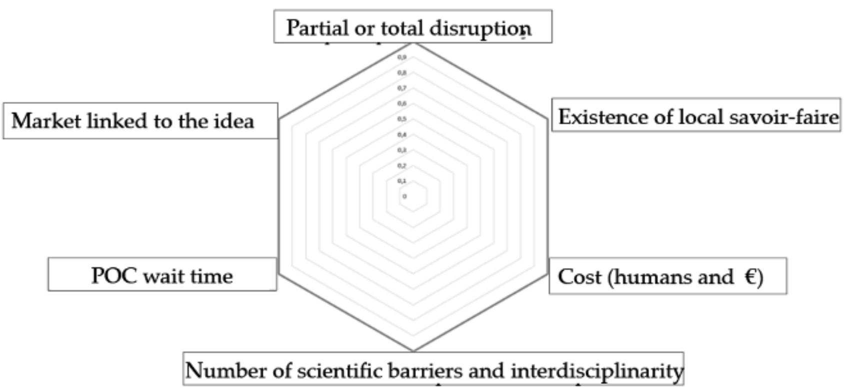

Figure 1.13. *Basis for "strategic" project evaluation. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

The idea is to represent as a polygon a (very approximate) digitization of each of the criteria presented in this figure and to examine whether the center of gravity of said polygon is located toward the top of the hexagon (favorable position) or, on the contrary, toward the bottom (questionable feasibility). To indicate the low degree of acumen retained, a duration is low (e.g. less than one month), reasonable (6 months–1 year) and high if it is more than several years. It would be up to the experts of a group of researchers and/or evaluators to adjust to each other based on a learning process that depends on the "means" implemented by the organization on which they depend. Depending on its financial strength and pioneering spirit, the criteria may naturally evolve.

To illustrate the applicability of this presentation, we have chosen the old example of the innovative 3D printing project, launched in 1984 (see Figure 1.14). At the time, it was a real breakthrough. With the contribution of adaptive materials (present on the "shelf"), the same graph can be proposed today for 4D printing.

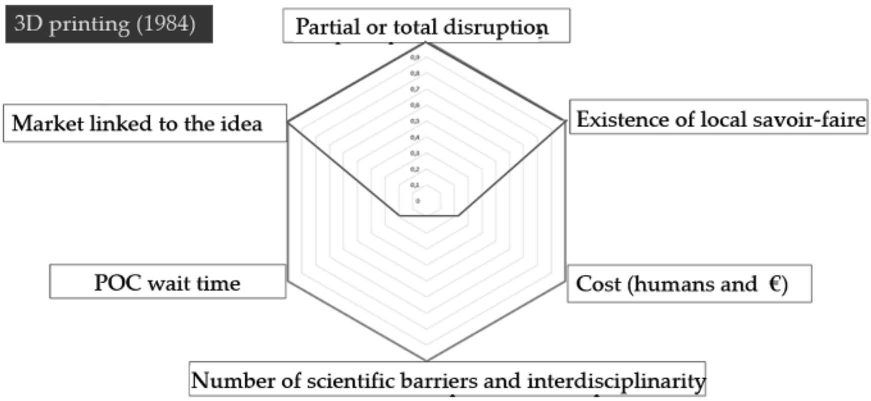

Figure 1.14. *Example of 3D printing (applicable to 4D printing). For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

The local know-how was present in 1984 (processes, chemistry, polymers and automation) with a motivated person, the market was obvious (at the time it was primarily a question of making prototype parts with a 3D photocopier), the interdisciplinarity managed by a single person (!) which allowed a POC in a few days by borrowing resins from the neighboring macromolecular chemistry-physics laboratory. Clearly, the center of gravity of the polygon is well located upward and falls within the criteria presented above (André 2017c). Nevertheless, and less obviously, it is still possible to ask whether the proposal would be supported by scientific experts today (assuming that additive manufacturing had not been developed)?

Another example is bio-printing, a recently emerging field aiming to manufacture biological organs and/or tissues with obvious applications to replace limbs following accidents, organs following serious diseases, develop personalized medicine, etc. (André 2017c). Figure 1.15 (which could have been envisaged 8–10 years ago when the concept emerged) shows the authors' assessment of the proposed basis.

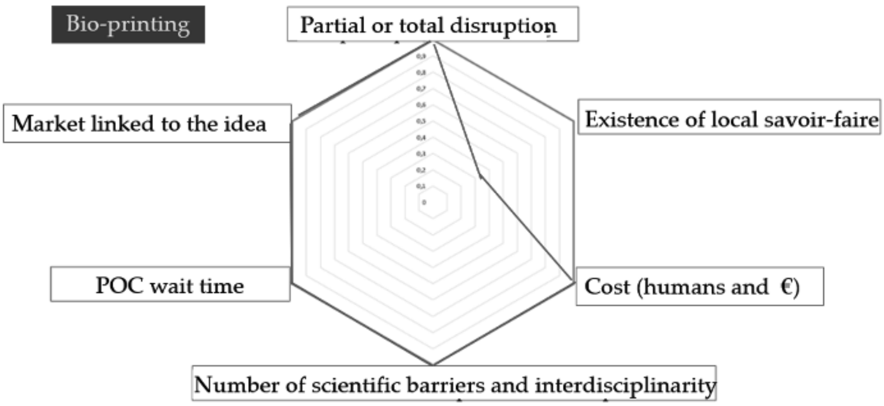

Figure 1.15. *Example of bio-printing. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

Bio-printing (4D printing of the living) represents a considerable market (probably several thousand billion €/year), but requires the convergence of many disciplines and the association of a very large number of researchers for medical applications. Obviously, the dimension of such a project goes far beyond the capacities of a single research team, which is generally mono-disciplinary. The conceptual development involves epistemological reflections, interdisciplinary convergence approaches and consequent risk-taking, which are generally poorly supported by the principal stakeholders. Indeed, it is necessary to move away from top-down trial-and-error methods that certainly complement the resumes, but do not allow viable solutions to emerge in the near future (Danzo and André 2020).

For Gozlan (2020), the evaluation of performance and the concentration of funds on the "best" ones are the key elements of the new system of governance of science. She writes: "This movement is characterized by an unprecedented formalization of scientific expertise practices. We are witnessing the creation of an arsenal of 'guidelines', 'charters', and other protocols that aim to frame the production of collegial judgement". What is important in the fields of research on borderline objects (as defined by Star and Griesemer (1989)) is the capacity to integrate disjointed scientific and technological knowledge, that is the possibility of leading interdisciplinary "project" groups, the capacity to produce, through heuristic approaches, programs involving a certain number of them, admittedly with obligations to question and take risks (Barrier 2011). However, not only are they difficult to evaluate quickly because of vertical disciplinary segregation (and especially quantitatively), but the risk-taking that can serve the long term can be seen as a possible use of the decision-makers' money. The short term is therefore strongly favored.

1.4.2. *Getting out of blindly following? Where to go?*

> What the engineer has gained in scientific spirit, they have lost in open-mindedness; is it not time, at the beginning of the 21st century, if they still want to play a role in technical progress, that the engineer rediscovers, from their illustrious predecessors, a universal concern and curiosity, in the face of the mutations that today affect all areas of human knowledge? (Jacomy 2015)

Once installed in the forms of a discipline, a methodology, a process, etc., groups of actors with common or shared visions are formed (learned societies, networks, etc.). From a historical point of view, the example of Thomas Edison can be recalled, imposing a view on the use of direct current (Corazza 2016). This situation, which may have met societal needs, was however undermined for scientific reasons by Tesla, imposing the use of alternating current. But it was necessary to go beyond corporatism, which is always a difficult process, especially if one does not have deep motivations.

1.4.2.1. *General context*

At the idea stage, almost nothing has been committed. To go a little further, it will be necessary to model and/or carry out POCs, which generally have the advantage of raising scientific, technical and epistemological questions, etc. An inherent dynamic of research (interdisciplinary or not) is to let oneself be carried away by one's curiosity or to commit oneself to spontaneous or stimulated requests for new questions or new objects, all the more so since in science, innovation should be a major criterion of success. This process sometimes leads to objects or questions that go beyond those defined by the cognitive and institutional structures that structure research, that is the disciplines. So, the innovator who has started with an idea, explored it and deepened it, can rely, at the outset, on a certain number of hypotheses on the elements of their perception of reality with a projection toward its possible use. It is from this stage that they may be able to carry out a POC, which may allow them to propose a draft of uses, if possible mirific. If a functional specification can be carried out, research and R&D work may allow, after many efforts, facing the complication of the system to arrive at a real demonstrator (algorithmic approach). But how can we go beyond the creative idea, the POC to reach concrete applications?

1.4.2.2. *Death valley*

A first "death valley" corresponding to this passage from POC to demonstrator exists and must be made explicit. The framework of possible development through external support (personnel, funding) is based on the importance of mutual understanding, sense-making and consensus-building between partners, both internally (especially if interdisciplinarity is involved in the action) and externally. Kijkuit and van den Ende (2007) consider breakthrough innovations to be focused on the structure and content of the different networks, and emphasize the need for strong linkages and related prior knowledge, the integration of decision-makers, and the need to move over time from a large, non-redundant and heterogeneous network structure to a smaller, more cohesive network structure capable of efficiency (see also Reiter-Palmon and Illies (2004)).

Innovation thus follows a complex process that leaves a lot of room for improvization and chance: idea, possibility of engaging in a deepening project, realization of a POC, market study, financing plans, business plan, initial financing, creation of an adapted organizational structure, industrial demonstrator, canvassing of new financial partners, complementary fund raising, prototyping and market tests, manufacturing, launching… An invention is not enough, because the road between the idea and its realization is long (Merle 2019). Figure 1.16 extracted in its principle from Harryson (2008) on the one hand, and Kotze and Purgathofer (2007), on the other hand, allows us to understand how one goes from a happy idea validated by a POC to an application.

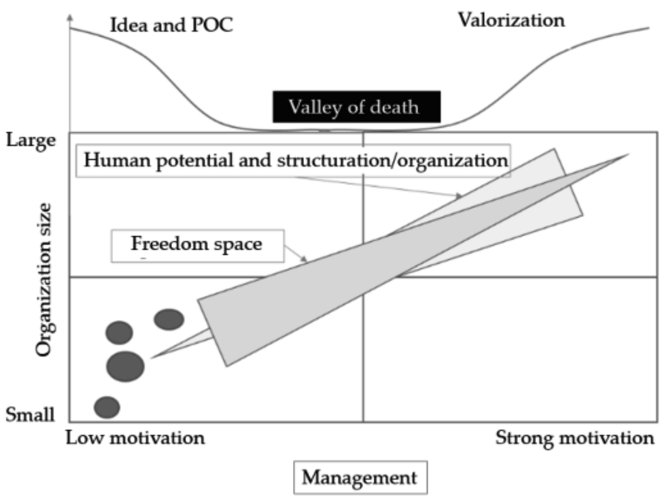

Figure 1.16. *From idea to application. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

But, on the frontiers of science and technology are placed ideas (brick red ovals in Figure 1.16) that increasingly require the mastery of complexity (changes in spatial and temporal scales (Dodet 2001; Puech 2016)) which are known to involve acts of interdisciplinary convergence (André 2017c). If interdisciplinarity is a means (which has its own implementation difficulties), can we propose approaches to tackle the complexity of situations from which alone the innovator must find scientific, technological and socio-economic alliances for the success of their idea? The role of foresight at this stage can be of great interest (as long as it is carried out in an appropriate manner and not, as is too often the case, to support certain lobbies…). The same is true of the strategy for supporting innovation, which must support creativity, the management of interdisciplinary projects, in short, risk-taking.

For this emergence, it is necessary to leave sole disciplinary research at least for a while to integrate spaces of convergence between normally disjointed disciplines which are by nature complex and which require, taking into account the associated risks, time and means, without being sure of the result. Enough to convince any politician to remain conservative (which they know is not satisfactory, but which is easily justifiable with regard to the electorate thanks to a low-risk management of public money)! And moreover, if it is too disruptive, would not the black veil of the precautionary principle make the happy and fragile idea disappear (even if the European Union tries to implement a principle of innovation…)? This means that it is necessary to consider taking risks in action, to manage lakes of uncertainty and lack of knowledge (heuristic approach), to find the paths (if they exist) of reasonable success…

Open innovation can remove traditional barriers by incorporating ideas, methods, technologies and solutions from external environments (Chesbrough and Crowther 2006; Enkel et al. 2009, West and Bogers 2017; Trabucchi et al. 2018). This situation where "customers" can bring their criticism, their proposals to industrialists and designers are not exactly the same in academia where paradigmatic approaches (Kuhn 1983) are generally maintained.

Traditional companies that develop new technologies have to reorganize to do so, which can lead to return on investment (ROI) difficulties and time delays. New entrants (startups), too small and with possibly prohibitive costs, cannot have reasonable margins, but they have nothing to lose when they enter the market and initially do not pose a threat to established companies. So, with disruptive, highly attractive technologies, their low inertia can allow them to operate sustainably and progress where incumbents could not. By penetrating more mature markets, they quickly compete with and disrupt incumbents.

Box 1.2. *Open innovation*

> No society can survive without a moral code based on values understood, accepted and respected by the majority of its members. We no longer have any of that. Can modern societies indefinitely master the fantastic powers that science has given them on the sole criterion of a vague humanism tinged with a kind of optimistic and materialistic hedonism? Can they resolve their intolerable tensions on this basis? Or will they collapse? (Monod 1970)

1.4.3. *Application to additive manufacturing*

To go further than the general view presented above, it may be interesting to examine the mapping that can be done in a case where we have real experience, that of additive manufacturing. The criteria used are the following:

1) potential market;

2) position of the work in relation to the current main axes (new 1, otherwise conformity 0);

3) risk taking;

4) interdisciplinarity;

5) solution to obstacles/challenges;

6) creation of new obstacles/challenges;

7) external funding (verifiable) and peer recognition (time between submission and acceptance);

8) ease of implementation.

Two extreme situations are targeted, the one corresponding to the start of the idea in 1984 and the present situation. They are shown in Figure 1.17. In 1984, the initial idea was, as already mentioned, to make a 3D photocopier. It was new, the risk-taking was high in terms of possible failure, interdisciplinarity was modest (one just had to know how to handle photo-crosslinkable resins with gloves), the obstacles were not known, funding was modest and did not require external support, recognition by peers was unthought of, and the simplicity of the process was high. But, in 2020, keeping the theme of stereolithography, things have changed with new markets, (conservative) principles acquired, modest risk-taking leading to incremental innovations, interdisciplinarity becoming modest (e.g. targeting the improvement of material properties), reduced barriers thanks to incremental innovation (with the possibility of creating new ones, such as finding new, more efficient materials), funding legitimized by industrial pressure and ease of implementation facilitated by the existence of 3D printers. The result is a clear evolution of mapping over time.

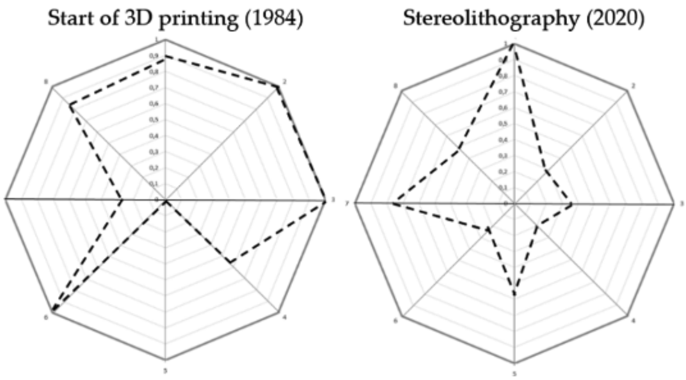

Figure 1.17. *Evolution of the mapping of scientific evolution. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

In the case of 4D printing, an element of complexity has been added corresponding to the exploitation of active materials allowing the exploration of space-time (with the stimulation not being restrictive in relation to the desired functionality).

1.4.4. *Application to 4D printing*

1.4.4.1. *General framework*

Figure 1.18 represents the authors' vision of 4D printing today with its limitations and its operation in supply logic. The potential market is questionable if the elements related to the specifications are not reached; for the second item, there is a need to operate differently in demand logic (top-down) with different partners, which defines specific risks and a possible loss of time to find the right partners and manage the scientific and technological project; these comments induce a low value attributed to items 3 and 4. In the same way, as it has been established, the coupling of 3D process – Materials + Stimulation – remains complex in general, which leads to the same assessment, with in item 6, the highlighting of difficulties of the same type with the probable appearance of new obstacles. Clearly, funding for such high-risk projects is unlikely to be plentiful, even if changes in risk-taking are beginning to emerge in some calls for tender. We have given an intermediate grade to item 8, because it will depend on the desired application activity.

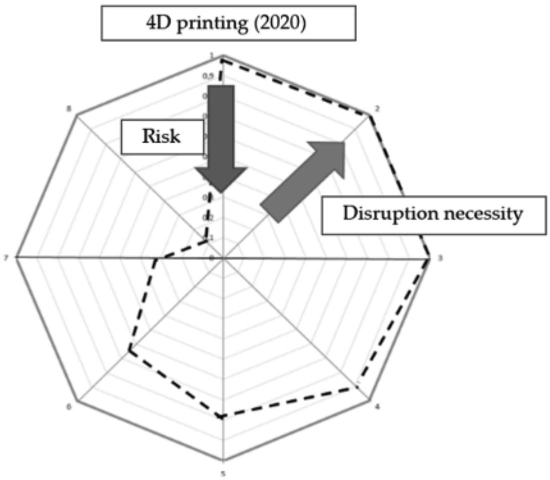

Figure 1.18. *Mapping of scientific evolution for 4D printing. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

1.4.4.2. *4D printing and structural electronics*

Two examples are discussed in this section: the integration of electronics into the core of objects (4D) and the realization of 4D acoustic wave absorption structures. Figure 1.19 illustrates the contrasting results between these two fields.

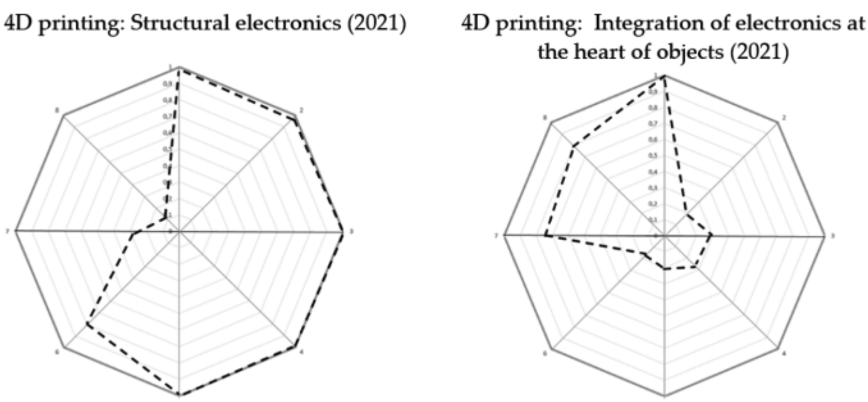

Figure 1.19. *Comparison between two situations. Left: electronics in the core of objects; right: absorption of acoustic waves. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

Some comments can be made to better understand these two figures. There is indeed a demand (more specialized in the second case than in the first one), but interdisciplinary management is very different since the case on the right corresponds to the realization of active origami/kirigami already dealt with elsewhere; consequently, the obstacles to be dealt with are more modest and should not raise new difficulties in the practical realization. Moreover, if the object is realized flat, in 2D, its transformation will only take place once thanks to a global stimulation (which cannot be the case of the inclusion of electronics in 4D objects). Finally, it is always easier to find funding when you are close to the goal (case on the right) than when you are far away with high risks.

These results therefore complement the previous proposals to operate in demand logic and to analyze the different criteria quickly presented to know if the risk is worth taking for a research activity to be carried out (independently of other criteria such as cost, ease of implementation, time needed before market introduction, environmental aspects, health and safety aspects, etc.).

1.5. Financial and organizational aspects

1.5.1. *Research funding and direction*

> Courage is a problem of organization. It remains to be seen who wants to be organized. (Malraux 1972)

> Innovation is essential to the formation and growth of firms and to the economic, social, and political health of nations. (Morton 1971)

From an innovation point of view, there is therefore a need to deal with the short term while having a vision of the long term, taking into account the major trends affecting the planet today, but also the various inertias that limit the possibilities of action. From this observation emerges the need for a general policy giving specific impulses to support 4D printing in its applicative possibilities and the creativity for innovations supporting the stated needs. On this basis, already in 1970 the Organization for Economic Co-operation and Development (OECD) Council (OCDE 1971) wrote regarding research: “It is important to pay more attention to its qualitative aspects [representing better living conditions] and to define the policies to be followed with regard to the major economic and social options implied by the allocation of increasing resources.”

Figure 1.20 reminds us of the obvious: the allocation of resources to research cannot go beyond a certain limit for various reasons. It is arithmetically impossible to exceed gross domestic product (GDP), there is a need to train researchers, research and R&D are only one element of the overall innovation process from primary innovation to market launch, etc. And then, for political reasons, there may be other priorities. However, in the 1960s, major impulses for the development of scientific research in France led to the belief that this age of support could continue for a long time to come, which induced, in the ambient conservatism of the constituted bodies, bitterness and violent reactions associated with financial limitations or attempts to optimize the credits allocated to public research.

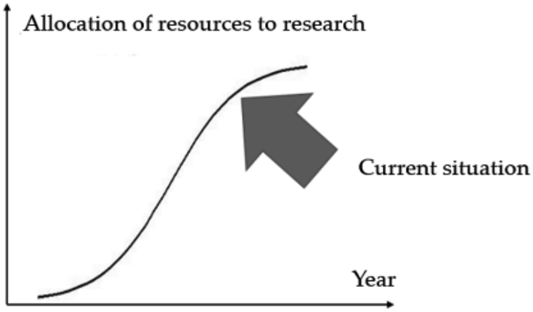

Figure 1.20. *Limitations on resource allocations to research*

At least since the Renaissance, the market and democracy have been based on the organization of competition within a central core, a real critical mass of humans. These cities (Bruges, then Venice, Antwerp, Genoa, Amsterdam, London, Boston, New York, Los Angeles, etc.) have a local market (agricultural, industrial), a trading site (port in the city or nearby) and a power of resistance, if not aggression, against competitors acting according to the same methods. Their senescence is due to the existence of one or more new technologies possessed by the new competitors who then take over Western leadership (Malthus 1999; Attali 2011).

These considerations imply a voluntarist attitude to sustaining progress through competition in order to maintain the supremacy of the structure, while at the same time proving necessary to have the warrior assets and information to compete successfully with other profit and power centers. Each structure of this type has lasted as long as it has been able to control its environment and has tended to disappear when the costs of maintaining the stability of its organization have become prohibitive (relative to the internal and especially to the resistance to various aggressions, hence the important place left to the improvement of war techniques). The capacity for technological innovation has enabled these competitive organizations to attain Western leadership, which was later replaced by that of the States, due to the obsolescence of their capacity to innovate (even if, as Japan did at the end of the last world war, it is possible to practice “second-hand” innovation for a short period). Similarly, there has been a shift from individual innovation to more collective processes relying on a body of researchers financed by the States.

It is therefore possible to consider maintaining one's place in international competition as long as it is possible to make strategic choices for research and R&D on the one hand, and to be able to finance it and recover the fruits on the other hand. In this context, the direction of technical progress is a condition of efficiency for the construction of the future (as long as we know where we want to go in this future). To achieve this objective, it is undoubtedly necessary to envisage reliable performance indicators that take into account the correct parameters of the social system and, above all, their complex interdependencies. Otherwise, by remaining in a rigid and conservative programming, not revisited (content and form), we risk leaving out new opportunities.

Box 1.3. *An obligation to innovate*

> Theory is when you know everything and nothing works; practice is when everything works and nobody knows why. Here we combine theory with practice: nothing works… and nobody knows why! (Einstein 2007)

For the citizen, what is visible are mainly commercialized objects, instruments used for medical applications, etc. While they have high technological values for the satisfaction of social needs, they only distantly represent the questions posed by unintentional science, an important mechanism for revitalizing knowledge (but which, in the 4D printing field, needs resourcing). Science and Technoscience are linked by a common fate. Figure 1.21, together with the results of the evolution of GDP as shown in Figure 1.22, represents the relationship between the importance of the social body of research (Research and R&D) relative to GDP per capita. Until about the 19th century, it was engineers (in the broadest sense) or relatively autonomous individuals who were the originators of innovations, then with the notable increase in purchasing power, research grew significantly exponentially to reach a considerable percentage of the GDP of Western States.

In Figure 1.21, technical progress is represented by a gray disk, with the resources allocated to scientific research in light beige. Between the beginning of the last century and the present, progress has mainly consisted of satisfying primary needs (food, shelter, access to electricity, etc.). With the increase in the standard of living, individual marginal utility decreases to be compensated by the satisfaction of collective goods, the number of which is increasing (infrastructures, health system, regional planning, transport, etc.). Several remarks can be associated with this figure:

– First of all, technical progress has had adverse effects in terms of pollution-related illnesses, stress, various accidents (at work, at home, etc.), even though people's life expectancy has increased for a long time.

– The environment has been deeply degraded (global warming, pollution, depletion of reserves).

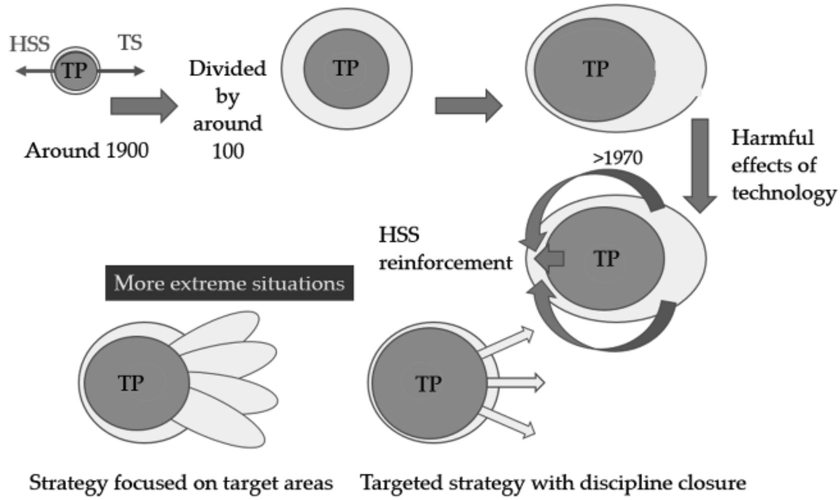

Figure 1.21. *Relationships between technological progress (TP) and strategic research policy (HSS: human and social sciences, associated with environmental sciences and hazard and risk management sciences; TS: technosciences and "hard" sciences). For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

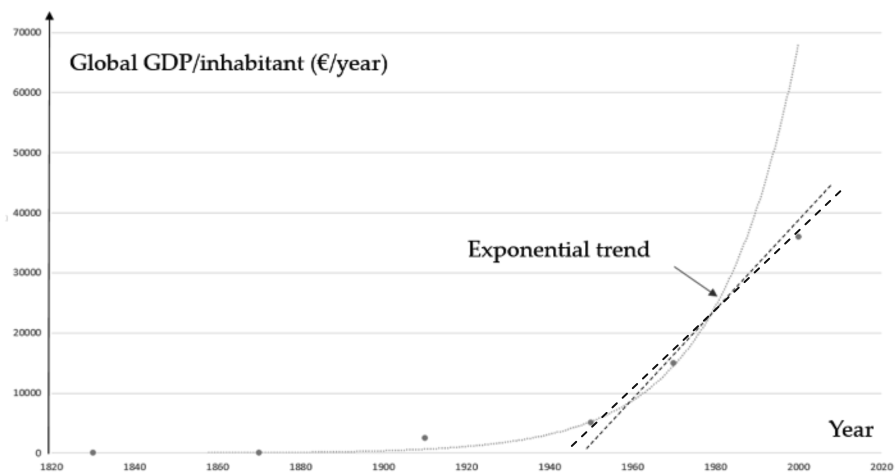

Figure 1.22. *Evolution of world GDP (black dotted line, linear evolution). For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

These elements of social dissatisfaction linked to the risks involved have in return imposed support for research work in fields initially considered as low priority, on the HSS (human and social sciences) side. However, some developed countries may not take into consideration the need to find a balance between technological innovations and public acceptance (if only because the public is often a client). The two sub-figures at the bottom and left of Figure 1.21 characterize strategies where specific choices are privileged (the case of a nation like Israel, e.g).

However, if the share of national wealth devoted to research is important, as it reveals the willingness of a State to support its innovation (Saint-Etienne 2015) (e.g. a little less than 2.2% of GDP in France, more than 3% in Germany, 4.1% in Israel and around 5% in South Korea), the distribution of funds may be more or less oriented toward the development of major programs with a technological focus (see Figure 1.21). The internationalization of basic research then makes it possible to fill, at least in part, any gaps in certain disciplinary fields that are more or less neglected in a country's scientific strategy. This "cuckoo" method has its limits, however, because competence remains external.

> Rome being a city without commerce and almost without arts, plundering was the only means that individuals had to enrich themselves. (Montesquieu 1968)

What we observe today is, at least for France, with a certain stabilization of its GDP no longer evolving exponentially, an impossibility to respect its promise to reach the 3% of the national GDP devoted to research, which certainly leads to a scarcity of resources, but also to a certain obligation of choices, increasingly oriented toward other promises such as employment and a dynamic image with the concept of *Startup-Nation* (L'Usine Digitale 2018). In this desire for action, the President of the Republic (quoted in this article) defines four main indicators to achieve this goal:

– Scaling up: "The first challenge is to scale up and accelerate take-off".

– Talents: "There has never been a start-up that has worked, that has become a large group, a unicorn or that has failed just to bounce back, without talent".

– Simplified rules: "We need to simplify certain rules. We have started to do this and those who think we are going to stop are mistaken".

– Europe: "My final conviction is that all this will also be achieved with, in and through Europe".

This commitment illustrates the need expressed by the State to move toward a greater orientation with the satisfaction of economic needs, but is this possible in practice? If the amounts allocated to research and their orientations are part of a reasonable decision-making process in principle, it seems obvious that a long-term strategy (and not a short-term one that can be practiced by connecting points and tangents) is a political art in which science has little place. Castoriadis (1999) wrote the following on this subject: “Politics is not a matter of episteme [science], but of doxa [opinion] […]. All doxas are not equivalent, and there is a kind of knowledge in politics that is not ‘science’, but a matter of judgment, prudence and plausibility”. Herbert Simon, who won the Nobel Prize in Economics in 1978 (quoted by Bruno Jarrosson (2017)), noted that, since everything cannot be known, decision-making is based on incomplete information about possible options and their consequences. Very often the decision-maker does not seek the optimal decision, but is satisfied with the first decision acceptable to them and their immediate environment.

Moreover, in the programming of research, one must take into account the immediate needs and those that will emerge over a longer period of time, which introduces an internal competition between short-term programmable needs and potentially useful speculations that will only produce their effects (if any) after the presence in office of politicians who have decided on behalf of the State to support this or that field relative to others… Of course, this uncertainty exists and is disturbing, because, unlike in the past when cities lost their influence relative to others that replaced them, we only have one planet!

1.5.2. *Constraints/opportunities related to research orientation*

> The more you want to speed up the progress of science, the sooner you will destroy science, just as a hen that is artificially forced to lay its eggs too quickly perishes. Science has made astonishingly rapid progress in the last ten years. Wonderfully so! But look at the scientists: exhausted hens. Really, they are not “harmonious natures”! They only know how to cluck more often than before, because they lay more eggs; it is true that these eggs are getting smaller and smaller. (Nietzche 1874)

It is therefore easy to understand the need to have the clearest possible vision of the whole system of interactions between technical, economic, financial, psychological, sociological and health factors associated with the transformation of society in a context of strong environmental constraints, if we are to try to optimize the direction of research (“toward a ‘good’ scientific policy”). At the same time, as Edouard Quinet (1984) commented on the French Revolution, everything is now moving very fast in terms of technological and organizational developments. He wrote: “Its genius is to suppress time. It puts nothing off until tomorrow, including the actions of years; it does not even give itself seven days to make a world”. The purpose of this paragraph is to try to reveal some of the elements that limit the optimism of the statement with a proposal linked to the promotion of creativity as a grassroots element that brings out breakthrough innovations.

1.5.2.1. *Short term*

> Even if they are competent, honest and devoted to the common good, some technocrats […] give me the impression that they are incomplete, boring, and stupid human beings […]. They are so afraid of the fear of others and of their own fear, that they have never sought to understand it, nor to see it as an unsurpassable fact of the human condition. (Dupuy 2018)

Observation of the Brussels framework programs (H2020 and now Horizon Europe), the ANR (French National Research Agency), the National Research and Innovation Strategy (MESRI 2020a) and/or the Ministries in charge of research and industry (MESRI 2020b) reveal funding oriented toward the short term, as described synthetically in Figure 1.23 in terms of operation: the products produced are generally incremental innovations. In continuity with the past, previous actions are continued, with small changes, in a copy-and-paste logic that does not take into account potential events that could disrupt daily life. During their manufacture and use (as well as their recycling), various nuisances appear that need to be corrected thanks to new programs (e.g. “green deal”, renewable energies and circular economy). There is thus a double increment, the second being temporally shifted, that linked to innovation and that linked to its effects, allowing in principle for a quasi-continuous improvement, whose temporal compatibility should (must) be set against the evolution of the major trends affecting the planet (social and environmental tension generated by temporal tectonics?). Most decision-makers are committed to supporting technological development, but there is nevertheless, and increasingly, a certain unease among the public because their response is considered insufficient for the survival of humanity.

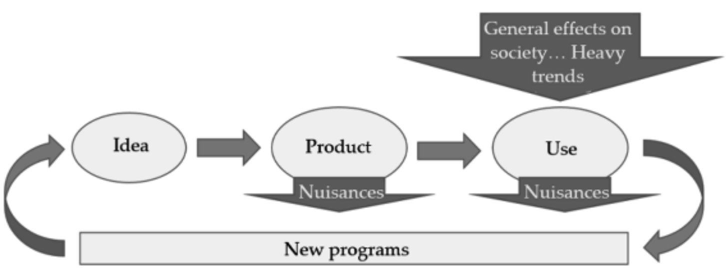

Figure 1.23. *Continuous improvement process associated with technological advancement. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

Moreover, the transformations of the economic system associated with the major research programs, a real instrumentalization of the future, do not only have positive effects on a society that is increasingly dubious about the effectiveness of these programs:

– Economic development is less and less shared (the “Gilets Jaunes” syndrome) with a gap between promises and facts.

– What is a new product for a few becomes an irrepressible need for the majority of society, reinforcing the nuisance; innovation creates new needs.

– Bouncing effects.

– The economic competition resulting from innovation leads to the decline of certain activities, which are partly compensated by less qualified jobs.

– The obsolescence of knowledge if only with the development of digital applications (see André (2019)) and progresses.

– Monopolistic companies impose their technologies.

– The effects of inertia (of dominant paradigms) leading by continuity to an intellectual *status quo* (Valaskakis 2014).

– And so on.

But, as Diemer (2007) reminds us: “The development of human activities has long led us to believe that the solution lay in improving techniques. However, these techniques are often reduced to a gain in productivity, and do not address the issue of the exponential growth in the consumption of natural resources”. If, in addition, the cost of manufacture falls, the rebound effects will amplify the problem. We use more “low consumption” light bulbs, which may limit their interest for the environment.

For Viveret (2002), “Europe remains in the middle of the road, losing the last vestiges of its former dominating power without displaying the dynamism of a creative power”.

In these contexts, in the current consumerist system, any radical attempt to assess and deal with dissatisfactions and problems expected in the long term, such as global warming, aiming at the possibility of formulating new objectives accepted by all States, goes against the policies established by those who have and continue to have a determining role in the appearance of nuisances. For France and for the EU, it is therefore necessary, in order to remain in the economic race, to take into account the others and to try to make proposals for improvements at the margin, without making a clean break. But is this enough?

1.5.2.2. *Inertia*

> If language is not available, trade cannot be carried out. (Confucius 2004)

> Like most who study history, Napoleon learned from past mistakes how to make new ones. (Taylor 1963)

If we accept the idea that it is possible to anticipate the demands that will emerge in the future (if only on the basis of a prospective approach), the crucial question will arise of how to reorient the body of academic research engaged in a permanent transition. Indeed, are we capable of organizing and directing with precision the progress resulting from science for an expected service to society? How, moreover, is this service to be defined? An excessive orientation of science could run counter to the objectives sought after because of the complexity of the questions to be dealt with; this consideration certainly does not mean that one should give up operational reflections, which are all the more important as the resources available cannot increase infinitely.

With the development of increasingly "specialized" scientific disciplines, will the vitality of research (already engaged in a search for funding that can affect its freedom and performance) be undermined? How will it be possible to develop training adapted to missions with changing disciplinary profiles? How long will it take to train these researchers? Is it possible to anticipate this training? Moreover, the French government has recently presented a new draft law on multi-year programming of research, called LPPR (*Loi de Programmation Pluriannuelle de la Recherche*). According to the Sud Education union (2020), this project has been prepared by three working groups, whose spokespeople are deputies of the presidential majority, presidents or vice-presidents of universities and research organizations and a former executive of multinational companies. "It is therefore not surprising that the three reports [for the LPPR] are in line with the government's policy by recommending an increase in the logic of competition, casualization and intensification of work".

This union, among others, considers that national research would be considered by these spokespeople as insufficiently competitive, requiring support for scientific excellence. This aspect is based in particular on a speech by the President of the CNRS, who is said to have said: "We need an ambitious, unequal law – yes, unequal, a virtuous and Darwinian law, which encourages the scientists, teams, laboratories, and establishments that perform best on an international scale, a law that mobilizes energies". At the risk of confusing Darwin with his brother-in-law Galton (the originator of the concept of eugenics), what Figure 1.3 shows with its disciplinary challenges does not support this desire to exclude the weak (unless one seeks to define the concept that is excellence along with all its baggage). It is true that Darwin (2008) wrote: “All organized beings struggle to fill the vacant places in the economy of Nature: consequently, if any species does not modify and perfect itself as quickly as its competitors, it must be exterminated”. The message is clear, if a little violent. But, as Dufourmentelle (2013) points out: “To be gentle with things and beings is to understand them in their insufficiencies, their precariousness”. Finally, it must be remembered that, in the current system (which may change), research is not (yet) an activity imposed at the finest level by programs to be “decanted” and specified as it descends to the rank-and-file performer. There is (still) a living research with an association between freedom and responsibility (Jonas 1998).

It is an all-encompassing concept defined in the Larousse dictionary as: “The eminent degree of quality, of value of someone, of something in its kind”. But what is the status of this concept which can be applied to very different fields? Does it not raise the need for epistemological reflection on its use when we know that it can be applied in many fields: disciplinary relevance, originality, openness to others, management of interdisciplinary projects, etc.? The polysemy of this notion can lead to misuse in current use, in particular in judging a personal or team research activity.

Box 1.4. *Notion of excellence*

> But [people] seem to have observed that this newly-won power over space and time, this subjugation of the forces of nature, which is the fulfilment of a longing that goes back thousands of years, has not increased the amount of pleasurable satisfaction which they may expect from life and has not made them feel happier. (Freud 2010)

By provoking a body of researchers who have already been involved for a long time in the search for significant funding (with generally low success rates of around 15% for the ANR and for H2020, and with prohibitive preparation times for applications), it is difficult for all those who are concerned with their real activity as researchers to participate for the benefit of society. Indeed, in order to regain a minimum of serenity, it seems useful to have a little rationality, a weak partisan spirit and a real willingness to listen to different points of view. This is what the Minister in charge of research has been trying to do recently (Vidal 2020). Let us remember that the generation of ideologies based on reflections translates into simplifying incantatory formulas, but sometimes it is necessary for certain brutal positions to be taken in order to awaken collective responsibility. Who knows? In any case, by shifting the forms of thinking about national research toward two opposing ideologies, it is difficult to exchange through the sclerosis of discourse.

But, who to believe if we follow Roux (2011) who writes: "Political lucidity and maturity consist […] in organizing the production of choice and action by giving voice to partisan interests and people of competence […]. To orient political conduct according to a supposed general interest is therefore to sin by naivety." Is this a good way for informed and weakly state-supported research staff to manufacture consent (Bernays 2007)? With cognitive dissonance (Van Veen et al. 2009), the conservatism induced by belonging to structured networks where mimicry is the rule (Bohler 2019), each party runs the risk, in an attempt to alleviate them and recognize possible biases in their judgments, of reformulating their options in such a way as to justify their positions, without actually accepting the debate. The openness necessary in research, the scientific doubt, is likely to be undermined.

Indeed, while the method may be subject to criticism, it should be remembered that the French research and innovation system is not among the most efficient in comparable developed countries (Fernez-Walsh and Roman 2013). New ways must therefore be found to better operationalize the system of research at the service of society if we want to put to shame what Marc (1987) wrote: "How can we provide the necessary sustenance when anyone can shirk work, because no one is pressed by need and everyone can rest lazily on the zeal of others?"

1.5.2.3. *What about foresight?*

> Anticipation is not merely forecasting; it is much more than predicting what the next event will be. It is more than dealing with the next event, it is creating the next event. (Follett 1949)

In the preceding paragraphs, there has been much mention of defining the goals to be reached in the future with the means to reach them, and Follet's sentences that introduce this paragraph illustrate the importance of foresight in defining, on the basis of scenarios, the distant future and the goals to reach it. But for all that, the future that is taking shape must be considered in the same way as operations aimed at the short term, as long as we agree to get out of the cognitive biases, the theory of rational choice (Berthet 2018). In fact, the approach taken in prospective processes is based on complex heuristic approaches where not everything is rational. The reality that emerges is, let us remember, uncertain and determined by processes that cannot be isolated from each other (holistic reality).

"We are in the midst of a long and painful process leading to the emergence, in one form or another, of a global society whose probable structure it is not yet possible to imagine" (King 1999). Recent trends, which the reduction of a certain balance of terror during the Cold War has allowed, are reflected in the multiform phenomena of association on a European scale, of a globalization of exchanges on the one hand, but also of environmental concerns, of the re-emergence of forces of disenchantment, of irrationality, of xenophobia and other fundamentalisms, of a return to the self, of competition, etc., on the other hand. In short, the future outlined by the liberal system is no longer as certain as it was yesterday, which imposes a look at possible strategies that condition and are also conditioned by the digital world, which can no longer be ignored. Indeed, social structures are innervated by the new immediate digital information channels, suffer exclusion, no longer have an assured collective vision, see their values modified with their culture sometimes reaching a sterile uniformity, in a few decades many obvious things have become obsolete.

Three decades separate us from the horizon of 2050, and in all probability the world will be, in the middle of this century, quite different from what we are able to imagine. Figure 1.24 recalls some of the elements to be taken into consideration in order to estimate the needs of the future, based on new scientific paradigms, the field of economic possibilities, social, political, reserve and environmental aspects, etc. This figure defines possible objectives but does not aim to take into account all the means to achieve them.

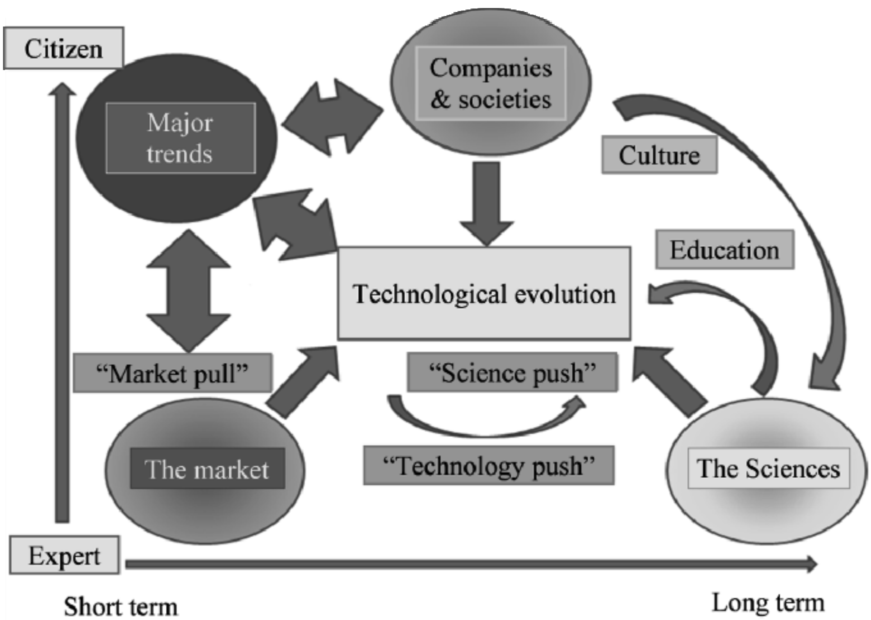

Figure 1.24. *A vision of linkages to be considered in techno-scientific foresight. For a color version of this figure, see www.iste.co.uk/demoly/4Dprinting1.zip*

In André (2019), major trends that will affect the planet and the production system were identified, leading to several possible scenarios. These data can be used to define a vision of the future, shared with society, coupled with the possibility of defining paths to reach it. In his inaugural speech, President Roosevelt (quoted by Pigasse (2014)) said: “Their efforts bore the stamp of an outmoded tradition. They came to exhortations, pleading with a tear in their eye for a return to trust. They knew only the rules of a selfish generation. They had no vision and without vision the people die.” This observation of sharing induces a certain robustness to the projection on the future, robustness that research needs because time is an important element to take into consideration. Complexity is at work with paradoxical injunctions and uncertainties and, in a constrained framework, it is important not to make too many mistakes about one’s choices (see Bauman (2006)).

Figure 1.25, inspired by Dieng (2014), highlights the different interacting elements that enable the definition of innovative activities relying on a probable future.

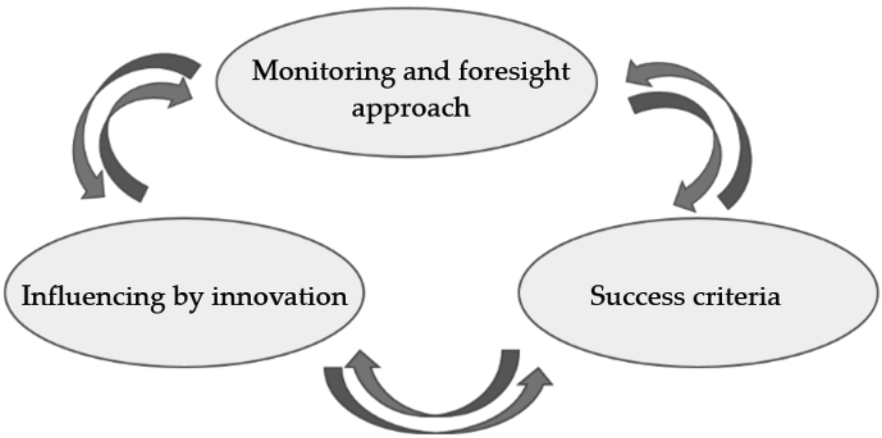

Figure 1.25. *Research-foresight association*

However, it will be necessary to take into account the various temporalities at work: that of technological and organizational innovations currently accelerating, the rhythm of life with the acceptance of the new and cultural changes. This asynchronous aspect discussed by Revault d’Allonnes (2012) results in losses of reference that can lead to misunderstandings, even rejections and crises, especially in a possible logic of decline (which no one takes into account in their forecasts). Perhaps then, in an interdisciplinary approach, incremental or disruptive innovators will need the insights that have become essential from specialists in the HSS. What will be done if they have not been considered in the LPPR?

1.5.2.4. *Supporting creativity as a solution*

> To accomplish anything worthwhile in research, one must necessarily go against the opinions of others. (Livio 2017)

> We must not mince words. This “engineering” is a modest tinkering that is much more akin to the empirical procedures of the amateur gardener than to the reasoned knowledge of the agronomist. But once again, this very discrepancy between the term and what it designates is instructive. On the one hand, we can recognize the prestige, supposedly legitimizing in our societies, of technology or its appearances, and on the other hand, the recurrent fantasy of control, extended in this case to the unforeseeable: “Even invention we manage to plan; producing innovation is our specialty; let’s not rely on luck, let’s force it”. (Gordon 1961)

The European Union’s response to meeting the needs of its citizens in its R&D framework programs is fairly simple in terms of innovation: it should rather be incremental with high TRLs, predictable, continuous with simply adaptations at the margin to keep the old principles that no longer work very well, but which are accepted by the countries of the Union (European Commission 2019). The case for disruption is a strong strategic element on how the EU intends to take global leadership on some key areas. Indeed, neither Amazon nor Apple were created in Europe, and the Union’s strategic plan could have been written by slightly informed people who had watched a few TV shows about the future of the world. So, let us make a big place for digital (while forecasts for 2050 show that 50% of the energy produced by that date could be consumed by digital, as André reminded us in 2019), sustainable development, low-carbon economies, the circular economy, the “green deal”, etc. This will certainly not be useless, but probably not enough.

Let us remember that digitization reinforces globalization by accentuating the movement of fluidity, as the German sociologist and philosopher Hartmut Rosa (2010) pointed out in his book *Acceleration*. He wrote: “Acceleration goes hand in hand with petrification, change accompanies inertia, and contemporary society is perceived as both fixed and frenetic.” However, we can try to change the situation by moving from traditional programming to real time regarding what can be mobilized, from the short term to divergent ambitions for the future of Europe. But, in order to do this, will we be able to count on the numerous committees of experts in contact with decision-makers of all kinds who will give researchers the initiative and who will accept the risk of failure in their attempts to create something new?

To get out of the game, it is therefore necessary to go beyond the current increments that are already significant disruptors (as they occur faster than most citizens can accept, or the old frog syndrome applies…). Today, those who practice divergent thinking risk being eliminated from the group of researchers recognized by the evaluation structures. It is increasingly difficult for them to have their articles accepted and their applications for credit are generally rejected by their non-inclusion in the ambient paradigms. In fact, they do not have any influence on the research system. The system thus shows its unwillingness to take risks, a real form of conservatism that concerns the body of researchers as a whole (since as peers they participate in evaluations). So, the answers to the questions of innovation and support for wide-ranging creativity should be based on divergent minds (too little supported in the national academic world) and by the development of broadly interdisciplinary forms of action that assume radical innovations, but allow for possible failures, reorientations, agility and flexibility, and obtain trust on the part of the hierarchy, all of which are indispensable for exploring the complexity of the world. But this largely remains to be built (even if the cost of such operations is likely to be modest, because it is not a question of money, but of organization).

Alas, it is the human components among many policy makers, including those of the Union, which are difficult to quantify, that should be addressed. "The mistake in the face of disruption is to want to start from the old and adapt it to fit the new world" (Maillard 2018). It is therefore by inducing principles of economic and social responsibility that it might be possible to get out of the current technological slump from which the EU is suffering. But their caution in making strategic choices is probably due to the weakness of the theoretical resources available to analyze sudden and unexpected changes (Bessin et al. 2010). We should then trust those who wish to engage in this adventure of supporting divergence, those who accept without reservation to be responsible and answer to society for possible mistakes. But is it so easy to find today courageous decision-makers to support them in their desire to act for the satisfaction of society's future needs?

Since creativity leads to varying degrees of disruptive innovation – which is valued by the authors – the decision-maker must undoubtedly consider the relationship between continuity (incremental) and discontinuity (disruption). By disrupting the order of the company, or even of society, how can we support the disruptive moments of irruption that put the old continuities at risk? For a decision-maker who is not very committed, even in good faith, small day-to-day successes are likely to prevail over support for the breakers of the old order in order, perhaps, to satisfy society's needs in a different way. Indeed, it is hard to imagine candle manufacturers supporting research on electric lighting… except in situations where they are obliged to change.

Blumenberg (1993) writes in this regard: "Modernity does not so much resort to what is given to it before as it opposes it and responds to its challenge." The periods we are living through are conducive to change because of particular turning points in which the questions arrive in excess of the possible reasonable answers, favoring the emergence of ideologies and “fake news”. Tensions in society correspond to over-solicitation, social, organizational or technological demands that the hierarchs cannot escape, challenges to previous certainties, etc. These strong reactions (the “gilets jaunes” syndrome, e.g.) either fall within nostalgia for the past or demand a future more in line with their innermost wishes by striking down the productions from previous periods as outdated. It is at this undoubtedly opportunistic stage, that creativity unleashes its full potential.

One might think that programs such as the “green deal” envisaged by the EU will follow the incremental logic that has proved successful in the past in reducing the environmental problems that threaten society. Reducing is good, but it only postpones the deadline. Giving imaginative people a chance to come up with radical innovations may be a way (though not the only one) to bring about original solutions. By trusting creative people, practicing divergent thinking, POCs could be realized and debated for applications satisfying the future demands of society, which is now forced to make hard choices if it wants to survive. As Marsan (2020) points out, “let us offer profusion, let us vitalize the diversity of productions and let natural selections take place through a sieve of our choice.” To hope to survive in the near future (a few decades), humanity must accept to support risk-taking on the part of no doubt atypical researchers who offer POCs of their imagination, but supported by researchers more committed to scientific depth. These could contribute effectively to interdisciplinary project approaches.

Moreover with the Pact law voted in May 2019, a new impulse is given and extends the Allègre law of 1999, which gave the opportunity to researchers in the public domain to create startups in parallel to their public employment. According to Nguyen (2020), only 231 civil servant researchers have requested authorization to create their company since 2000, that is, less than 0.01% of the people working in public research. Today they no longer need to go before a deontology commission and can work part-time in their laboratory while working the rest of the time in the company they have created. They can also contribute their scientific expertise to the company developing the results of their research up to 50% of their time while retaining their full remuneration. They can also keep up to 49% of their company’s shares for life (as opposed to the obligation to sell their shares within one year under the Allègre law). Everything is in place to help researchers’ innovation, if only through the financial support of the State via the *Banque Publique d’Investissement* or BPI (Rolland 2019).

It is clear that the authors are taking the risk of making mistakes, but they wish to involve their readers in a reflection on ways of renewing innovation, which can no longer be satisfied with predictable increments in a world in open revolution, in a context where severe limits to technological development are clouding the atmosphere that was still serene a few decades ago. The ethics of the future therefore imply, through the changes necessary if human society is to survive, trusting responsible research, but promoting a break with the past in terms of imagination (while still using the rational knowledge of science).

1.6. A hopeful conclusion within an organization that learns

> My possibilities are naught, they make themselves possible. But probabilities do not make themselves probable; they are in themselves, as probabilities. (Sartre in *Being and Nothingness*, 1976, author's translation)

> The people always want the good, but of themselves they do not always see it. The general will is always right, but the judgment that guides it is not always enlightened. (Rousseau 2006)

> "[I]t is necessary for one to be certain, that to imagination be added something which is reasoning" (Spinoza 1954) or "it is necessary for one to change things, that to reasoning be added something called imagination" (Cargnelli 2020).

1.6.1. *General framework*

Hegel (1991) wrote: "It is not difficult to see that our epoch is an epoch of birth and passage into a new period; the spirit has broken with the world in which its existence and representation stood until then; it is about to bury this world in the past and is in the work of its own transformation." Everything is moving fast and, apart from elitist principles, what the author has tried to show is the difficulty of fine-tuned programming of research "from above", either because it is unrealistic, mere bookkeeping, or because it forgets that most radical innovations do not come from research in fields considered to be priorities carried out by "excellent" researchers, like the founder of Apple, Uber or Amazon.

In fact, for a general programming of science, it seems that it is necessary to have a better knowledge of the future in order to refine our vision of the means to be implemented to reach distant objectives of a few decades. It would be wise to master the system of interactions between different elements such as technological evolution, the economy, general politics, the psychology of citizens, access to reserves, current and future effects related to global warming, all elements of a complex system. On the basis of such an understanding, leading to a shared vision of the future to be allowed, we should try to identify sub-systems that are sufficiently disjointed for their study to be possible with the possibility of converging the knowledge acquired toward the final goal. We should try to make progress, if only by trial and error. Without this investment in multiple risks to be humbly shared with society and with the social body of research, it seems difficult to hope for credible results, except by chance, imposed by a too rigorous and too precise programming.

If we remain on a narrow panorama of foreseeable possibilities, we obliterate the many options necessary for the emergence of good options for tomorrow. To do this, we must undoubtedly change the paradigm of civilization, but for public research, this means re-founding our imaginations and developing a narrative on a revised basis that leaves more initiative to researchers. We must therefore encourage a craze for the truly new and exploit it as an opportunity to produce a responsible scientific narrative. The CNRS has partially undertaken this on the occasion of its 80th anniversary, even if there remain many continuities (CNRS 2020). Thus, in order to get out of a subjectivity sensitive to uncertain futures, perhaps we need to give researchers the chance to function differently, through a liberated creativity, accompanied at last by the hierarchy. Under these conditions, desire, passion and emotional intelligence must be supported in order to move forward. Perhaps, in a context where not everything can be decided, it is necessary to leave it to those who are the actors in the field to limit as much as possible the contingencies (but undoubtedly not in any old way). That is all the bad news we can wish them. Let them dare, trust them and better still, members of our hierarchy, help them! The risk is worth it! The future of our children depends on it.

1.6.2. *Organizing research in 4D printing*

> By placing enormous and very poorly defined costs and benefits on the same scale, normative evaluation is condemned to undecidability. (Dupuy and Roure 2004)

What has been shown throughout this chapter is a spectacular aspect which, admittedly, hides scientific and epistemological difficulties, but which can represent very interesting avenues in fields which are partly niches, but which can constitute at least partly autonomous fields, such as soft robotics or structural electronics, which correspond to obvious economic markets and for which France is no worse positioned than other industrialized countries. However, these two fields are aimed at more complex applications than those in medicine and drug delivery, which are essentially the result of work in homogeneous or hybrid 3D printing that has been pushed to its limit. If we want to satisfy the ecosystem defined in Table 1.1 (which is not exhaustive), the French position could be held by:

– a central core with a set of 3D printers which can, after some adaptations, cover the field of 4D printing and engage in generic research on the subject of 4D, in particular (but not exclusively) on heterogeneous 4D printing with the exploration of the obstacles defined at the beginning of this chapter (changes of scale, voxels of variable size, multi-materials);

– a local mirror research unit with knowledge in the fields of electronics and robotics allowing internal developments to the group constituted by the central 4D core and the "mirror" component;

– a very large external demand allowing upstream-downstream operations for the realization of 4D devices adapted to an external demand (see Appendices 1 and 2 in this chapter);

– scientific and technological advice to guide the choice of risky operations, taking into account the socio-economic impact of the work to be carried out;

– specialized research units located throughout France, selected for their expertise in fields such as materials, chemistry, mechanics, processes, etc.

> Rationalism can no more transcend knowledge by analogy than the famous Baron Münchhausen can pull himself out of quicksand by pulling on his own hair. (Stengers 2020)

The activities must allow on the one hand to continue to further the 4D theme while at the same time allowing the development of POCs in a first phase, then industrial demonstrators in a second phase. This means that it is imperative to associate a transfer structure with this type of proposal (which could advantageously work locally with external applicants who have expressed a specific need retained by the scientific opportunity board).

Faced with the increased demand for innovations that are of societal interest, we would like researchers to stop relying solely on their intuitions, to dare to create and to multiply exchanges with their application targets in order to develop solutions that respond to real difficulties and needs. To do this, we must abandon the classic "linear" processes for iterative, integrative, learning and shared approaches: brainstorming, openings, development, testing, evaluation of feedback, corrections, testing again… until the solution is finally ready to find its place in industrial appropriation.

This is a profound change of strategy in order to be a major competitor. By questioning future users, we exploit the full potential of co-creation. A product is no longer created by a person in research and R&D who has a hunch, but by a win-win alliance between designers and creative users. "This paradigm shift is transformative and innovative in companies" (Mayard 2021). Thinking about such co-construction is also based on a critique or deconstruction of previous technicist and rational approaches. Instead, we must seek to exploit principles for action-oriented reasoning, that is, a heuristic for defining and conducting co-constructivist devices. This is another form of intercultural (rather than interdisciplinary) project.

The approach cannot be based on a general method of optimizing the conduct of such upstream-downstream associations, which must be dealt with on a case-by-case basis, but on the postulate that a system can be designed collectively on the basis of reasoning and deliberation in confidence. Co-construction processes are obviously complex, contingent, situational and "are characterized by an irreducible unpredictability, because the actors always remain partially free and can never be totally instrumentalized in the service of an end that would be external to them" (Foudriat 2019). It is therefore, in a way, a question of achieving a 4D organization, flexible and stimulating, but coherent! In jest we have called this open group Min-Max 4D or 2M4D.

> The real world, unlike the sciences which carve out closed domains, is not divided into disciplines. It is the isolation of economics and the science devoted to it that is the problem, and it is also the need to build a renewed science of economics which, without ceasing to be an "autonomous" science and without reducing itself to a simple technique, recognizes that economic parthenogenesis is conditioned and submerged by the action of exogenous variables that define its environment and opens itself to multi-dimensionality. (Bartoli 1991)

> We must find the way back to a multidimensional way of thinking, which, of course, integrates and develops formalization and quantification, but does not get locked into it… The economic, the psychological, the demographic, which correspond to specialized disciplinary categories, are all sides of the same reality; they are aspects that must obviously be distinguished and treated as such, but they must not be isolated and made non-communicative. This is the call to multidimensional thinking. (Morin 1991)

But the transition that can be associated with 4D printing needs rough edges, a vision, topography to conquer in order to get out of the various solicitations that occupy all the available time (of which we are the consenting victims, but not always conscious). The co-constructions that are part of these concepts are not systematically systems of shared leadership aimed at developing the professional self-esteem of all the members participating in them. But for all that, in these operations where intellectuals are convened, the exchange can be horizontal.

Co-construction processes are complex and sometimes fraught with unpredictability because the applicant-designer couple remains, outside of the contract, partially free and can never be totally instrumentalized in the service of an end that is external to them (Foudriat 2019). Co-construction remains "a complex process, eminently contingent and situational, which is distinguished […] by its high level of deliberation and involvement in the decision-making process" (Leyrie 2017). The interest is that all stakeholders can be involved, which leads them to get involved, to act with their diverse skills and to have an influence on the upstream-downstream project that concerns them.

In these operations, it is necessary to leave behind the belief in certain principles, first and foremost the principle of scientific determinism in the harmonic connection of things. It is necessary to construct new relationships between non-objectified desires and what is scientifically and technologically possible, based on the findings of experience in order to satisfy a requirement of positivity. The linkage of forms of determinism with laws that are first causal, then functional, and finally with the laws of probability based on statistics, can be defeated, which requires humility on the part of the researchers involved in these operations. Indeed, there is a rearrangement of previous knowledge and the emergence of new debates (with, for researchers in a hurry, a loss of time and a return to the previous paradigmatic focus).

In the minds of scientists, even when discussing interdisciplinarity, there is a concatenation of causes, each cause generating one or more effects normally known and controlled. However, when approaching the realization of an object in a co-construction, organization and individuality caught in a network of relationships, some of which are rigidified by habit, the existence of unevenly shared information, a memory organized in silos, uncertain anticipations and project management can have an effect on the desired result. This may be the result of interaction behaviors in the host structure (which will implement the translation of the idea) which is already organized, arranged and regulated, and in dependence on the operators' operating skills which have already been or are being constituted. The work of co-construction is the result of scientific research into "intention" and sharing, and is therefore a moving reality, rebellious to the idea of an absolute "law".

"Science is only illusorily definitive" (Granger 1960). Bartoli (1991) writes that because it is marred by errors and inadequacies, it corresponds to a risk "boldly" taken. In principle, he writes that it is "operative, hard-working, conquering, essentially unfinished, it never ceases to rectify, expand, complete, open up previous knowledge". But, in reality, the researcher's situation is more complex insofar as their evaluation takes into account their productions rather than divergent attempts (unless they are successful). Co-construction is therefore not a natural process. It is therefore necessary, as Gouil (2010) suggests, to relearn how to cooperate. This collective learning can, moreover, avoid exclusion, the incomprehension of a world that may seem forbidden, which prevents a will and a willingness to emulate in order to "be" in the adventure.

Riccardo Pucci (2021) in one of his emails wrote to us:

> Although we obviously cannot predict the kind of impact [4D printing] will have on the environment around us and the laws that dominate it, through creativity we can bring important elements in a two-way relationship between the creative and the engineer. Only time, patience and passion for 4D can show us the right methods to make this technology shine.

So let us co-create!

Box 1.5. *Co-construction*

> Knowledge is blind when it is reduced to its only quantitative dimension, and when the economy and the company are considered in a compartmentalized way. But the impermeable compartments have become established. The dominant logic being utilitarian and short-termist, we no longer explore fields, activities, specialties or ways of thinking other than our own, because a priori they do not directly and immediately serve the accomplishment of our tasks, although they could enrich it.
>
> Culture is not a luxury, it allows us to contextualize beyond the furrow that becomes rutted. The obligation to be technically ultra-performing in one's discipline results in a withdrawal into this discipline, the impoverishment of knowledge, and a growing in-culture. People believe that the only "valid" knowledge is that of their discipline, and that the notion of complexity, synonymous with interactions and feedbacks, is mere chatter. Is it any wonder then that the human and civilizational situation on the planet is so bad? To refuse the lucidities of complexity is to expose oneself to blindness in the face of reality. (Morin 2016)

1.7. Appendix 1: Processing an external file

> Our world has set itself a crazy mission: to "modernize" – for their own good – all humans on Earth. To eliminate all other worlds from the planet, such is its program. Is this not totalitarianism? This mad conquest of humanity began in the name of true faith, of civilization; it continued in the name of progress, of reason; it continues today in the name of freedom, development, democracy, Human Rights. Is the "major risk" not, more than ever, the gigantic violence that the totalitarian project of our world entails? (Solé 2004)

Figure 1.26 brings together the different elements that need to be taken into consideration in order to attempt to build a case (that could be supported later by 2M4D) from a creative idea that falls within the scope of 4D printing.

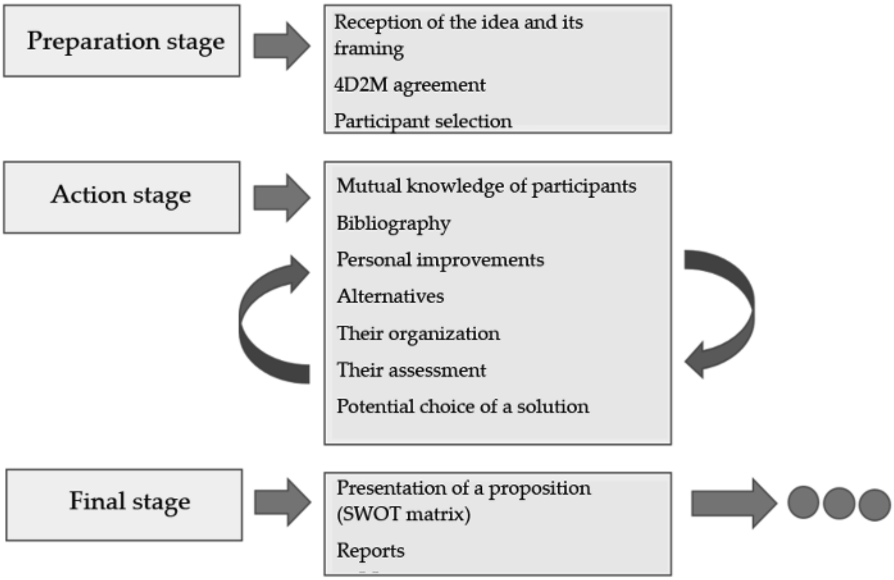

Figure 1.26. *Envisaged overall (flexible) procedure*

Between the choice of an action and its implementation, real feedback loops can occur over time, leading us to consider the decision as a dynamic process and not as an instantaneous act.

> Starting from an initial state of knowledge about the alternatives that the decision situation involves, the search for information is refined and then consists of inquiring only about the critical points of the problem on which the state of knowledge does not allow for a reliable definition of a decidable situation (indiscernibility of alternatives, uncertainty of an evaluation, unattained objectives, instability of evaluations, no consensus, etc.). To reach this situation, it is necessary to fill an information gap which, as long as it remains, induces epistemic uncertainty, in other words, a decision-making risk linked to the insufficient state of knowledge at a given moment in order to be able to decide. The further the quest for knowledge advances (when it is well managed), the more epistemic uncertainty is supposed to diminish and the situation that can be decided upon takes shape. The challenge of this dynamic cognitive process is to know how to conduct the search for information with insight during the deliberation: on which aspects of the problem will it be most judicious to acquire additional information to reduce this uncertainty as best as

possible, as quickly as possible, and thus accelerate the decision-making process? (Imoussaten 2011)

The choice to engage in new solutions from uncertain environments implies taking risks with a certain control of complexity, which is often the case in 4D printing. A confident and dynamic framework to deal with this type of situation is necessary to move forward in a "good" horizontal collective organization, which is very rarely practiced in the academic research world. It is necessary because of the need for mutualization of multiple forms of knowledge in the scientific, technical, social and organizational fields. There is therefore and a double responsibility in this operation, that of 2M4D, but also that of the participants who must really get involved with agility, motivation (Mauchand 2001) and confidence in these operations. For the Institute, the hopes of its managers must be confronted with operational constraints, the objectives with the means, and a dialog with the project group must be established to define achievable objectives. Facilitation by a 2M4D representative can be advantageously proposed to improve the organizational performance of the group. From the group's debates, a contradiction should emerge "between the social process of design, full of uncertainty and ambiguity, and the ideal image of the instrumental process in which the participants believe they are involved" (Darses 2009).

The purpose of this disruptive proposal is already to show that the conditions for involvement in forms of complexity that are on our doorstep with limits and/or constraints of various origins can be overcome and that we must invest in this new, henceforth inescapable challenge if we want to be recognized as credible actors capable of breaking out of the daily routine (training made reductive by the teaching of certainties, difficulty in recruiting "prepared" minds, effective management of interdisciplinarity, systemic approach, understanding of the issue in a world governed by the short term, involvement of the "best" in what is recognized as a promising field, etc.). In short, we must think outside the box… or else…

In an in-depth evaluation by 2M4D, is the "consensus" proposal from the project group one of preference modeling or one of meeting material constraints? Do these views provide antagonistic or complementary perspectives? And so on. These are questions to be asked. But the evaluation that comes out of the decision-maker must avoid a totally "creaticid" operation that would risk "nipping in the bud" any initiative. It would be better to do nothing!

But if 2M4D makes this proposal, it will only have credibility if its associates – anyone assigned to its research unit – feel concerned by this type of meaningful and hopeful action, otherwise Lewis Carroll will be right!

> In the Red Queen's kingdom, all subjects must run as fast as possible to stay put. As a puzzled and bewildered Alice remarks, this is a very tiresome way of getting nowhere! (Lewis Carroll 2010)

1.8. Appendix 2: Going a step further (working document)

> Individuals draw out their information and keep only that which is relevant to their system of thought: they seek to reinforce certainties already acquired in the past. The processes of anchoring and objectification account for this need. (Orfali 2005)

In this ambivalent setting, national research and university training systems have evolved in two modes: stable trajectories and a few bifurcations under dynamic conditions (the world is moving around us). They are continuously changing under the action of dynamic processes, both internal and external. If a structure emerges and is maintained in a sufficiently persistent manner to be recognizable, it is nonetheless the product of this evolution. This is why the engineering sciences (including computer science and materials) still constitute a respectable scientific force (even if it is a bit aging, on the side of research organizations). Finally, to the processes of self-organization, we must add the evolving specificity of regions wishing to redeploy their scientific and technical resources, which implies that the creative capacity of motivated university centers must also be taken into account, as the flow of innovations and the creation of new wealth are the only factors capable of explaining the continuation of an attractive dynamic. How then can science on an emerging subject be a real leavening agent of this design, which obviously concerns it only very imperfectly?

Any centralizing research and innovation system only really makes sense if it is thought through and challenged, at regular intervals, to maintain a level of excellence relative to some vision of the future. What we observe is that everyday mechanisms and procedures are put in place to control researchers and teacher-researchers in an increasingly sophisticated way, whose operations continue to be "business as usual". In the field of additive manufacturing, growth is 20% per year; in the particular case of 4D printing (adding a temporality to 3D printing, it is 40% per year, and for bio-printing the number of publications doubles every 18 months…). It is – at least in this example – not possible to remain in a wait-and-see logic.

The most successful systems today are open, pluralistic, living, agile, reactive… Moreover, we speak of "ecosystems", which increasingly imply integrating randomness, risk-taking, emerging actors in decisions, resourcing actions through science, etc. In fact, by making "objects" ever easier to acquire, by reducing their duration of use, by exploiting too quickly the reserves available at low cost, the consumer society knows without expressing it that it is running to its ruin (even if some people think that technology will remain the solution in the developed countries). Is there a desire on the part of the population and its elected representatives to be consumers of these goods or to participate in some aspects of a renewed economic activity that is always provisional and based on the knowledge of scientists?

Can they rely on a dynamic industrial environment? The answer is clearly negative, leading to local academic circles which are out of touch with the economy of their city. Can they then rely on the will of the so-called scholarly community? A recent survey conducted in a large laboratory in Nancy does not provide a long-term vision either. Defining an original societal need and the technical and organizational means of satisfying it does not, of course, systematically enter into the leadership of techno-scientific research, which must retain its scientific character, creativity and depth, while at the same time having specific approaches because of its position at the interface with the applicability of scientific concepts resulting from research. The legitimacy of science is in fact built by the dynamic and recursive mutualization of scientific knowledge with a view to an end whose origin comes from the scientific component or from that of the applicators or from a demand from decision-makers. But then, where are the motivated decision-makers at the local or national level?

> At a time when the space offered to individuals thanks to modern techniques of movement and communication is undergoing a process of enlargement, a promise of emancipation for individuals who are no longer riveted to a territory, the proliferation of misbehavior exerts the opposite pressure: it reduces the possible space. Beyond a certain level of disorder, a devastating doubt about the intentions of others takes hold of everyone. Incivilities, by expelling conviviality from the public domain, confine it to reserved niches. (Peyrat 2003)

Thus, in order to avoid confining researchers to their discipline, a discipline in which they exercise their freedom (their autonomy) and their activity, allowing them to go beyond the limits of knowledge, it is probably necessary to find and invent ways of “transgressing”, of support for risk-taking, which must authorize and support new cultural couplings associating divergence (or disruption) and creativity. These must allow the promotion of adapted synergies, authorizing the creation of new concepts or new artifacts useful for society (notion of self-fulfilling competition). This is what is expressed by the (happy?) idea of coupling between science and technology and the social body. By supporting creativity at the interfaces, by developing creative hybridization, it is therefore a question of going beyond other frontiers of knowledge, but undoubtedly on the basis of new or revisited methods, by resituating research and researchers in the context of the life of the city rather than in national or European life. This exercise must be undertaken. 4D printing is there as a basis for experimentation.

With this aspect comes a singular element in research, that of rarity, of originality, which can induce exchange through the dynamics and attractiveness created. It is interesting to examine why and how exchange relationships (in the form of knowledge sharing, client-supplier relationships, bartering or money) are developed with difficulty internally or externally, how researchers in their scientific quest have financial and human support (this problematic raises the question of research management (or in other words, the researcher's autonomy) and possible cooperation to help some people stay on course in the "ocean liner" that a large laboratory can be). Indeed, how can the erratic funding experienced by researchers in the support of the agencies be smoothed out? What forces can act to ensure that separate researchers can "hold together" and form what the academic world calls a research unit whose mission is certainly to produce scientific knowledge, but also to be useful to society? The survey conducted (Horckmans 2016) attempted to uncover social mediations through which these individual-to-individual relationships are transformed and shaped to avoid anarchy, and also to fit into a meaningful global compatibility. What energy is supplied to reach this state of dynamic equilibrium, which makes it possible to fight against the second principle of thermodynamics where entropy dilutes efforts? In fact, is there not a clear conception of the world of research centered on itself, its promotion and a normative fetishism of the evaluation that is adapted to it? The relations between societal actors then appear in the background, almost in antagonism. Is this a diversion from the mission (as long as it is well defined)? So, what could be the link between the economy of the nation and an emerging subject like 4D printing?

One line of thought is to know whether we belong to an elite of scouts, of those who prevent us from thinking in circles, and how we can judge the societal impact of creativity, rational unreasonableness and the associated scientific depth of vision (foresight), provided we give it consistency and transparency; a second line of thought is that of the "virtuous followers" – wise, learned, useful, but compliant. Producers of stabilized knowledge represent the necessary backbone of a research unit that needs to rely on common and effectively shared values; a third, which is not opposed to the first, relies on the development of links, exchanges and sharing, both internally and externally, across disciplines and/or inter-disciplinarily.

> When a team makes arguments designed to appeal to funders or the public, but which members and their peers know are empty, the rule is silence. The citizens of the "Republic of Science" know that, in a self-interested society, such incentive mechanisms are "unfortunately necessary". (Stengers and Bensaude-Vincent 2003)

This represents another form of intellectual mobility. Between solidly established positions, the merit of scouts or openers can only develop if there is a call for air, if there is for a time, a space for action, human and financial support to explore the uncertain with its real risk-taking. There is therefore probably not a single merit, a single "excellence", but the diversity and harmony of skills (not only scientific) must constitute the wealth of a laboratory, as long as we get out of the symbolic balances, the non-aggressions, the opaque reality of certain local practices and that we calmly manage with empathy the tensions between these tendencies that sometimes come under the paradoxical injunction to be "readable", "credible", "driving", in short, "excellent" (a very vague notion…). It is this governance that must strengthen a collective imagination that is confident of having a space for freedom and joint action, freeing itself, as much as it can, from an administrative technocracy considered to be "superior", that thinks it is piloting research to meet the needs of society (as it unfortunately imagines them) and that continues to apply principles of "meritocracy" adapted to all and perhaps to nothing. But perhaps this is the price to pay for continuing to undertake, if one knows what one is and where one wants to go (and how).

Everything, a survey conducted a few years ago revealed, is about beliefs: belief in a future in continuity with the past because no major clouds obscure the sky, in leaders who assume scientific and administrative responsibility. Since then, Covid-19 has hit us. So, why try to practice activities that fall under the heading of divergent thinking (criteria that are generally unknown at the time of hiring), as long as there is no obligation to change? Are the temporal bases of resourcing adapted to the maintenance of the scientific and technological leadership of a research unit or to the personalities in this laboratory? That is the dilemma! Who should be credited for these sudden changes? This risk has apparently not been evaluated, and this in turn does not allow the urgency of the necessary changes and their anticipation to emerge. This work of social engineering is to be done in the academic world, for which the processes of integration and mutualization, of common or complementary values, have not been engaged in any notable way. The ball is in whose court?

These different "manifestations" of external tensions must therefore be shared in order to create a common sense of action and a shared collective feeling on the part of the members of the scientific community. Intelligible representations by the whole staff presuppose a minimum of trust between its members so that they can interact in a valid manner; one possible means could be a common or partially common scientific project. This material project would not be there to reveal the "mental" state with which the members are associated, but a means of bringing energies together to do things differently. "This solution implies an ability to identify the needs of the members and to find solutions to these needs. This solution implies an ability to identify reliable informants, who collegially test their ideas through demanding procedures" (Farina and Pasquinelli 2020). In order to win better together, it would consist of externalization in the movement enabling the creation of links, participation in the evolution of the image, strengthened because all the partners have contributed to its creation. This pooling would then have, in a rational anticipation in an ambient uncertainty, a renewed attractiveness and a strengthened power of integration, allowing shared risk-taking.

There is a need to explore the mobilization capacities of the “troops” in relation to the “incapacities of organized action”, by situating it in the wake of reflections on the continuity between action “within” the organization and action “outside” – the latter being very often already organized and supervised (ANR, EU, CNRS, PIA, etc.). It is an in-depth exploration of the degrees of formalization that would give access to both the capacities of organized action and its incapacities and thus to an additional dimension of scientific anthropology. This work to be carried out should allow a conceptual clarification of the notion of incapacity to move the lines.

Torn between vocation and ambition, between emulation and competition, today’s researcher is a somewhat “paradoxical” character, who only partially masters the logic of their actions (reflect on the interactions between scientific knowledge and actions toward/for society to better understand why and how it is possible to enter into a more responsible approach to research, due to very important developments). The quest for a scientific reputation now resembles a sport competition; a race for “refereed” publications, under the umbrella of a new research management culture that is more reminiscent of the old Soviet central planning than of the free market of ideas (which is modestly allowed to blossom). The researcher finds themselves more than ever a slave to a system that they helped create, somewhat in spite of themselves, and from which they find it increasingly difficult to distance themselves.

The scientific world in Nancy would do well to critically examine these new reputational mechanisms, if only to enable researchers to better master the rules so that they can be more concerned with their humanist mission, which is open to the needs of society and the dynamics of the city, instead of with their “simple” evaluation based on criteria that are partially removed from the scientific target and their mission. Evaluation mechanisms have consequences on the way personal and collective reputations are built. The tangle of different tools, norms and customs reveals a mixture of practices of recognition of esteem and prestige (the classic mechanism of peer review, the citation system, the economy of greatness indexed on distinctions, prizes, and national and international rankings). How does individual performance contribute to the recognition of the scientific activity of a research unit (and vice versa)? How can this performance, when it exists, validly participate in the entrepreneurial dynamics of the city? Obviously, this point of view does not answer the question, even if it raises more of them.

> Leaders seem to have been trained, even formatted, in a world of realist thinking that leads them to perceive the world as something external to them: this intellectual heritage […] seems, in fact, to prevent or at least slow down the apprehension of this complexity, constituting a sort of realist filter. (De Geuser and Fiol 2003)

But several new things are happening today. Apart from a decent average quality of national research (see Shanghai ranking), without any locally useful nuggets of gold, research is totally globalized. The companies cover the same world and we must give value to these companies if we want to participate in a public utility contribution from (and turned toward) the interest of our country.

Moreover, in the present situation, an essential element must be taken into account, that of the reduction of temporalities, something that stems first of all from an authentic technical "leap" that has taken place in just a few years. Ten years ago, the development of smartphones was only in the latent state; the autonomous car was still a distant project; the prospect of a computer expressing itself as fluidly as a human or composing musical works "in the manner of" resembling an authentic work was a matter of the imagination. This technical leap is generating cultural evolutions, a change in lifestyles, such as an addiction to the instantaneous fulfillment of desire, to the individualization of performance. The interaction between the digital world and the real world is increasingly close: the exchanges born in the former are increasingly translated into the physical world and, conversely, our activities continuously generate data that enlarge and feed the virtual world. This sudden irruption of a new reality disturbs, upsets and creates tensions. But it also raises expectations and offers tremendous prospects for development. Who, on the research side, is actively participating in this revolution?

While there were 138 in 2015, the number of digital platforms is close to 250 in 2019 with a business model based on matchmaking. But these platforms, which are at the heart of the ongoing economic revolution, do not constitute a technological breakthrough: they use existing digital processes (albeit particularly innovative ones). The effects of such an ecosystem, particularly on productivity gains, are clearly not the same as those of the widespread use of "digital" in the industry. Who in the country has participated in this organizational revolution, in this change of economic and social paradigm, linked to the use and dissemination of new technologies, when it calls into question the very foundations and structures of the industrial economy? Even Paris is not in the top 25 in the world on this subject!

In addition to these external dynamics, there is another, cross-cutting one, which stems from the intrinsic characteristics of the economy and the systems that are generating the current upheavals. It has to do with the scale on which we can act, which can no longer be that of the national territory. The platform economy is a global phenomenon, whose instruments and levers for action are almost inherently a-territorial. Acting on too small a scale – that is, in this case, on the scale of a single research unit – means running the risk of losing innovation without gaining anything in return.

> The daily life of individuals and organizations is made up of poor decisions, because it is difficult to agree and work together, human intelligence has its limits and hazards are inevitable. Poor decisions are the result of action that revolves around the goal. (Morel 2002)

1.8.1. *Can we break the deadlock?*

It is therefore appropriate to ask what the ideal of local government can be, that which is at the extreme of programming without resourcing, and that at the extreme of resourcing without any intentionality. Both are incapable of bringing about an "acceptable" harmony between the freedom/autonomy of the researcher and the general local interest. However, can we not consider that responsibility does not have only one face, that of the researcher, but that it also involves society as a whole?

> We are all "guilty" and all "responsible" for the situations we live in, and this in spite of ourselves, because we did not choose them or build them. We are responsible because this structural "equality" is not an elite that is called upon to make decisions at the critical points of the situation, it is all of us. (Benasayag 1994).

What this little reflection tries to show is the absence of a clear steering from those in charge and the presence of the conservative "tertiary deposit" that constitutes the academic world committed to goals that do not sufficiently understand the future of their country. There are several directions that should be explored in an attempt to get out of the sad trends presented above:

What future exists for France?

It is up to citizens and their representatives to reflect on the dynamic image they wish for their city. Various well-framed organizations (or certain personalities) can make a scientific contribution on the factual aspects and on prospective approaches, but it is up to the social body to determine itself (ends, means, communication, openings, etc.). Among the reflections, it would be useful to examine the multiple consequences of inequalities: they prevent those with less income from reaching their full potential in terms of education and inventiveness, which results in a decrease in the spirit of entrepreneurship. Furthermore, if wealth is concentrated in a small segment of the population, the demand for imported luxury goods increases, but creates little or no industrial development.

> In general, only rough assertions and estimates are possible regarding the concrete nature of these distant effects. (Rapp 2000)

Introducing disruptions in the mechanics of research

The present situation leads to a "Darwinian" life for researchers, linked to the survival of the most able to manage in the emerging normative universe linked to the modifications of their institutional research environment, thanks to a good perception (or even anticipation) of the new rules, explicit and especially implicit, of the functioning of the academic system. By introducing changes, the conservative body (at least in their discipline) of many researchers is led to modify their ways of acting, which can be beneficial. Indeed, in the absence of stimulation, an instinct develops tending toward the resurrection of the old order (the Freudian automatisms of repetition). Specialization is probably a necessary evil in the sciences, but how can we avoid premature compartmentalization and unsuitable programs which risk "ossifying" specialists, walled up in their system of thought and incapable of rejuvenation (Elgozy 1966)?

Fostering interdisciplinarity

The disciplinary approach is too scattered, hence the key idea of percolating through disciplinary boundaries so that the complexity paradigm can truly unfold, particularly because the re-composition of categories of thought is no longer based on disciplinary boundaries and objects, but on border objects. This context requires the convergence of disciplines. When working on border subjects aimed at the creation of instruments, machines, processes and software, the scientific aspects must integrate broader forms of convergence concerning uses, human and economic aspects, and involve integrated work with technologists, making it possible to integrate their skills as far upstream as possible (or even to develop them, as well as those of researchers) in order to satisfy the application needs (both technological research and societal) in a robust manner.

Supporting creativity

In systems where unknown areas exist, it is necessary to enter into a heuristic approach to try to find "profitable" avenues of action (rather than, as is often the case, waiting for others to do it for you). How to create interdisciplinary groups practicing "divergent" thinking and having expertise in the chosen subject, likely to define, with external input, what is possible and therefore known, as well as partial or total areas of unknown knowledge. Depending on the goals defined, it must be possible to define scientific and technological scenarios adapted to the achievement of the scientific goal (originality) and why not industrial goals as well.

etc.

Other ways are possible, we must think about them together, but they must avoid the “ship continuing to sink slowly”.

> We are on the threshold of a new cultural compromise in which traditional humanism will have to settle its affairs with the third culture of which it has never taken note. And the third culture is neither the hard sciences nor the humanities, but all the knowledge of engineers. (Sloterdijk 2000)

1.8.2. *So what?*

> In a civilization saturated by technology, there is no more adventure, only the risk of being late. (Sloterdijk 2006)

We propose just one example to illustrate how we can support the search for disruptive ideas that could create economic development (depending on possible feedback, other ideas for action could be expressed, including a complementary action of prospective reflection). The principles of the action initiated by and for 2M4D are based on the general document presented above:

Project summary

A candidate, with about 5 years of higher education (without this being a strong selection criterion), develops, with the help of 2M4D and research structures, an original, even revolutionary or disruptive idea (some would say “crazy” because it comes out of a “reassuring” continuity), but likely to trigger a creative cascade leading to the subsequent development of the job. The selected candidate is supported financially, but above all by researchers and teacher-researchers, company managers and their engineers, 2M4D’s technical services and the local media, in particular during an initial 3-month stay with the host scientific and/or technological structures. The support to the project can be concretized by the attribution of a prize allowing the continuation of the work.

Call for proposals

In the current internationalization of science, it is possible to provide the widest possible information, beyond the hexagon. Support by the scientific advisers of the embassies could allow this externalization (to stabilize). Normally, the call concerns all citizens, but it is hoped to reach young people who are likely to be mobile and who are not yet too formatted by their educational and/or professional activities. Essentially, it is expected to use knowledge or devices in an original way to take up challenges that should be able to solve concrete problems from an economic activity focused on 2M4D.

Response to the call

As already mentioned, apart from the classical administrative aspects, the candidate will be asked to make a proposal for an original scientific challenge that excites them in one line (illustrative example: being able to read an (old) book without turning the pages corresponding to an achievement of the MIT in the USA; a disruptive proposal that has applications for the reading of very old documents). A few lines of explanation on how the candidate envisages achieving their objective. It is indeed originality in the 4D domain that is targeted with a framing by the candidate's knowledge of the real and the possible.

Initial assessment (E1)

A committee (C1) composed of representatives of 2M4D and independent scientists (to be defined) sorts through the applications received and, if necessary, directs the pre-reviewed applications to external experts. According to the answers, the candidates are informed via 2M4D of the committee's decision.

Interview with the candidate

On the basis of the selection (also taking into account the financial means envisaged by 2M4D), the candidates will be called for an interview with the C1 committee and experts designated by this committee. During the interview, this enlarged committee (C2) measures the candidate's willingness to show initiative (if possible leadership) to address an original issue. Based on this first phase, the committee may intervene to refine the project with the candidate.

Consecutive expertise

Applicants selected by the enlarged committee are asked to revise their proposal, taking into account the opinions and advice of the C2 committee. The file is examined for possible commitment (interest of the proposal and possibility of funding) and the results are communicated to the applicants. At the same time, C2 will propose to the selected candidates the possibility of a grant, the amount of which should not exceed €10,000, distributed as follows: €5,000 for the candidate (accommodation and travel expenses); €5,000 for the host laboratory (by host laboratory, we mean academic structures and industrial centers, with, in both cases, the need to clarify the industrial property aspects, which must be used in the event of success for an activity under the local control of 2M4D). In this context, C2 will seek, in consultation with 2M4D, to find host laboratories for a period of 3 months.

After the course

After the internship, the candidate will prepare a confidential report (taking into account the possible added value in terms of innovation, which must be at least partially owned by 2M4D), in consultation with their tutors, which will be sent to C1. The examination of the file will have to show the implementation of the ideas of the file validated by C2 and their positive impact in terms of potential valorization. This file should also showcase a measure of their ability to promote their ideas, of their competence (analysis of the aspects of inspiration, creativity, spirit of cooperation, risk taking, technological opportunism, etc.).

Toward a creativity award

2M4D and C2 will seek to set up a consortium with partners from the State, the EU and the business community to form the 2M4DF Foundation, which should be used to award a prize to the best candidates (and with appropriate information to the public).

Depending on the available funding, it could be envisaged to award research grants for a period of more than 3 months (up to 3 years), bearing in mind that the results are (at least in part) the property of 2M4D. If the recipient develops an activity in France, 2M4D could transfer its property rights within a framework to be defined. This operation could be carried out in an adapted festive framework with a large-scale public information (after Covid-19!).

> Indecision-making is reflected in a whole series of measures – in this case the re-launching of research and the postponement of the final decision – that allow the range of possibilities to be expanded […], it is a mode of exercising power. (Barthe 2006)

> By maintaining an upstream object-centered division of science, some finite and reactionary researchers maintain a comfortable illusion that they are not really being evaluated by their peers. (Lecointre 2005)

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