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Designing generic technologies in Energy Research: learning from two CEA technologies for double unknown management

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Abstract (174 words)

The aim of this paper is to shed light on an innovative strategy for the design of generic technologies (GTs). Research on radical innovation management, while recognizing the success of GTs, generally describes their design according to evolutionary strategies featuring multiple and uncertain trials, which would finally result in the discovery of common features between multiple applications. Building on a case study conducted on two technological development programs at the French Alternative Energies and Atomic Energy Commission (CEA), we exhibit an anomaly to this rarely discussed idea: we describe an alternative strategy that consists in intentionally *designing* common features that bridge the gap between *a priori heterogeneous applications and a priori heterogeneous technologies*. This anomaly brings three main results: 1) The usual *trial-and-learning* strategy is not necessarily the only strategy to design a GT; 2) beyond technological breakthrough, the value of GTs also relies on the capacity to reuse and connect existing technologies; 3) the design of GT might require sophisticated organizational patterns to be able to involve multiple technology suppliers and applications' providers.

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Introduction

In the energy sector, a *double unknown* characterizes innovative R&D projects, as they are simultaneously looking forward new markets (first unknown: the markets) and new technologies (second unknown: the technologies). The traditional risk management tends to consider that the chances of success are inversely proportional to the initial uncertainties, condemning these projects with high failure rates. Yet, the various unknowns may also be seen as many opportunities, leaving open the likelihood of success such as "General purpose technologies" also called generic technologies (GT) (Bresnahan and Trajtenberg 1995), *i.e.* one technological innovation that impacts or generate many markets and many technical variations. From a statistical point of view, a generic technology addresses *several* markets so that even if each market has a very low probability to appear, a generic technology has a very *high* probability of experiencing at least one market success! Hence GT might be a way to manage double unknown situations.

What do we know on the design of GT? As we show in this paper, very few studies tackled this question; nevertheless, the works on technological innovation lead to believe that GT can only unfold through complex random walks. Technologies would follow a kind of evolutionary path from one application to the others and along this path a GT emerges and succeeds over the less generic ones. This *trial-and-learning* process might result in being successful but is very likely to be risky and expensive. Hence GT are seen as the 'Holy Grail' of double unknown situations, but the quest would be just as risky and unmanageable. In this paper we show that the evolutionary path is not the only way to design a generic technology by exhibiting an anomaly, a counter-example, compared to the usual evolutionary strategies the literature describes.

The research strategy proposed in this paper is to formulate alternative management models, drawing on an original empirical material from a case study analysis of two technologies that the French Alternative Energies and Atomic Energy Commission (CEA) has developed since more than twenty-five years. The main result of the research is to empirically test the research assumption of a systematic evolutionary technical development and to highlight some interesting alternatives for risk management, different from the evolutionary approach. From the case-study learning, we thus propose alternative organizational patterns for the management of the design of generic technologies. This pattern can be described by contrast with the evolutionary model: 1) the "generic" features (that characterize the GT) are not the result of random exploration (they are neither given from the beginning) but they are intentionally designed in the process; 2) whereas GT is often praised for its technological breakthrough, its value also relies on the capacity to reuse and connect existing technologies; 3) whereas GT might appear as the mere result of lone entrepreneurs, we show that the design of GT might require sophisticated organizational patterns to be able to commit and involve multiple technology suppliers and applications' providers.

Such management models might support the development of generic technologies and appropriate action models for managers in charge of the assessment and the management of innovative R&D projects of energy research, leveraging on the interdependency of numerous potential markets opened by generic technologies.

Literature analysis on the design of generic technologies

1. Generic technologies definitions and their emergence in double unknown

a) On the notion of generic technology

Generic technologies (GTs) are often considered as technological platforms whose exploitation can "yield benefits for a wide range of sectors" (Keenan 2003). GTs are more likely to emerge in fast-paced dynamic environments (Miyazaki 1994, Maine and Garnsey 2006, Cantwell and Qui 2009): semiconductors, biotechnology, electricity, nanotechnology are domains which are a priori well positioned to take advantage of GTs, given their wide industrial application areas, technological diversity and rate of scientific breakthroughs (Bresnahan and Trajtenberg 1995, Moser and Nicholas 2004, Youtie, Iacopetta et al. 2008, Shea, Grinde et al. 2011).

Various benefits of GTs to new companies who develop and exploit such technologies have been noted, among them: the flexibility to extend the scope of initially considered market applications, including to markets of heterogeneous maturity levels and across various domains; to share risks and decrease R&D costs between several applications; and to help attract venture capital and large corporate investment (Shane 2004, Maine and Garnsey 2006). By exploring GTs, companies could design solutions suitable for several uses, and so increase company benefits, making the development and diffusion of GTs a key area of their strategy interests. Technological change provoked by GTs appears as an important mechanism that drives the economic growth (Rosenberg 1982). As shown by (Bresnahan and Trajtenberg 1995), beyond pervasive GPTs often lie generic functions or concepts. For example, the generic function of integrated circuit (IC) ("transistorized binary logic") was applied in many sectors. The way these functions are spread across the organizational structures and appropriated by application sectors determine the future success and value of GTs (Bresnahan and Trajtenberg 1995, Maine and Garnsey 2006). At the same time their breakthrough character limits the integration of these technologies within emerging objects, poses high barriers for their commercialization Moreover, the widespread adoption of a core technology occurs thanks to the actors that are capable to coordinate their beliefs across the generic technology (Youtie, Iacopetta et al. 2008).

The literature on generic technologies mostly deals with the GTs that already exist, and prior research has mostly focused on their dissemination and commercialization, providing extensive analyses of GTs from an *ex post* perspective, *i.e.* once the technology has been shown to be generic, commercialized and its value been acknowledged. For instance, David (1990) indicates that the dissemination of electricity was driven by the invention of the dynamo, which promoted the development of light bulbs, electric motors, further innovations in plant and urban design. Thoma (2009) made first attempt to study the features of GTs from an *ex ante* perspective. The author investigate the evolutionary changes in control industry and demonstrates the GT diffusion was driven not by applying directly breakthrough feature of GTs but by a unique recombination of the existing capabilities. They stress the importance of various institutional mechanisms to coordinate the emergence of GTs and demonstrate the technological diffusion occurred thanks to its standardization, interoperability and universality, which correspond to the modularization principles of technological platforms (Baldwin and Clark 2006).

Overall, it is clear that 1) GTs emerge through the generic patterns that are diffused across different sectors. Yet, the principles of these generic features identification is little (if not at all) investigated across the literature on history and economics of GPTs. 2) The principles of GTs' diffusion across the existing and emerging markets are generally investigated through technological platform and evolutionary perspective. 3) The institutional mechanisms, actors involved and their coordination are important for the future success of GTs. In the following, in order to shed some light on the organizational patterns of GT design in double unknown, we propose two examine these three aspects.

b) The organizational patterns to account for generic technologies design

The theory of technological platform provides the insights on firstly how to build value by growing the ecosystem of platform users, secondly how to profit from platform to provide complementary innovations built on platform cores and orchestrate the ecosystem of players by taking a function of platform leader (Schilling 2002, Baldwin and Clark 2006, Gawer 2009). Still little is known on how to design a platform. For instance, some authors provide indicators on when a platform should be changed (Meyer 1997, Meyer and Lehnerd 1997). Two different ways have been analysed so far. The first case is when there exist several applications addressed by different technologies, platform design consists in identifying commonalizing technical elements between these multiple known applications (Farrel and Simpson 2003). But in double unknown situations the applications and the technologies to address them are not known *ex ante*. In the second case, technologies are still unknown but several applications are defined gives an opportunity to define functional requirements that are common to each applications. These functional requirements in turn lead to define the design of platform as a technology that addresses these common functional requirements. But here again in double unknown situations, not even the applications are known from the beginning.

At this point the reader might wonder whether such a situation might really occur – this is precisely the interest of the recent works on technological platforms (Gawer 2009) to show that the latter are not necessarily based on pre-identified applications but lead to design new ones. Hence how does one identify *ex ante* the common core of a platform when potential applications and related technologies are unknown? The managerial logic behind platform design in double unknown is missing.

GTs are used and explained as a mechanism that ensures economic growth where growth proves insights on the long-term potential trajectory of GTs development (Bresnahan and Trajtenberg 1995). Yet the commercialization and diffusion of GTs attracted innovative scholars who focused on the investigation of the technological nature and its effect on productive dynamics and innovative activities (similar for instance to the technological paradigm shifts (Dosi 1988), or that of radical technologies). This offers a new perspective to deal with GTs that often refers to evolutionary theory while investigating the dynamics of a particular innovation, which is concerned with the patterns that lead to a successful diffusion of particular technology and product; or even broader transition processes that might transform sector structures (Malerba 2002, Markard and Truffer 2008). Evolutionary economic theory of socio-technical change was extensively developed by Freeman and Soete (1997), Nelson (1993) and many others, and often considers a technological innovation as a technology and market matching process (Freeman and Perez 1986). The importance of networks, learning processes, interdependencies and the role of institutions for successful innovation process had been highlighted (Burgelman 2009). Following Schumpeter's (1939) logic of growth, the evolutionary perspective establishes similarities between GTs and the emergence of dominant design, it sees the evolution of GTs as an evolving process in time that shape the configuration that the economic landscape is undertaking.

These evolutionary models help to account for situations where optimal choice is not possible due to the lack of knowledge. In the particular case of innovation, it has long been shown that new product development (NPD) (*e.g.* Koen et al, 2001) processes could not follow the well-planned, stage-gate, linear processes. NPD processes had to adapt to changing market conditions and technological uncertainties by integrating more evolutionary logic in *flexible product development* and *fuzzy front end* (Eisenhardt and Tabrizi 1995, Iansiti and MacCormack 1997, Koen, Ajamian et al. 2001, Reid and De Brentani 2004); and the rapid assimilation of knowledge and new ideas, in *open innovation* approach (West and Gallagher 2006, Chesbrough, Vanhaverbeke et al. 2008). These studies most often consider disruptive innovation as an evolutionary process that requires making multiple consequent or parallel trials while reducing costs and incorporating learning. For instance, Cheng and Van de Ven (1996) have pointed out that learning in yet unknown conditions can be viewed as an expanding and divergent process of discovery which differs from more narrowing and converging process of experimentation once the uncertainties are reduced. Thus, the creation of technological strategy would be determined by the evolution of technical capabilities, by firm's industrial and organizational context. Consistently with this assumption, variety of strategies is shaped to deal with uncertainty while pursuing technological innovation, such as (McGrath and MacMillan 1995, Van de Ven, Polley et al. 1999, Loch, Solt et al. 2008, Sommer, Loch et al. 2009). One of the most advanced strategies to explore new technologies and markets when uncertainty is high is *trial-and-learning* or "probe and learn" (Lynn, Morone et al. 1996, Danneels 2002, Loch, Solt et al. 2008). *Trial-and-learning* strategy takes advantages of learning through selection of the particular development trajectory. It consists in iterative trying of selected trials and flexible changes in the course of action. This strategy attempts to maximize probability of trial existence and minimize unknowns through the process of sequential learning.

When it comes to the design of generic technologies, we are then led to consider that it should follow an evolutionary process: a technological kernel is developed in order to address a most promising market trial and then it is progressively reused in multiple applications, which in turn lead to improve the technology. Step by step the *trial-and-learning* process results in a technology that is more and more generic. Still it is important to stress that primarily objective of the evolutionary perspective is not to explain the ways of technology design, its arrival but the way it shapes the value creation across different industries and ensures growth.

Interestingly enough, the evolutionary perspective also lead to emphasize specific organizational patterns:

1) The 'generic' features (that characterize the GT) are the result of random exploration;

2) GT appears as a technological breakthrough, specific and different from all competitors;

3) Just like any "innovation journey" (Van de Ven, Polley et al. 1999) the design of GT relies on networks of actors and determined entrepreneurs.

2. Limits of evolutionary perspective of technological innovation in case of generic technologies design

When trial and learning strategy considers reuse of the acquainted learning to develop other market alternatives, the success highly depends on the results of the trial. Still the probing step that consists of introducing a product to a "plausible initial market" is less important than the learning and subsequent steps which take place later (Lynn, Morone et al. 1996). This process can result in a too narrow exploration area when new markets and technological opportunities are not presumed within a first trial exploration. Moreover, this strategy implicitly proposes to build a platform based on the interdependencies created during trial exploration, but do not develop organizational patterns to make it happen. In this perspective, generic technology development can be build upon a sequence of trials and their reuse, where the latest is often selected from the known list of alternatives (Miyazaki 1994).

This sequential process corresponds to the evolutionary mechanism where GT appears as an emerging design that is consequently applied to address several emerging markets. The efficiency of this process highly depends on the choice of the first applications (market trial). It is assumed that strategies like *trial-and-learning*, enable unknown exploration and lead to generic technologies development through the consequent process of selection and mutation of trials. For instance, in the *trial-and-learning* strategy, the trial might result in platform design, which does not address only the trial application but can be generalized for other contexts. This offers some kind of evolutionary path for GT design. Yet as shown in (Kokshagina 2012) there are cases when the sequence of chosen market trials does not correspond to the markets that finally win due to the high volatility in uncertainty and the development results in a rigid platform core. The exploration presumes knowledge and existing marketing and technological competence to build a trial (Sarasvathy and Dew 2005). This process can result in a too narrow exploration area when new markets and technological opportunities are not presumed within a first trial exploration. In this perspective the reuse of the acquired learning is limited and therefore genericity design is not possible. Is it the only way to obtain generic technologies?

This work aims to demonstrate that there is a more intentional way of designing generic technology that can result in developing even more "generic" solutions. Design of GTs in double unknown might add a new action possibility for technological breakthrough and major innovation management. The idea behind is not to deal with probable states in order to *reduce uncertainties* (like evolutionary perspective where learning reduce uncertainty) but to *design a new probabilistic space*, where the *interdependences* between the uncertain states actually increase the chance of success. Organizational patterns of genericity design would offer an action possibility that structure unknown and design generic technologies. Is it possible to define the patterns for GTs design that offer better performance than evolutionary logic? To account for GT design in double unknown, multiple technological and market interdependencies should be designed. Therefore the strategies that are able to deploy the reasoning towards genericity have to deal with markets, technologies exploration and *intentional creation of the interdependencies between them*.

Interestingly enough, if there is such a strategy, then it might not meet the features identified above. We will precisely exhibit an alternative strategy for the design of GT in double unknown that lead to discuss the previously mentioned features:

1) The "generic" features (that characterize the GT) are not the result of random exploration but they are intentionally designed in the process;

2) Whereas GT is often praised for its technological breakthrough, its value also relies on the capacity to reuse and connect existing technologies;

3) Whereas GT might appear as the mere result of lone entrepreneurs, we show that the design of GT might require sophisticated organizational patterns to be able to commit and involve multiple technology suppliers and applications' providers.

Methodology and research settings

The research relies on a case-study analysis (Eisenhardt 1989, Yin 2009) of two technologies developed by the French Alternative Energies and Atomic Energy Commission (CEA). The case study method corresponds more precisely here to a logic of anomaly (Siggelkow 2007). These empirical data have been investigated through two main methods: analysis of the patents filed by experts from the CEA and semi-directive interviews with the main stakeholders, the CEA's researchers and industrial partners, on the contexts of invention, development and dissemination of both technologies.

1. Validity of the case-study context: Energy as double unknown context

In the energy sector, technological breakthrough R&D projects are facing high and various uncertainties. Firstly, the energy transition requires the exploration of radically new types of markets and uses. Neither societal analysis nor public policies allow framing these new uses, these new markets and related functionality. The first one highlights today rather the variety of emerging applications (*e.g.* the impacts of sustainable development expectations on European Energy funded programs), the lack of structured and segmented markets, the difficulty to predict volumes and prices of energy at any term. Public institutions that are traditionally able to select norms and standards in terms of the public interest, are faced with a proliferation of proposals on fashion trends or rather lack of them in some critical areas, while steering models appear sometimes inadequate to decide the best assessment criteria (safety, cost expenditure, potential of success). Secondly, relevant technological paths are also highly uncertain: scientific and technologic researches make possible the exploration of technological breakthrough concepts (new materials, new possibilities opened up by the semiconductor, new systemic management models for energy, new industrial processes managing differently energy resources, *etc.*). Issues of lifespan and amount of investment traditionally associated with energy sector, do not allow anymore excluding some tracks that would have seemed very unlikely still little time ago. The emulation and inventiveness on new technologies does not provide for much great tenacity and great continuity in the exploration and design strategies that extend over several years (learning, exploration, establishment of businesses, industries, networks and competent techno-economic ecosystems, etc.). Consequently, technological breakthrough R&D projects of the energy sector are facing both market and technological unknowns and appear as relevant industrial context to study the risk management in double unknown.

2. Selection and relevancy of two technical programs: sealing systems and supercritical fluids

To select relevant technologies for our research, we started by focusing on innovative projects of the CEA with successful patents portfolios, i.e. technical developments having led to a patent that subsequently (and possibly due to other technical developments) resulted in the payment of royalties. This method has several advantages: 1/ bringing innovative technologies well ahead of markets, it identifies with a fairly high probability cases of innovation with "double unknown" in the sector of energy; 2/ the amount of royalties may constitute an objective criterion, although rude, of the success of project; 3/ patent analysis allows the identification of several key information for the analysis: some elements of engineering principles critical to the technical proposal, some of the key actors (the authors of the patent to begin investigations) and alternative concepts that were known in the drafting of the patent (section 'state of the art' of the patent).

Our partners from the CEA screened their patent database in the field of energy to identify those who had the most significant financial impact during the last fifty years, both in amount and duration of royalties' payments. The final choice of selected patents and related programs has been achieved in identifying in such screening those with the greatest potential contribution to conduct the research program (number of patents, duration of technological development, accessibility of the main stakeholders involved in the technical development). Two technical programs have been elected:

- *The program on sealing systems*: this program started in 1969, is developed from the early outset through collaboration between the CEA and an industrial firm, Technetics (formerly Cefilac then Garlock). The initial objective of the program was to develop and to design joints and technical systems for static and dynamic sealing, mainly composed of metal, graphite or ceramic systems for the gaseous diffusion process used to produce enriched uranium. Major patents were filed as FR2823824 (Caplain, Mirabel et al. 2001) and FR2823825 (Rouaud and Caplain 2001). Initially engaged in developments for high-temperature range, the program was gradually extended to larger temperatures, especially the low temperatures. Those applications of sealing technologies have been made in other areas such as space propulsion circuits for cryogenic Vulcain engine of Ariane 5, or the oil industry.

- *The program on supercritical fluids:* This program was initiated at the beginning of the 90's. It was originally a purely nuclear purpose, to separate (supercritical CO_2) or transform (supercritical H_2O) nuclear waste. From the R&D programs made to meet this need in the nuclear sector, more than a dozen of patents have been filed. Shortly after the beginning of the program, opportunities for applications in other areas than nuclear have been identified by the CEA's researchers. For example, one of them concerns such application as reducing the "cork taint", a distasteful flavor left by some corks in the wine. From the filing of an initial patent, FR2798879 (Lumia, Perre et al. 1999), then extended to all wine-producing countries, collaboration between CEA and industrial partners was reached. Several plants implementing the process started or are under construction. This program also gives rise to development of research facilities such as Extralians platform in Nyons for supercritical CO_2 extraction of high-value substances from herbal substrate for perfumery, cosmetics or nutraceutics. New applications continue to grow as one of the supercritical CO_2 extraction of compounds contained in micro-algae "*Dunaliella salina*" to fully develop the biomass produced (Project Salinalgue). A major advantage of this program is that beyond the unquestionable success of some applications, some applications to other domains were failures, which in some cases have helped to create success elsewhere.

For all this characteristics, these two programs were therefore considered as relevant to: (a) assess the generic nature of the technology, (b) explore how genericity was built, *i.e.* in practice, work on the structures of independence initial, final structures and the changes that stakeholders have experienced, and (c) the potential both programs presented of containing risk management strategies leading to such development.

3. Descriptors investigated in interviews

To determine if the technologies emerged in double unknown context, the guide for semi-directive interviews has been built from the analytical framework issuing of literature on GTs to investigated several descriptors:

- *Analysis of the initial structures of independence:* What were the targeted markets, the available technologies and what were the relations between these elements? We searched first for classical descriptors (cost, price, volume, probability, ...) and we completed these data by the analysis of interdependencies between technology and markets. We also seek to identify the "unknown", *i.e.* markets with volumes and prices highly uncertain, but for which the actors still had knowledge such as functions and uses that could be associated with the technology. We sought to investigate these markets from functional algebras emerging from the interviews with the actors. Similarly interdependencies between technical building blocks could be modeled as graphs. Indeed, this type of descriptor consists to model the interactions between technical bricks as Wang algebras (Wang 2006). Some of the authors have already mobilized them, in particular for the modeling of the design approaches involved in the design of experiments in R&D programs (logical interdependencies between variables plan experience) (Kazakçi, Hatchuel et al. 2010) or for initial analyzes of generic technologies success in semiconductors (Kokshagina, Le Masson et al. 2012).

- *Analysis of changes in the independence structures:* how did a generic technology (if any) emerge? What were the alternatives? What reassembling of independence structures did it induce? On this point, we looked for identifying potential reconfigurations through a design approach that supports us to distinguish projects characterized by an increase in genericity from projects relying on reduced uncertainty about alternatives initially identified. Recent studies have validated this method for the analysis of strategies dedicated to increase the number of generic technologies in the semiconductor (Kokshagina, Gillier et al. 2013).

- *Analysis of organizations and processes that made possible these changes:* is it possible to identify strategies that looked for increasing the genericity of the technology? Can the stakeholders think that these successes are the result of chance or providential hero, or can they highlight structural factors or specific routines (methods, processes, *etc.*) that had supported these successes? This type of analysis was conducted on risk management processes in companies that manage large portfolios of advanced R&D: it was used to study all facets of organizations for risk management (skills, type performance, organizational structure associated evaluation process and management, etc.) (Kokshagina, Le Masson et al. 2012).

4. Data collection

Both technical programs have been investigated through the same data collection process. First, CEA's Industrial Property valorization unit provided us the list of patents from their database filed by each technical program. Then, the corpus of patents have been consolidated by authors from the database of the European Patent Office, looking for other patent deposits by leading authors and the corresponding cross citations. This data collection process led us to a base of, respectively, 40 patents for sealing systems program and 47 patents for supercritical fluids program. Both portfolios have been studied following in-depth screening of the contents and analyzing the strategy of patent deposits through the area and the evolution of codes of International Patent Classification covered by the portfolio.

Then, a few interviews have been conducted with main stakeholders of the technical developments from CEA and industrial partners, looking for the descriptors presented above. In detail, authors met 2 researchers and one industrial partner who is in charge of the technology development for Technetics since more than 15 years, and 3 researchers of the supercritical fluid program, including two experts involved in the program since respectively 1991 and 1999.

Finally, analysis has been triangulated (Flick 2004) through the scientific publications of each CEA research teams and internal archives and specialized press communications provided by CEA and interviewees. In particular, one of the main inventors of sealing systems had written a rich and detailed note (Rouaud 1997), to the internal use of the CEA research department, on the history of the technical development before his retirement. Edited in 1997, this document has been very helpful to understand in depth the emergence of the helical technology of joint, and the search for applications that had been led by the research team.

Case study analysis

1. Revealing genericity of the technical programs and the adopted patenting strategy

a. Two technical programs of generic technologies

Both studied programs feature an interesting design history of coping with double unknown, that is, unforeseeable clear markets and ever-changing technological settings. Since our analysis is carried out *ex post* on programs started more that 25 years ago, the results of the strategies implemented for these projects are well-known today and it is possible to say in both cases that a high degree of genericity was attained. Indeed, although, as highlighted before, these technical programs were chosen amongst the most profitable technologies to have been developed in their division of the CEA, the analysis of initial targeted markets shows that in both cases, their success is due to the emergence in the course of the programs of a wide variety of partly unforeseen and mostly low-signal markets. Most notably, the most profitable exploitations of these technologies today are not the ones these technologies were designed for, and are not even in the same industrial sector, which is evidence of their generic character. For example, whereas the CEA launched these two programs to advance knowledge and technology on nuclear processes and their derivatives, some relevant markets for the technologies we studied were space or car racing industries for the first one, and agribusiness, pharmaceuticals, or fossil fuel processes for the second one.

b. *Different strategies for patenting a generic technology*

Although in both cases, the technologies that were developed can be deemed as generic, the two projects shown very different strategies in terms of patenting. In both cases, the technical programs gave birth to respectively 40 and 47 patents (as of 2013). In the case of the sealing systems program, all patents were filed in the same class of the international patent classification (IPC), the F16J 15/08 that gathered technologies of sealing with exclusively metal packing (WIPO 2010) and patents only described the technical aspect of the innovations. Not surprisingly, the terms used to describe these innovations are the standard terms found in the same patent classification. But compared to existing systems, the first major patent claimed to address an unprecedented technical performance, thus attaining levels of potential exploitation that were completely new in the field. Successive patents show improvements and variations on the initial concept, with subsequent notable additional gains on performance, and thus opening further new fields of application.

On the contrary, the patents filed during the second program (Supercritical fluids) were from the beginning registered in a high variety of IPC classes, as for example, C14C 3/00 of chemical composition of tanning of skins, hides or leather, B27K 7/00 of chemical or physical treatment of cork, and C10G 31/09 of cracking hydrocarbon oils by filtration (the growth of the number of classes is shown hereafter on fig. 1). In this program, however, patents specified not only the technical aspects of the inventions but also the process of exploitation, and thus the corresponding applications. Accordingly, a single patent reveals limited genericity and it is only at the patent portfolio level that the technical program reveals important genericity. Thus, genericity seems to have been progressively acquired, which can be proven by the large variety of industrial sectors in which these patents have today applications. It is to be noted though that on two occasions, respectively 1997 and 2007, radically new sets of IPC classes of patents were explored, showing that the initial technological base lead to new technological developments, hence highlighting the initial uncertainty also associated with the technologies.

[Insert Figure 1.]

Fig 1: Growth of ICP classes investigated by the program supercritical fluids since 1985

As a result, our analysis of the patents over this long period of time confirms the generic character of the programs we have studied. In both cases, such an analysis can prove that a high number of applications can stem from the patented technologies, either as an unprecedented performance affecting a high variety of systems built on a given class in sealing system program or thanks to a consequence of the variety of IPC classes concerned by the patents in supercritical fluids program. To go further, these differences in the patenting strategies might be clues indicating that different technical development management processes were pursued to reach genericity. However, the patent analysis reveals to be an insufficient method to identify the nature of this management and the organizational patterns that support it. To be able to describe these processes, we have thus further analyzed the changes of independence structures of markets and technologies during the course of the programs with stakeholders' interviews and scientific publications, and archive material analysis.

2. Organizational patterns to deliberately design generic technologies

a. Initial independence structures and foreseen genericity

In both projects, the designers looked for and suspected a potential for a large variety of industrial applications from the beginning, which could now be identified as an intentional strategy to build genericity.

In the sealing systems program, the historical documents show that the team designing the first patented systems was aware of the breadth of applications that their technological developments could address, even though their original specification sheet was drawn from a very specific nuclear-oriented application. In this project, designers' team seemed facing a typical problem-solving situation: a new enrichment plant needed for seals with a need for unprecedented performance on functional requirements: dimensions that exceeded a few meters of diameter and a very high temperature of use. These functional requirements challenged drastically the already known designs of sealing, but we could have expected that the existence of a reliable target market had urged the researchers to look for a specific design to that plant: relying on this specific, foreseeable and well-described functional requirements, the design resulting from traditional problem-solving approaches would have been very unlikely to address a whole class of unforeseen other markets beyond enrichment plants. Instead, archives highlighted that designers deliberately looked for a design that would benefit from the variety of knowledge on existing systems and markets of sealing systems, by introducing independence between two critical functions of a traditional seal: plasticity and elasticity. With this original design strategy, the new family of sealing systems was not only capable of addressing the whole variety of applications in which a traditional seal was used, although with performances much beyond those of known systems, but also to address new domains of constraints. The design of features that seemed to be common to a variety of potential applications would later enable extensions to space or automotive racing systems. Genericity is thus confirmed as an intentional objective pursued by the first design team.

At the beginning of supercritical fluids program at CEA, a variety of already existing markets positioned in the technical domain offered rather strong evidence that the physical phenomenon could be used for numerous applications. Thus, as demonstrated in Sarrade, Rios et al. (1998), the CEA researchers involved in the program stated that "the hybrid integrated process coupling supercritical extraction and nanofiltration would reach a high level of separation for current applications in various fields: waste treatment to remove strong pollutants, effluent clarification; food processing in sugar, dairy applications; biotechnology applications for purification of reaction products; cosmetic and pharmaceutical industries for separation of high value compounds, etc." Scientific concepts such as (temperature; pressure) couple and solubility already existed to describe duty points that are specific to several industrial applications. Yet, it was not acquired that a common technological core could exploit this physicochemical phenomenon with a performance high enough to challenge interestingly other ways of achieving the same results (mainly to separate two chemical substances within one body). Furthermore, the matching between targeted applications and appropriate duty points of supercritical fluids was not made. To investigate these two key points, the CEA therefore made the decision to adopt an experimental strategy of technical development, that did not presuppose of specific industrial applications, to explore simultaneously the technological options for controlling these fluids, as well as potential interesting industrial uses. Here again, we can see an intentional strategy of researching common features to potential applications instead of developing random specific trials.

b. Evolution of independence structures and extension of targeted markets

To further the analysis of these strategies of genericity building, we tracked the evolution of independence structures as presented in method section to understand how genericity can be sustained and enhanced over time. Because the potential genericity of the innovative sealing systems was acquired from the beginning by a powerful design, the further development of the project implied to rebuild progressively the design rules to quickly address a wide variety of applications, markets and interested customers, while reusing existing technologies in the field. Abacus and software were created to quickly find appropriate design (mainly along dimensioning parameters) for several applications. Yet, the main industrial partner of the program, Technetics, involved its techno-commercial representatives in a particular effort on attracting customers that required extending the frontiers of the known abacus. Indeed, although numerous fields of application were already attainable thanks to the first innovative design, research teams strived to develop successive improvements to address whole new directions of performance, sometimes even adding new dimensions to the design such as rotational movement, radial forces *etc*., or exploring extremely small or large dimensions of sealing.

Concerning supercritical fluids, further research to better understand the physical phenomenon led to create a new set of scientific concepts, notably replacing the chemical notion of solubility by the 'entrainment' concept to illustrate the increase of solubility performance with specific pressure systems, and the introduction of new representations of thermodynamic areas of supercritical fluids efficiency (Sarrade, Rios et al. 1994, Sarrade, Rios et al. 1996, Sarrade, Guizard et al. 2002). These new concepts enabled the CEA's researchers to describe the technological duty points very differently, and consequently they started addressing completely new ways of using the same fluids: they investigated application of supercritical fluids beyond the separation function, for example in creating and shaping new kinds of material with novel properties. Remarkably, it was these major evolutions in scientific description of the processes that lead to the substantial growth of filing of patents in radically new fields in 1997 and 2007; and scientific publication of the CEA's research team on new potential applications (Sarrade, Guizard et al. 2003, Guizard, Julbe et al. 2005). Finally, the acquired genericity made it possible to attract various potential "customers" in very diversified fields. One of them was precisely the cork-making firm that started to develop their own test facilities in partnership with the CEA, which lead to the development of a very profitable application in removing the cork taint in wines. Accordingly to the definition of generic technologies, this market was hardly foreseeable at the beginning of the project, but the acquired genericity enabled a quick understanding that such potential market fell within the domain of applicability of the technology.

This latter application also illustrates the logic of technology reuse in the genericity building strategy. Indeed, the aim of the CEA was to build a common technological core that would be able to address multiple markets while enabling the construction of links with existing technologies already used for these markets. For example, the technologies to make aggregated corks from mashed raw material were already known, as well as the chemical compounds responsible for the cork taint in wine. The originality of the strategy is thus to design a technological core that links these existing pieces of knowledge: methods of 'entrainment' of supercritical fluids with selected additives, decoupling targeted extraction properties from the actual circulation system of the fluids, independence in the installation size to fit with a particular market's needs, *etc*.

c. Organizational patterns that sustain genericity design

Original organizational patterns, mainly partnership structures, appeared central in both programs to the development of genericity building strategies. Indeed, the creation of both research programs at the CEA was quickly related to "technological diffusion programs", whose aim was precisely to benefit from the technologies initially developed with a specific nuclear application in mind, in a growing number of technical contexts, industrial applications, and research projects across the institution. This objective was a strong incentive to the funding of facilities dedicated to the exploration of genericity in both projects, and to the attraction of relevant partnerships with varied industrial sectors.

In particular, the implication of experts from both commercial and technical skills was used to bring technically interesting cases upfront, that is, application cases at the frontier of the known abacus for sealing systems, or that were still unresolved in supercritical fluids program. That way, both teams ensured that the industrial partnerships themselves, in addition to bringing financial support, were designed to support the quest for genericity. For the sealing systems project, this was carried out thanks to the creation of a joint research laboratory between the CEA and Cefilac (now Technetics), thus dividing the genericity building strategy into fundamental research advance on the best scientific concepts at the CEA, exploration of potentially interesting application fields at Cefilac, and attractiveness of the most challenging customers thanks to this collaboration. In the case of the supercritical fluids, this was first achieved through the participation of numerous potential partners in a lab-scale resource for original applications to food processing industry, then in the pilot-scale plant, including for instance an oil industry firm, a renowned French national library, or a pharmaceutical laboratory. Today, a new non-profit association, with an original governance system promoting equal participation from both big players and new single entrants in the field, has been created to promote the collaboration between industry, academy and any interested actor around the potential of these fluids that may still need to be further explored.

Findings

As highlighted above, literature traditionally analyses technological breakthrough processes from an evolutionary point of view. Radical innovation would then be the result of a progressive and selective integration of former knowledge and experiences of designers. This learning would occur thanks to multiple and uncertain trials, aiming at progressively reduce uncertainty by randomly discovering common features to numerous applications. Strategies such as *trial* and *learning* correspond to this kind of uncertainty reducing strategies. Yet, we have already demonstrated the limits of such approaches in the case of generic technologies. For instance, as Gambardella and McGahan (2010) suggest, businesses problems can arise from the lack of techniques for effectively designing and putting GTs to use, which can require both overcoming existing technological lock-ins and simultaneously investigating new uses. Subsequent challenges include how to transform an emerging technology into a future GT, and how to organize a development process that can broaden the technology's genericity.

Our comparative case study in fact reveals an anomaly that shows that evolutionary approach does not appropriately describe all cases of radical innovation development processes. It shows that evolutionary strategies neglect the possibility to intentionally investigate both uncertain technologies and markets all through the design process.

On the whole, instead of a strategy aiming at reducing uncertainty, the uncovered alternative strategy consists in building interdependencies between what we already know about multiple potential markets and technologies. It aims at freeing from the orientation of the partly random result of a first trial, whose unpredictability is due to the uncertainty surrounding both technologies and markets, by designing technological cores that are able to benefit from the current and potential future knowledge to be acquired on both markets and technologies. Thus, the case study presented here demonstrates that a deliberate genericity building strategy is an interesting alternative for the management of breakthrough technical development, which in fact benefit from both technology and market uncertainties. Based on the uncovering of this new possible strategy, the results of our case study are threefold.

First, compared to the evolutionary approach in which the first trials either rely on or aim at specifying markets or technologies that are for the most part presupposed (that is, market pull or techno push strategies), this alternative genericity building strategy relies on the specific context of double unknown, i.e. simultaneous multiplicity of potential markets and technologies but each highly uncertain. In the first case, disrupting innovation is often thought to result from a technological breakthrough that emerges first, and then leads to identify previously unknown common features of a high variety of applications, thus transforming and recomposing the entire ecosystem of actors and markets.

In the second case conversely, the strategy aims first at investigating the potential common features that may connect different previously unrelated markets and technologies. In this way, the technological development is oriented towards the design of common cores that rely on both the variety of possible markets and potential technologies. This common core can therefore not be the result of a particular trial or single application-oriented development, but rather of an exploration aiming at gathering all existing related knowledge.

This leads to the second result. Consequently, the performance of this common technological core to lead to a generic technology is built on its capacity to reuse and link knowledge acquired through all resources that the designers succeeded to involve in the R&D program, whether from technological potential partners or potential market players. This core must then be designed to be able to connect the maximum of previously unrelated knowledge about potential markets and technologies, thus creating the interdependency structures we identified earlier. This first excludes the dominance or the precedency of one of the dimension (technology or market) on the other. But it also logically leads to the identification of possible future links, using the common core as a platform that preserves at any time the possibility to address a multiplicity of markets, each requiring a less costly development to be connected and in turn reused for further genericity. In doing so, the strategy involves designers in such a way that they always integrate the maximum of former knowledge in each new development. This latter point makes this intentional design of common core diverge from trial-and-learning strategies, which are more sequential, and generally induce either a lower re-use of the learning from first trials that may have been too specific or even have failed, or at a much greater cost because of their specificity.

Third, the case study shows that the management of the design of generic technologies according to this strategy requires varied and sophisticated organizational patterns. Designers, in our case-study CEA researchers, must indeed develop specific capabilities to gather a triple interdependent mechanism of learning. 1) They must be able to lead scientific and technological developments, first towards a core that takes abounding peripheral knowledge into account, then towards specific developments built on the common core. 2) They need to challenge the genericity of these development through particular prototypes that embed the twofold goal to support the learning and catch new potential applications, meaning attracting new potential partners. 3) They have to manage the emergence of an industrial ecosystem that gathers the effective stakeholders to both deploy already identified specific applications and contribute to explore the frontiers of the known application field.

This late point is supported by the specificity of generic technologies, as their exploration is no longer grounded on a single root technology, but rather involves creating and managing technological interdependencies, so that the initial generic technology gives birth to a richer technological platform (Tierney, Hermina et al. 2013). Moreover, in this process, the role of owners of shared organizational patterns becomes crucial in encouraging platform adaptation (Rochet and Tirole 2003) and flexibility, so that its application to another domain does not involve a complete and costly redesign. In our case study, organizational patterns that assumed this crucial role take different shapes. In the one hand, we observed integrated forms with the research lab in co-ownership between CEA and Technetics, and the pilot-scale plant created for supercritical fluids diffusions. In both structures, to support a wider diffusion of the generic technologies and thus greater market penetration, these organization patterns look for cost-effective adaptation, *i.e.* reach certain levels of efficiency so that they trigger further innovations (Youtie, Iacopetta et al. 2008). On the other hand, we also observed a fragmented organization in the supercritical fluids program, with the original initiative to create an association in charge of managing the genericity through simultaneous technical learning and ecosystem emulation.

Conclusion

Generic technologies (GTs) are widely recognized as successful cases of technological breakthroughs, especially in the domain of energy, but their design is under-investigated. Research on radical innovation management traditionally assumes that such successful breakthroughs are the result of evolutionary strategies, in which selective learning occurs through multiple and uncertain trials, which finally lead to identify common features between multiple applications. Building on a case study conducted on two technological development programs launched more than 25 years ago at the French Alternative Energies and Atomic Energy Commission (CEA), we demonstrate that this approach does not describe all cases of GT design, and that an alternative strategy is possible: the intentional design of a common technological core that bridge the gap between *a priori* heterogeneous applications and *a priori* heterogeneous technologies. This genericity building strategy precisely relies on the characteristics of the context of GT design, which is the simultaneous multiplicity of possible markets and technologies, also referred as double unknown contexts. By promoting research for technological cores that build interdependencies between previously unrelated potential low-signal markets and technologies, this strategy aims at reusing the maximum of already acquired knowledge to address multiple markets at a significantly reduced cost. This strategy thus substantially increases the chance of designing a successful GT. But it also requires varied and sophisticated organizational patterns to be able to benefit at the same time from prototyping outputs, quick design rules reconfiguration, and partners' integration, which continue bringing essential knowledge and also challenging demands that require building new links, thus advancing the genericity of the technical program. This paper thus offers new avenues for research in strategic management for the risk-controlled design of generic technologies in high uncertainty contexts, for which existing works fall short of applicable theory, and which they generally describe as unmanageable.

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Fig 1: Growth of ICP classes investigated by the program supercritical fluids since 1985