

Socio-technical transition processes: A real option based reasoning

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Abstract

Using a real option reasoning perspective we study the uncertainties and irreversibilities that impact the investment decisions of firms during the different phases of technological transitions. The analysis of transition dynamics *via* real options reasoning allows the provision of an alternative and more qualified explanation of investment decisions according to the sequentiality of pathways considered. In our framework, flexibility management through option investments concerns both the incumbent and the future technological regime. In the first case it refers to *ex-post flexibility* management and in the second case to *ex-ante flexibility* management.

Key words: Real option reasoning, technological transition, flexibility management

1. Introduction

Several contributions dealing with the evolution and development of large technical systems (LTS) (Hughes, 1987; Davies, 1996; Walker, 2000; Markard & Truffer, 2006) have helped to better understand the emergence and transformation dynamics of complex technological systems characterized by heavy infrastructures and capital intensive investments and organized around a variety of actors and institutions. An important contribution of the LTS literature has been to insist on the multiplicity and the composition of factors (political, technological, social, economic, scientific, etc.) contributing with a similar and parallel force to the development of technical systems and to phenomena such as technological trajectories, path-dependency or “lock-in” and also to the emergence and adoption of radical innovations.

In a similar vein, by insisting on the co-evolutionary dynamics of system innovations, the socio-technical transition approach (Geels, 2002; Smith *et al.*, 2005; Geels & Schot, 2007) has focused on the way some societal functions such as transport, communication and energy supply are structured around systems of complementary elements including technology, infrastructure, retail and distribution networks, regulation, user practices, markets and culture. The socio-technical transition approach considers transition processes from the multi-level perspective where system innovations come about through the interplay between dynamics at three different levels: (1) technological niches; (2) socio-technical regimes; and (3) the socio-technical landscape. Stress is put upon the idea that system innovations and transition processes evolve through the interactions between the dynamics that characterize each level. The multi-level perspective thus underlines different transition pathways, each possessing its proper logic and corresponding to specific interactions among these three levels. Transition dynamics are in this way not the consequence of a single driver but result from ongoing processes at different levels simultaneously whose interactions can either accelerate system innovations or slow down their deployment.

Our contribution both builds upon and departs from the literature on socio-technical transition processes. It builds upon the socio-technical transition approach in that it is based on the different stylized pathways that characterize the transition process (reproduction, transformation, de-realignment, deployment paths). We adopt however areal options reasoning approach in order to better account for the uncertainties and irreversibilities

(characterizing both incumbent and future technical systems) that impact the investment decisions of firms during the different transition phases.

By taking explicitly into account the role of uncertainty in investment decisions, real option models insist on the importance of flexibility in adjusting decisions as uncertainty resolves and give an alternative vision of transition dynamics through a more qualified explanation of firms' investment decisions. In fact, uncertainties and irreversibilities are not confined to specific pathways; rather their nature and form change when one goes through distinct pathways. We thus explicit more precisely the impact these changes might have on investment modes by analyzing the appropriate options at each phase. From the real options perspective investment behavior along the transition process can be expressed as a dynamic portfolio of parallel (within the same path) and sequential (representing the transition process) options through which firms manage the sequence and temporality of their decisions in a proactive way. During this sequence, the transition pathways, the options selected and those exercised reflect the will of actors to balance strategically between on the one hand holding a certain degree and form of flexibility necessary to preserve their adaptive capacity and on the other hand cultivating progressively irreversibilities contingent on their positioning and their individual trajectories in order to orient future systems. As we intend to show, this tension between flexibility and irreversibility punctuating the transition process and explicitated through the dynamic composition of option portfolios structures investment strategies and regulates the possible evolutions of system innovations.

Section 2 presents our analytical framework integrating both the socio-technical transition approach and the real options reasoning. Section 3 uses this integrative framework to provide a detailed analysis of transition dynamics from the real options perspective. Section 4 concludes.

2. Integrating technology transition dynamics and real options

This section provides a brief survey on real option reasoning. It then presents an analytical framework integrating technology transition dynamics and real options.

2.1. Real option reasoning

The real options approach (Dixit & Pindyck, 1994; Trigeorgis, 1996) constitutes a fruitful framework to better understand investment decisions in the presence of uncertainty. Contrasting with traditional investment rules based on the net present value (NPV), this perspective takes into account the capability of managers to react flexibly to environmental changes and stresses the impact of varying uncertainty levels and sources between different project phases in explaining investment decisions. When investments are at least partially irreversible, NPV does not in fact consider the benefits of sequentially organizing decisions in the presence of uncertainty in order to better integrate into the decision process information and knowledge revealed and accumulated through time. In this sense the real options lens provides a methodology to assess the benefits associated to the opportunities created and generated by flexibility.

Several types of options have been highlighted in the literature, including i.e. the options to wait, to stage, to expand, to abandon, to switch and to grow. According to the financial terminology, most options can be grouped either under the category of *call options* or *put options*. Investments in call options may concern R&D activities, establishing joint ventures, or positioning within new markets. Whereas put options may concern the flexibility to contract the production scale or the possibility to retract through for instance equipment renting or exit provisions foreseen in a joint-venture contract. Switching options among production modes (or resources or products) include both put options (abandoning one mode) and call options (adoption of another mode). In each case, an initial investment is realized or a cost is borne to remain flexible in order to reduce the adjustment costs of firms' strategies.

The value of a real option depends on six basic variables: (1) the present value of risky assets (called underlying assets) to be acquired in order to realize the project on which an option is held; (2) the cost of holding the option (the expenses to hold the option to invest in the

project); (3) the cost of exercising the option (expenses to acquire the assets of the project); (4) the duration of the option until its expiration date (decision date until which the option stays open before being exercised); (5) the volatility of the underlying assets; (6) the riskless interest rate during option duration.

If there is no volatility, there is no reason to adopt an option strategy since flexibility has no value. In return, for a given level of irreversibility, the option value (of flexibility) increases with volatility. Since an option is defined as the right but not the obligation to acquire or abandon an asset, holding an option creates an asymmetric risk profile: an option to invest benefits from risky events when uncertainty gets resolved in favor of the investment under consideration by giving a preferential right to exercise the option. If conditions end up unfavorably, the option is not exercised and the only cost borne is the one of holding the option (assumed to be largely inferior to the investment cost).

Whereas earlier contributions on real options have mainly insisted on the value associated to the option to wait or to defer (McDonald & Siegel, 1986), several contributions have recently considered more proactive option strategies such as growth options giving firms a competitive advantage (Kulatilaka & Perotti, 1998). Even if the logic that underlies both deferral and growth options is based on the value of flexibility, this value does not derive from the same source for each option. Deferral stresses the value to delay investment in order to benefit from the arrival of new information. Growth options insist on the value of early investment in order to develop the capabilities necessary to facilitate preferential access to future opportunities (Bowman & Hurry, 1993; Kogut & Kulatilaka, 2001).

Both options (growth and deferral) advocate a different investment strategy if we take the NPV as a reference. An investment which could be justified by the NPV rule ($NPV > 0$) may not be engaged if firms adopt the logic of the deferral option. According to this option, a firm will only invest if the revenues expected from the uncertain project cover not only the investment cost but also the additional option value of waiting. The reason why a risk premium has to be paid to motivate investment becomes clear when one considers that by investing a firm loses its flexible position. In the case of growth options, an investment can be initiated even if the NPV rule advocates not to invest ($NPV < 0$). Some form of irreversibility may be accepted in order to create preferential access to potential opportunities. Since the value of future investments depends on already engaged investments, an early investment

can be considered as an entry price to create the opportunity to participate in the sequence of expected projects to come.

This ambiguity about the investment behavior of firms under uncertainty compels us to have a closer look at uncertainty sources and to differentiate the role of different contingencies which characterize the competitive environment of firms during the successive stages of a project in order to better understand option strategy choices (Folta & O'Brien, 2004; Leiblein & Ziedonis 2007). This dynamic perspective is all the more important as the issue we are dealing with relates to the transition process from one technical system to another. Bowman & Hurry (1993) stress the sequential character of discovering, holding and exercising options. The development of an option strategy for firms is in fact a challenging one. It forces them to act under radical uncertainty which only gets resolved as firms take actions (Nooteboom, 2000).

Unlike traditional investment models where projects are assessed independently and where their values are considered additively, real option models insist on the importance of interactions between investments (Trigeorgis, 1996). Generally the acquisition of an option is the key to open new options. Furthermore, since options interact, the choice of an option is likely to affect the value of pre-existing options. Similarly, since holding an option has a cost, adding options to a portfolio does not necessarily increase the portfolio value. An option portfolio strategy should therefore be considered as a trade-off between different options according to the uncertainties firms prioritize (firm-specific, technological, market, and/or policy uncertainty). We can thus assume that an option strategy in the socio-technical transition perspective will consist in trading-off in a dynamic way between different parallel and/or sequential option types according to the priorities regime actors set upon the uncertainties they are faced with during the transition process.

Before developing further our main arguments on socio-technical transitions, we briefly insist on some key points which fuel the debates on the applicability frontier of real options (Adner & Levinthal, 2004). These debates stem from the assumptions that underpin financial and real option models.

For Adner & Levinthal (2004), three assumptions are key to extrapolate in a proper way the financial options assessment methodology to real options: (1) the financial option value (and

that of the underlying asset and its strike price) is exogenous to the investors' actions, i.e. the investor cannot influence the intrinsic characteristics of an asset. Yet, contrary to financial options firms do not hold real options passively. Rather the decision to hold an option motivates a firm to improve its value by trying to change the value of the underlying assets; (2) the market signal on the financial option value is observable. Here again, the difference relates to the difficulty to observe correctly the value of real options by merely relying on market signals; and (3) the expiration date of the financial option is fixed *ex ante*, whereas most options on strategic opportunities do not have an explicit expiration date. Their expiration date is rather contingent on resources committed by firms and on their competitive context. It is thus an endogenous choice. Adner & Levinthal (2004) argue that these differences can disable the abandoning or the striking of a real option at the appropriate moment because of organizational bias and stakeholder interests. Therefore when firms can endogenize uncertainty through strategic actions, the validity of the real option methodology to assess appropriately investment opportunities can be seriously questioned. Other authors, on the contrary, stress the importance of endogeneity in evaluation models in order to manage uncertainty proactively and account for the strategic behavior of firms (Kogut & Kulatilaka, 2004).

We would argue that the violation of these assumptions, if it complicates the application of option theory to 'real' investments, contributes at the same time to better take into consideration the strategic dimension of actors' rationality. For instance, whenever these assumptions do not hold, the fact that options correspond to a right but not an obligation exacerbates the strategic dimension of decisions and creates agency problems. By holding options, firms generate future decisions rights. They act according to the value they attach to their future decision rights to realize investment choices. This strategic rationality might thus be the source of option traps (Adner & Levinthal, 2004) since it may bias decisions in abandoning options (tendency to disqualify valuable opportunities) or in maintaining them (tendency to overestimate opportunities). In a collective decision process, optional thinking can thus create decision dilemmas and lead to indecision or generate escalation effects. In fact the value of an option depends on the specific uncertainty and knowledge profiles of each firm. A corollary is that the same option may be held by several actors for different reasons. Thus, holding an option to grow may be motivated by the decision right it confers to wait as well as to invest. In fact holding options confers the right to participate in the bargaining process within system innovations and to the transition governance dynamics.

Holding, abandoning or striking options can here be interpreted as shaping the ability of actors to orient trajectories and to influence the balance of selection criteria during the transition process. To the extent that options concern future investment choices, their value results from the convergence of actors' expectations as well as the flexibility of their interpretative schemes concerning their potential opportunities. The value of an option is thus a question of interpreting problems (and solutions) and of competition between possible world visions. These perceptions influence in turn the recognition of opportunities and firms' action strategies.

2.2. Transition processes, real options and flexibility

We present in this section our analytical framework, the originality of which is to reconsider technological transition processes through the real options perspective.

A typology of transition pathways has been recently proposed by Geels & Schot (2007) by focusing more particularly on the interactions between the socio-technical landscape, the socio-technical regime and technological niches. Considering the nature and timing of interactions between these three levels these authors distinguish different transition pathways and dynamics.

(a) Reproduction path of the existing regime

This path is characterized by the absence of pressure from the landscape and the existing regime is dynamically stable and reproduces itself. Even if innovations emerge within niches, they are not adopted by the regime. The perception shared by actors is that the regime has the required capability to solve internal problems without relying on innovations developed outside the regime. Progressively, the incremental innovations develop and build up internally to improve the performance of the regime.

(b) Transformation path of the existing regime

Although the pressure from the landscape is assumed to increase, niche innovations outside the regime are still not sufficiently developed to respond to these pressures. Faced with changes in their selection environment, regime actors feel thus the necessity to innovate internally and to use their adaptive capability to reorient their technological trajectories. The

propagation of these technical developments modifies the regime from within. During this path, regime actors might import competences developed by niches if they are not too distant from the competences of the regime.

(c) Reconfiguration path of the existing regime

Innovations emerge essentially from niches. When these innovations have a symbiotic relationship with the regime they are adopted as local solutions to improve the performance of the regime by keeping its rules unchanged. As regime actors begin to experiment new combinations between existing and new technologies these progressively trigger more profound adjustments within the regime. This process leads to changes in research heuristics by opening up new opportunities for the broader adoption of technologies developed in niches without profoundly destabilizing the regime.

(d) De-realignment path

The regime is confronted with difficulties to respond appropriately to the pressures of the socio-technical landscape. This leads to the de-realignment of the regime and its progressive erosion. When there are no immediate substitutes to the regime, the pressure exercised by the landscape creates an uncertainty on how to allocate innovative resources and the domains to prioritize. This favors the emergence of multiple niche innovations and the exploration of multiple technological trajectories encouraged by actors external and internal to the incumbent regime. This path is thus characterized by a prolonged period of technological co-existence and competition for limited resources. Eventually one of the innovations becomes dominant to trigger the adoption of a new regime.

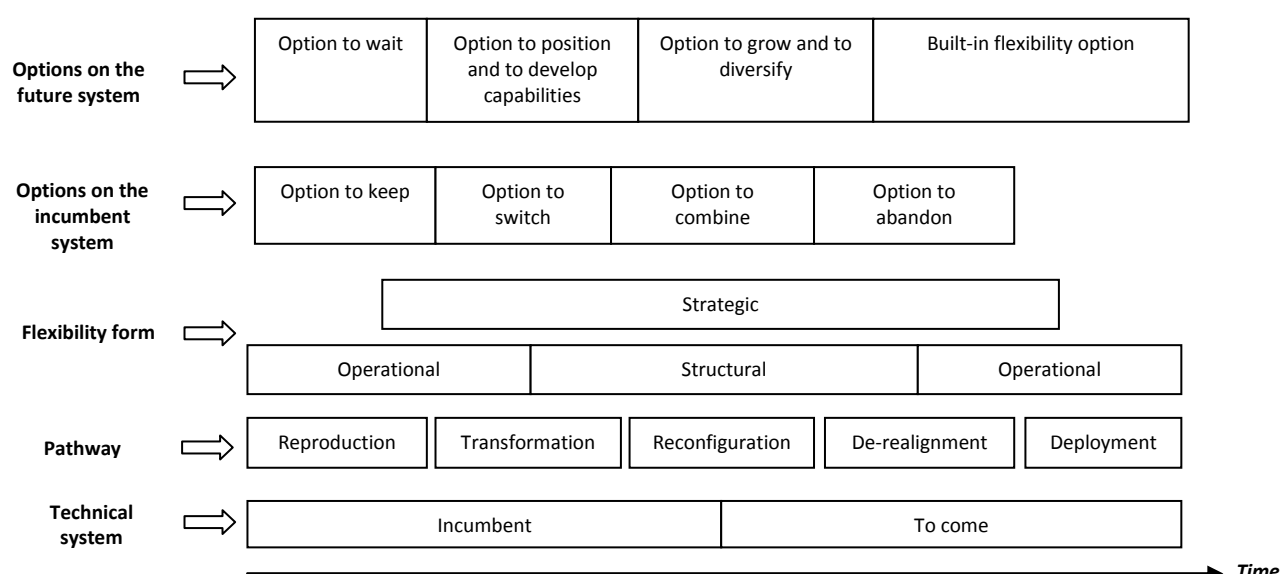
(e) Deployment path of the new regime

As opposed to the preceding path, niche innovations are here sufficiently developed. Strong landscape pressures open up windows of opportunities for niche actors to diffuse their innovations through a process of niche accumulation to finally penetrate main markets. Competition ends up by the substitution of the incumbent regime by a technological system initially developed within a niche.

The evolutionary framework on socio-technical transition processes which we have briefly presented helps to better define the interaction dynamics between the socio-technical landscape, the regime and the niches in order to explicit the trajectories that might structure the transition from one technical system (incumbent) to another (new one). Although our approach is closely based on this evolutionary framework and uses the transition pathways explicated above, we particularly focus in the following on the strategic dimension of transition processes. Our interest is on the strategic investment behavior of actors in a context where the future performance of and the choice concerning the future technical system is highly uncertain. In a prospective vision, if the current state of the technical system is known, the question of which technical system might dominate the future, the trajectories and specific processes that might lead to this hypothetic system cannot have a definitive answer. Furthermore uncertainty is not confined to the first phases of the transition process but changes its nature when one goes through different pathways. In this perspective the transition process to follow is not determined by a given future system assumed to be superior. Rather, because of different uncertainty sources, the complexity of technological systems and path dependencies, flexibility and irreversibility management modes should be considered as essential determinants of the strategies engaged by actors during the transition process.

The importance of considering different flexibility forms during transition processes has recently been stressed by Frenken *et al.* (2007). In order to give a dynamic real option perspective on investment decisions during such processes, we refer to the distinction introduced by Volberda (1998) between *strategic*, *structural* and *operational flexibility*. This distinction is used to elaborate an integrated approach between different flexibility forms and the real options framework (Burger-Helmchen, 2005) to highlight the strategies that might be deployed by actors to manage the transition process. As we point out each type of flexibility and each type of option are likely to correspond to and dominate specific paths of the transition process (Figure 1).

Figure 1: Real Options, flexibility and transition processes



Strategic flexibility is developed to respond to circumstances where changes are largely unknown, uncertain and unpredictable and where the outcome can have wide-ranging impacts. These changes may be due to technological breakthroughs, to unexpected modifications of the environment that disrupt practices, to new legislation that modifies dramatically the competitive and industrial landscape. We define strategic flexibility as the capability of regime firms to choose, initiate and exercise different types of real options during the transition process. This strategic capacity corresponds thus to the capability of firms to combine several types of options according to the uncertainties and irreversibilities they are confronted with. The key role of strategic flexibility is to prepare, influence and develop in a proactive way the structural and organizational flexibilities that might prevail during each pathway. In a transitional perspective such flexibility refers to the capability of firms to manage a portfolio of options both in parallel (during a given path) and sequentially (as a sequence of holding and exercising cascading options representing the transition trajectory). Furthermore, taking into account the nature of interactions among options can be an additional way to illuminate investment strategies pursued by firms. Such a strategy reflects also the trade-off between different forms of uncertainty and irreversibility during the transition process. Although our analysis relates to the regime level, it does not exclude differences among firms in terms of option strategies. Even if the expectations at the aggregate level may reflect the domination of certain types of options these do not imply necessarily homogeneity of firms. These expectations define at a given moment in time a dominant option strategy at the industry level and illustrate the nature of problems to be

solved and the nature of competition among firms and among technologies. If in a situation of uncertainty and incomplete knowledge some mimicry can be observed among firms, this mimicry creates at the same time opportunities to increase competition and differentiation and offers thus the possibility to observe a diversification of option strategies. In other words, if for a given pathway a type of option (or a portfolio of options) may be dominant, some firms can always keep options on the preceding pathway and others engage option strategies that announce future pathways. Furthermore, firms may not only have different perceptions on the timing of holding options but also on the timing of exercising or abandoning them.

Operational flexibility corresponds to frequent and short term changes of operational activities within a given technical system. They concern the volume and the mix of activities without however impacting substantially the relation between the technical system and the landscape. The aim is to create adequacy between the technical system and the landscape through a set of clearly defined routines. From the transitional perspective this repertoire of routines should be significantly different between the reproduction pathway (operational flexibility of the incumbent system) and the deployment pathway through which a new system emerges (repertoire of routines defining the operational flexibility of the new regime). This flexibility is principally supported by privileging exploitation activities within the new system.

Structural flexibility corresponds to the capability of firms to adapt the technical system to respond to landscape mutations or to change the structure of the landscape. This form of flexibility is a response to the limits achieved by operational flexibility and aims to create a new repertoire of routines. Structural flexibility may develop gradually through the exploration of several alternative technical systems. The objective is to create variety with respect to operational flexibility forms and to select the appropriate operational flexibility form according to the landscape characteristics that might prevail.

In our framework flexibility management can concern the incumbent technical system as well as the future system. In the first case we refer to *ex post* flexibility management and in the second case to *ex ante* flexibility management. To explicit this flexibility management dynamics we associate option strategies both to the existing technical system and to the future system. Real options on the incumbent system tend to optimize *ex post* the

organizational and structural flexibilities of the existing system by trying to create new breathing spaces. Real options on the future system manage and build up *ex ante* the structural and operational flexibilities of the system to come.

3. Option strategies and regulation of transition processes

In the following we qualify more precisely the options that regulate the different transition pathways. We consider the transition process as a cycle of exploitation and exploration activities to which we associate option strategies. During the reproduction pathway option strategies focus on the exploitation of the operational flexibility of the existing regime. Given the limits attained by the exploitation of the regime, during the transformation path, firms orient their option strategies towards the exploration of new potentials within the incumbent system. In both cases regime improvements are supported by internal resources. During the reconfiguration pathway, firms continue predominantly to explore the existing regime's structural flexibility potential by interacting however more closely with emerging technologies developed outside the regime. By contrast during the de-realignment and deployment pathways firms' option and flexibility strategies are dominated respectively by the exploration and exploitation of alternative technological systems that might replace the incumbent regime.

3.1. Options regulating the reproduction path

During this path two option strategies may dominate firms' investment behavior and reinforce each other to manage the uncertainties they are confronted with.

The first is the *option to wait* or to defer. When the new technical system to be selected is unknown and the investments required are irreversible, keeping a flexible position by deferring investments is considered to be economically more beneficial than immediate commitment. The higher the uncertainty about the future performance/price improvements of emerging technologies, the higher also the value of the option to wait. The abdication of the option to defer (or the option to invest once more useful information is revealed) creates an opportunity cost which must be added to the cost of immediately investing. The option to wait indicates also that although the NPV of a project might be positive, it might be beneficial for firms not to invest. In other words, the adoption of an investment strategy based on the option value of a project integrating the value of flexibility increases the

threshold for investing: firms invest only if the NPV of a project exceeds its cost by an amount equal to the deferral option value (McDonald and Siegel, 1986).

Beside the deferral option, the *option to keep* the incumbent system reinforces and extends the reproduction path. Delaying exit, even if the NPV of a project becomes negative, may be a rational decision to manage the uncertainty and irreversibility of the incumbent regime. Investments on the incumbent regime may continue until the economic losses exceed the option value to keep the incumbent system. The option to keep the existing system may be justified because of the perception that the technological frontier of the incumbent system has not yet been exhausted. Consequently, in a very volatile environment and when change is costly, the exploitation of the incumbent regime may be further encouraged. As Chi & Nystrom (1995) argue, a higher uncertainty on the evolution of the incumbent regime means a higher learning potential for the regime firms and conduces them to exploit it more intensively until the cost of such learning becomes higher than the benefits expected. Furthermore, the more important uncertainties on future technological alternatives and their adoption costs, the more regime actors will rationally choose to persist on technologies that might prove inferior in the long term. In other words, the higher the uncertainty level, the more firms will be keen to lengthen the life span of existing solutions with a low capital cost. Inertia in this case is not related to the *lock-in* of the incumbent regime, but mirrors the expectations concerning the value of present and future technologies and the cost of change. Inertia increases with uncertainty since firms are rationally hesitant to support the cost of change towards competences which might become obsolete if the environment returns back to its previous state or because of the risk to choose the wrong alternative.

A real options reasoning provides also a rationale for the hysteresis phenomenon (Dixit, 1992) that may affect the incumbent system: when environmental conditions do not support the incumbent regime anymore, investment decisions can be unaffected and induce the regime to continue as in the past. Between the level of profits required to justify investments in new technical systems and the losses to motivate exit from the existing system, there exists an inertia zone where the regime keeps its *status quo*. As shown by Dixit (1992), this inertia zone widens with uncertainty and irreversibility. The hysteresis zone may also widen when several alternative technologies are perceived as potential substitutes to the dominant technology. In fact, when several technological alternatives compete, their option value to wait may differ. Thus, the return necessary to trigger an investment on a new technology

might depend not only on the value of waiting for this technology but also on the value of waiting for the other technologies. Therefore, the decision to invest in a new regime might depend on the technological system possessing the highest threshold value. Alternative technologies when considered together may thus increase the value of waiting compared to the case when they are considered independently.

Before concluding our analysis of the reproduction path, it is important to insist on the perception actors have of the uncertainty they are confronted with and which plays a key role with respect to the type of option strategies they choose. Technological uncertainty can be perceived either as exogenous or as endogenous by firms (Folta, 1998). While exogenous uncertainty is principally resolved by the passage of time, endogenous uncertainty creates learning opportunities. Although both types of uncertainty increase the value of option based strategies, they create opposing pressures on investment decisions. The uncertainty on the new technical system, which is perceived by incumbent firms as exogenous during the reproduction path, induces them to wait until such uncertainty reaches an acceptable level before committing investments. By contrast, the reproduction trajectory justifies the option to keep and to exploit the dominant system because incumbent firms perceive its uncertainty as endogenous. In the following we assume that during the transition process the uncertainty affecting emerging technologies will confer an increasing strategic importance to learning opportunities and to proactive irreversibility management by firms. When firms perceive uncertainty as endogenous it becomes also more appropriate to consider option strategies sequentially. The sequential nature of the transition process allows in fact diversification of option strategies. It also suggests that investment decisions should be evaluated according to the efficiency of a set of sequential moves and through the path dependency effects created during the transition process rather than the efficiency of a single move.

It should also be noted that, even if the option to wait dominates firms' strategies during the reproduction path, this does not mean that after the shift to the following path, the threshold value to trigger investments on the new technical system is reached. Such a shift means rather an evolution in the option strategies pursued by firms because of changing conditions affecting the uncertainties they are confronted with. Therefore, the values of the option to keep and to wait depend also on other possible options that firms might choose during the transition process such as e.g. the options to position, to grow or to abandon. According to the type and level of uncertainty considered, the option to wait may for instance have a

different cost and all investments may not have the same degree of irreversibility if actors have the opportunity to hold low cost technology positioning options or options to abandon or to switch technologies.

3.2. Options regulating the transformation path

As for the reproduction path, the transformation trajectory aims to foster the existing regime's flexibility by focusing on internal resources. Nevertheless, during this path, the exhaustion of the exploitation opportunities of the incumbent regime leads to reorienting *ex post* research strategies towards exploring more intensely the possibilities to push its technology frontier envelope and to regenerate its structural flexibility. A first option strategy is thus structured around *switching options* (Kogut & Kulatilaka, 2001). The aim is to smooth the transition process and to avoid disruptive changes. It consists in minimizing the distance between exploited competences and those new to be acquired and to be mobilized. Firms invest in new technological alternatives which increase the value of switching¹ by at the same time minimizing their adoption costs through exploration of opportunities on the vicinity of the incumbent system. This may correspond to options held on "best available technologies"

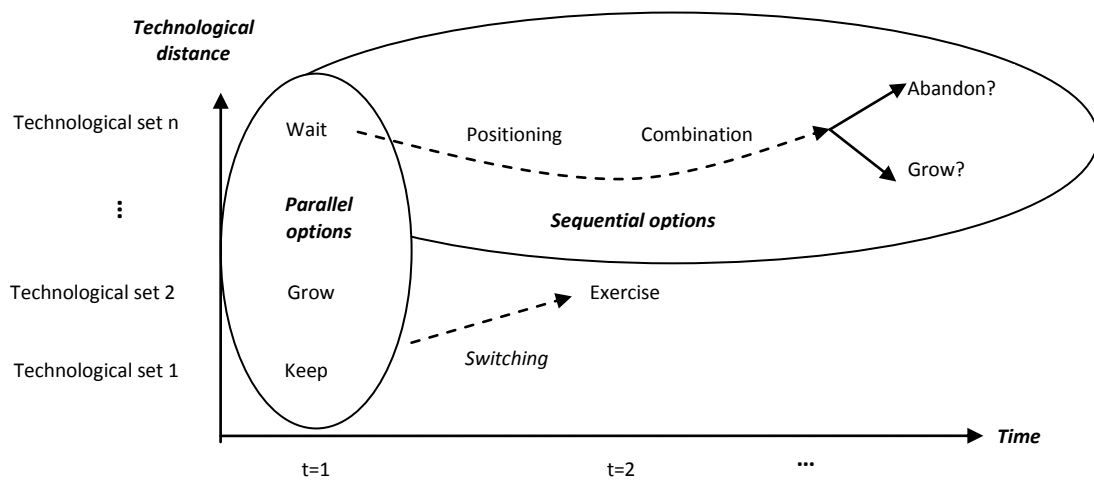
At the same time, incumbent firms, widen their competences on radically new technologies to improve *ex ante* their long term capabilities. This consists in initiating a proactive behavior on emerging solutions in order to direct uncertainty rather than to incur it. Efforts on emerging solutions, which are far from being stabilized, allow firms to create and structure opportunities through technological and organizational investments largely guided by their beliefs, their intuitions, their perceptual biases, their interests in order to influence the orientation of long term decisions. A second option strategy is thus related to *positioning options* (McGrath, 1997). Positioning or capability investments constitute a first step towards holding options on the long term which gives firms the right but not the obligation to adopt emerging technologies. Positioning options are held to develop absorptive capabilities on emerging technologies in niches that might reveal critical in the future. The essential purpose of these options consists thus to become familiarized with the knowledge dynamics that

¹ We define *switching options* in two different ways. The first definition which is the one adopted here assumes the replacement of a technological system by another within the same technological paradigm. The second definition refers to built-in flexibility options mentioned in section 3.4 and concerns changes within the same technological system (in terms of resources, processes or outputs). We use the term transition for the passage from one technological paradigm to another.

shapes these emerging technologies. Such positioning options provide firms with decision rights on subsequent paths and options along the transition process.

Like the option to wait, positioning option value increases with uncertainty but causes an active commitment by firms. It becomes useful to invest for instance in R&D even if *ex ante* the NPV of a project proves to be negative. Projects with higher uncertainty are considered to have also a wider range of potential consequences and thus more growth opportunities. Since the positioning option value increases with the opportunities that a technology can generate (Kogut & Kulatilaka, 1994), the tendency of firms during this path might be to invest on generic technologies having a wider range of potential uses. It is however possible that some firms, particularly in niches but also within the incumbent regime adopt more targeted positioning options either to differentiate themselves from others or to be leaders in the transition process by preempting following paths.

Figure 2: Transition as a portfolio of parallel and sequential options



Positioning options can be assimilated to a trial and error management strategy. Since alternative technologies are emergent and their scientific and technical proprieties are not completely established, positioning investments may have a high rate of failure. Firms may thus integrate the abandonment risk of projects in their option strategy. This should be all the more so when the options considered involve high cost R&D activities. These options may thus either end up by the abandonment of projects (when uncertainty is resolved unfavorably) or motivate additional resource commitments (when uncertainty is resolved favorably). For instance, investments in generic technologies may be considered as motivated

by a portfolio strategy of options to wait, to position, to combine (see next section), to grow or to abandon (Figure 2). Whilst providing firms with the flexibility to commit additional resources to opportunities in case these might reveal promising, generic technologies increase the value of the option to abandon since the resources committed to a failed project can be transferred to other more promising projects by minimizing the losses of keeping the positioning option. In fact, during the transformation path, factors increasing the value of the option to abandon increase also the value of the option to position and decrease the value of the option to wait (and thus shorten the reproduction path) since the value of the option to abandon makes up part of the positioning option value. It is the flexibility to abandon or to act sequentially that confers to the positioning option its attractiveness.

But, during this path, the propensity of firms to develop option traps might also be strong. Firms' assessment of switching and positioning options depends on their opportunity set which is often biased by their past experience. Firms' intentions to influence technological uncertainties in a context characterized by technical controversies can thus motivate them to shape contingencies according to their own interests. These intentions might prevent firms involved in technological niches to timely abandon emerging alternatives because of the importance they attach to them even though learning outcomes reveal disappointing. As for incumbent firms, their behavior may be biased towards abandoning positioning options and overestimating switching options.

As shown by McGrath (1997), the value of positioning options does not only depend on factors specific to the technology itself (cost of absorptive capabilities or cost of developing the new technology which determine its option price) but also on the uncertain environment within which it might be deployed and which determines the revenue streams and the costs of its commercialization (the value and cost of underlying assets). Revenue can be influenced by uncertainty sources such as the structure of demand, the possible adoption speed of the technology, blocking strategies by incumbent actors or the existence of potential substitutes. Commercialization cost uncertainties can concern access to or deployment of infrastructures and complementary technologies. Some factors, such as the need for a new infrastructure or for complementary technologies can have a negative impact on the value of positioning options and exacerbate the value of switching options. Although actors may develop strategies to influence favorably uncertainties affecting these factors, they may discourage resource commitments on positioning options and favor switching options to extend the

transformation path. However, the impact of these factors on option values may be different according to the path considered. In fact, the need for a new infrastructure/complementary technologies may influence positively the value of commitment options during subsequent paths since investing quickly in such network assets should have a key impact on the selection between technologies and their diffusion (Lin & Kulatilaka, 2007). Thus, when the dominant uncertainty is related to the competition outcome among technologies these factors should positively influence the value of commitment options and reduce the critical threshold level to strike them.

3.3.Options regulating the reconfiguration path

Although regime firms may adopt during the reproduction and transformation paths positioning strategies on emergent technologies to develop essentially their absorptive capabilities, they do not necessarily seek synergies between incumbent and emerging technologies. By contrast, during the reconfiguration path, innovations on these emerging technologies increasingly attract the attention of firms because of their potential to improve the incumbent system. The distinctive feature of the reconfiguration path is the intensity of interactions between dominant and alternative technologies even though these are not able to substitute for the former. In other words, during the reconfiguration path, firms begin to exploit emerging technologies mainly to continue to explore *ex post* the structural flexibility of the incumbent regime.

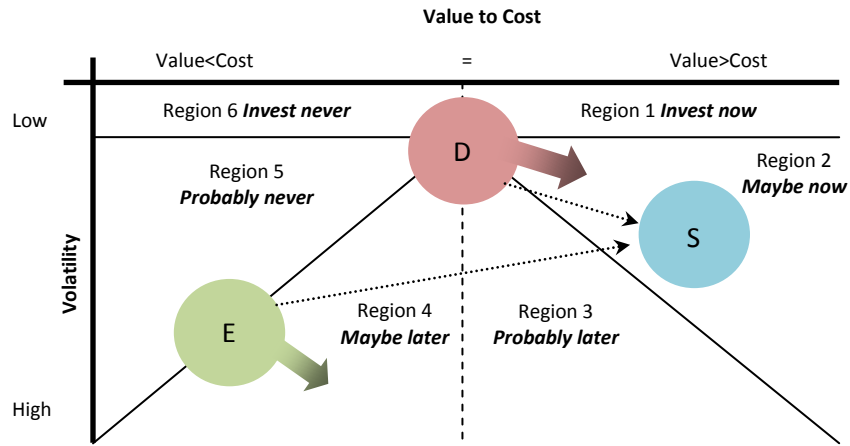
Pistorius & Utterback (1997) define technological interactions by examining the mechanisms through which technologies can improve or inhibit their respective growth rates. Their contribution goes beyond simple inter-technology competition by considering a multi-mode interaction framework between emerging and dominant technologies of which symbiosis, competition and predator-prey interactions are possible modes.

It is assumed that symbiosis between dominant and emergent technologies represents the distinctive trait of the reconfiguration path. Symbiosis creates a diversification dynamic within the incumbent regime since interactions with emergent technologies encourage further exploration of the dominant system without fundamentally questioning its established routines. Interactions consist in coupling niche innovations with a specific problem within the dominant regime in order to overcome its performance limits. For the

emergent technology coupling is also often necessary to favor its market growth rate. The emergent technology can at the beginning be integrated as an auxiliary device into the incumbent technology and might become, after a period of more sophisticated combination, the core element of the system (Islas, 1997). In fact, symbiosis introduces a qualitative jump in the learning environment of both technologies which have a-synchronic positions within the learning process going from experimental exploration to commercial exploitation (Llerena & Schenk, 2005). Since each phase of the learning process is subject to decreasing returns, the appropriate management of the different learning phases can be key for the success of both technologies. This relates directly to the value of options, which if not exercised in a timely fashion may have decreasing returns through time (Trigeorgis, 1996). In the case of the alternative technology, symbiosis avoids prolonging some costly positioning options beyond the time necessary and allows a better management of the transition from explorative to exploitative options. In the case of the mature technology, its combination with the emergent technology may set in motion a new period of intensive exploration in order to improve the symbiotic technology.

In the following we use the heuristic suggested by Luehrman (1998) to analyze the reconfiguration path from a real option perspective. Figure 3 depicts the option value space according to two metrics: (1) the *Value-to-Cost* ratio of technological assets to be developed which also includes the value of flexibility; (2) the *Volatility* of the technological assets returns. The option value increases when one moves towards the South-East of Figure 3. Applying NPV, all projects situated within regions 1, 2 and 3 would be implemented and all others abandoned. Real option reasoning widens firms' strategic space since decisions are no more limited to a binary choice between « invest » and « do not invest » but create a more refined decision set.

Figure 3: Option value of Dominant, Emergent and Symbiotic technologies



Source: Luehrman (1998) and authors

Figure 3 applies this reasoning to the interaction case between emerging and dominant technologies. We assume that the dominant technology reaches progressively its performance limit and that investment costs to improve the technology marginally become very high. The dominant technology is thus situated in a region where firms hesitate between two options: keeping it or abandoning it. Symbiosis with the emerging technology changes however the perception on the dominant system. It creates new opportunities for the incumbent system even if these are considered to be uncertain. Combination favors the option to keep the dominant technology (shift down-right), in other words it increases uncertainty with respect to its future expected Value/Cost ratio. A similar evolution takes place for the emerging technology. Its combination with the dominant technology shifts it from regions “5” or “4” towards regions “4” or “3” since it increases its positioning and/or growth option value and reduces the option value of abandoning or deferring it. It is easy to develop our reasoning further to explicit possible scenarios for both technologies by anticipating the pathways to come. One possible scenario may consist in C becoming dominant while E is abandoned as an autonomous technology. Another scenario could lead to the domination of the emerging technology by abandoning the mature technology.

One may distinguish the three paths that have been analyzed by the opposition between two distinct innovation perspectives that might influence the perception of options on emerging technologies: on the one hand the logic of large technical systems (incumbent regime) and on the other hand the logic of large projects on emerging technologies (niches). The incentives and the resource allocation process which underlie these two different innovation logics correspond to two different strategic visions of the options held on the emerging system.

Whereas for regime firms niche initiatives have an optional quality in the sense that abandoning them may not have significant consequences, niche actors are entirely committed to these options. Adner & Levinthal (2004) qualify this opposition by the difference between « *holding an option* » and « *being the option* ».

3.4.Options regulating the de-realignment path

The main difference between the paths already analyzed and those of de-realignment and deployment rests upon the following argument: whereas former paths exploit the *ex post* flexibility potential of the incumbent regime, the latter aim to preserve *ex ante* the flexibility of future technical systems. Furthermore, a difference between the de-realignment path and the deployment path concerns the way flexibility is managed. During the de-realignment phase operational and structural flexibilities are preserved through the diversity of underlying assets in competition, whereas during the deployment phase this flexibility is directly incorporated within the assets deployed.

Two types of uncertainty may structure option strategies during the de-realignment path. Technological uncertainty is here mainly induced by the lack of a dominant system. When technologies co-exist in a competitive tension, flexibility is maintained by technological diversity in order to hedge against the emergence of a dominant design. Nair & Ahlstrom (2003) provide several reasons for such technological diversity. First when technologies have a systemic nature, continuous innovation within sub-systems allows the whole system to survive by narrowing the gap among rival technologies and prevents a given system to have an overwhelming advantage over others. Furthermore, the interactions progressively developed among rival technologies may also favor their co-existence. Equally, regulatory and policy measures may postpone the premature adoption of a dominant design. Also the comparative assessment of the merits and limits of each technology, in the presence of multiple evaluation criteria, can delay technology selection. Firms may well assess and perceive differently the factors that determine the benefits and risks of each technology and, according to their experience, may support a different system in order to respond to the same objective. The institutional framework, the social, economic, strategic and political context, bargaining and power relationships can also blur technological differences.

Beyond technological uncertainty, firms' strategies are during this path also increasingly oriented by market uncertainties which may for instance derive from demand heterogeneity, latent needs and the acceptance by users of technological functionalities new to the market. Market uncertainty may be managed by investments in niches (Kemp *et al.*, 1998). In fact, technological competition and diversity create opportunities to develop more focused and differentiated segmentation strategies. During this path firms explore different segments by trying to exploit specific demand attributes. Strategic niche accumulation offers learning opportunities on technologies as well as markets in order to optimize the market-technology fit. As for technological diversity, strategic niche accumulation puts stress on the benefits to maintain market diversity.

Considering the nature of technological and market uncertainties, critical options during this path are options to grow and options to diversify. *Growth options* are justified by increasing market competition among firms in a context where uncertainty about the timing of adoption of technologies are exacerbated and where there exist competitive advantages to early entry in the market. Such options can have preemptive effects, confer cost and learning advantages, improve market share and profits, and discourage entry by potential competitors. Even if the value of deferral and positioning options increases also with uncertainty, the value of growth options increases more (Kulatilaka & Perotti, 1998; Folta & O'Brian, 2004).

If market uncertainty favors growth opportunities, technological uncertainty (technological competition) motivates diversification or *hedging options* (Hatfield *et al.*, 2001; Anand *et al.*, 2007). The tension between commitment and flexibility is thus expressed during this path by the trade-off between growth and hedging options. Whereas growth options commit early on market opportunities, hedging options focus on structural flexibility to control technological uncertainty. Thus, the value of the option portfolio depends during this path on the tension between the growth potential of each underlying asset and the capability to maintain structural flexibility by adopting a hedging strategy.

Particularly Anand *et al.* (2007) focus on the trade-off between growth and hedging options when firms face both market and technological uncertainty. To analyze possible portfolio effects, these authors consider beyond the volatility (σ) of underlying assets, (1) the correlation (ρ) between expected gains of underlying assets and (2) the exercise constraints

on options (as when there is a capacity constraint that limits the possibility to exercise all options or when in the long term only one technology is likely to dominate), such that if there is n options in the portfolio only m of them may be exercised ($m < n$). When there is an exercise constraint, adding new growth options to the portfolio decreases the marginal value of each additional option since it has a lower probability to be exercised. The expectations of actors on these exercise constraints constitute thus a natural limit to diversification. Correlation between assets has also complex effects on the portfolio value and structure. Whereas the hedging option value increases with a negative correlation (mutually exclusive technologies), a positive correlation (complementary technologies) increases the value of growth options.

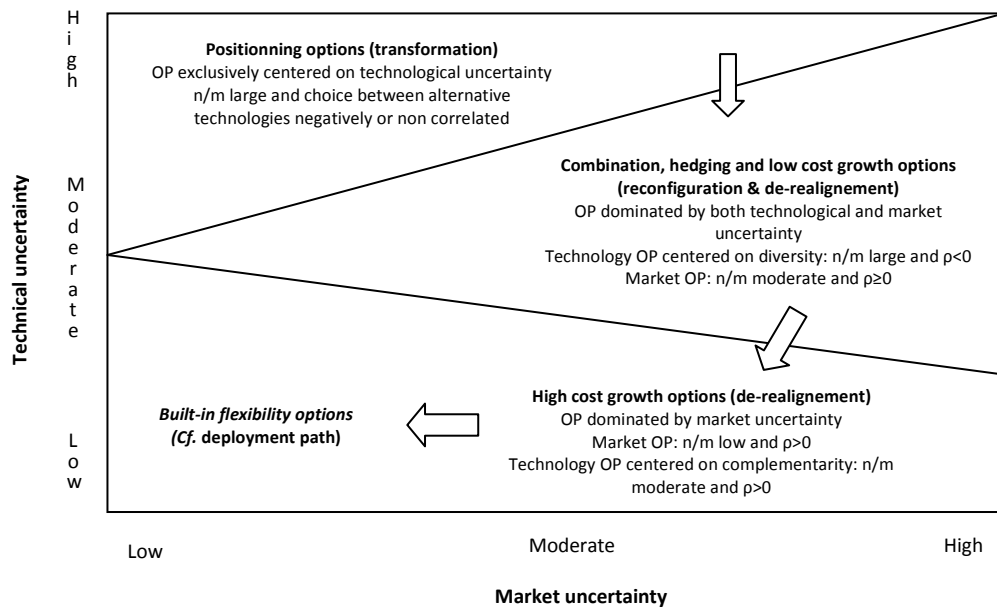
An important reason to distinguish between market and technological uncertainty is that they affect the value of options differently. When technological uncertainty dominates a firm's option portfolio strategy is mainly structured by: (1) the advantages of being a *technological leader* and (2) the negative correlation between the values of rival technologies (mutually exclusive technologies). The first aspect improves the growth option value since it increases the probability that the technology developed by the firm becomes the dominant design. The second aspect relates to hedging options. As competing technologies are mutually exclusive the option to diversify has an important value since it reduces the negative consequences of a bet on the wrong technology by preserving flexibility and by delaying commitment to a single technology (Hatfield *et al.*, 2001; MacMillan & McGrath, 2002; Anand *et al.*, 2007). Thus, even if the marginal contribution of a growth option is very low, firms may continue to add new options to their portfolio because of their positive impact on structural flexibility. Furthermore a severe exercise constraint should motivate firms to structure their hedging strategy around profoundly different technologies (technologies that have a high negative correlation). Option portfolios in the presence of technological uncertainty should thus be structured around assets negatively correlated ($-1 \leq \rho < 0$) and should be relatively extended in comparison to the capacity to exercise the options acquired (large ratio n/m).

In return when market uncertainty dominates, the correlation choice among assets on which growth options are held should tend to be positively correlated in order to exploit the growth potential of demand and to benefit from technological complementarity and

spillover effects. Furthermore, it should be preferable to choose as many growth options as it is possible to exercise and not more (convergence towards a ratio $n/m=1$).

By adopting a sequential and dynamic approach we can put forward the following proposal with regard to the structure of option portfolios on emerging technologies: whereas during the transition phase between the transformation and the de-realignment paths technological uncertainty should dominate option portfolio strategies, market uncertainty should dominate portfolio strategies during the transition phase between the de-realignment and the deployment paths. Furthermore, once technological uncertainty is reduced, technological investments will also have the tendency to be focused on positively correlated assets (i.e. on complementary ones). Technological diversification should thus be motivated in the first phase by technological uncertainty and competition and in the second phase by technological complementarities and interdependencies (Figure 4).

Figure 4: Option portfolios (OP) on emerging technologies under technological and market uncertainties



Source: MacMillan & McGrath (2002); Anand et al. (2007); authors

3.5. Options regulating the deployment path

The main difference between the de-realignment and deployment paths is the following: whereas the former promotes technological diversity to maintain *ex ante* structural flexibility, the latter is based on *built-in flexibility* to preserve *ex ante operational flexibility* by

incorporating options within the technical system which is deployed. Such built-in-flexibility aims to avoid lock-in into sub-optimal solutions by supporting the introduction of new innovations in the technical system (e.g. successive technology generations).

This path is characterized by capital intensive investments to support the adoption and diffusion of the new technical system. Large technical systems (transport, infrastructure, energy supply) generally require years to be deployed and are conceived to operate for a long time despite the uncertainties over future states of the world under which they will be exploited. They show frequent interactions between design, development and operation phases long after the end of the project (Hobday, 2000). This path is therefore defined by increasing interdependencies and connections between the components and sub-systems of the new regime where technical standards and organizational practices will have to co-evolve with the system to allow for compatibility, interoperability between different elements.

Insisting on the built-in-flexibility value of technical systems, the real options approach brings important insights on the design, development and investment strategies during the deployment path. Built-in option strategies focus particularly on the openness and regenerative capacity of the design of technical systems in order to preserve its ability to economically adapt to environmental changes and to avoid premature obsolescence. Whenever the evolution of the environment is difficult to predict, it may be critical, to think about how to organize the operational flexibility of the new system as early as the design or the development phases. Several options can during this path be incorporated within the technical system in order to maintain its built-in flexibility:

- *Expansion options* anticipate increasing the capacity of the system in response to events justifying its growth.
- *Staging options* spread the development of the technical system over several stages. The completion of each stage represents an option on the next stage.
- *Switching option* strategies pay a premium to adopting a flexible technology which can modify its operational mode by changing inputs, processes or outputs.
- *Platform options* aim to develop dynamic complementarities and substitutability between successive technological generations. Both switching and platform options

contribute to what Garud & Kumaraswamy (1993) refer to as “economies of substitution”.

One of the difficulties concerning the management of options during this path relates to the fact that once the technical system is in place, it can be very difficult and costly, because of path-dependency and complex interactions among the elements of the system, to exercise options which have not been taken into account appropriately during the definition, design and development phases of the technical system. Since built-in-flexibility options imply generally the substitution or the addition of critical functional elements, a critical step during the set-up of a portfolio strategy in the presence of budget constraints and limited information on the value of each option is to determine the outlays to be committed in order to incorporate the appropriate options from the very design phase of the technical system (Trigeorgis, 1996; Gil, 2007). Following the literature on product design strategies (Ulrich, 1995; Baldwin and Clark, 2000; Schilling & Steensma; 2001), it is useful to consider here the very architecture of the technical systems by referring to the *modular* or *integrated* nature of interactions between components and sub-systems². These two stylized architectural forms may highlight the differences that may be observed in terms of built-in-flexibility management during the deployment path.

Baldwin & Clark (2000) stress the advantages of modular systems by insisting on their capacity to facilitate the creation and the exercise of options. Modularization might be justified because: (1) it makes complexity easier to manage; (2) it allows exploration activities on several modules in parallel, and (3) it increases the tolerance of the system towards uncertainty in the sense that particular modules may be renewed after an unpredictable event as long as system level design rules are respected. Modular systems have thus a built-in-flexibility advantage which is not given as such for non modular systems. Such modularity can be critical for switching and staging options and for technological platforms. The degree of modularity of the technical system during its deployment should also increase the value of growth options as well as loosen the constraints restraining the exercise of these options and thus increase diversity during the deployment pathway. By contrast, for an

² The literature on the design of modular products defines the architecture of a product as being the scheme by which the function of a product is allocated to physical components and sub-systems (Ulrich, 1955). Products with perfectly modular architectures manifest: (1) a one-to-one relation between functions and physical components or subsystems, and (2) physically decoupled and standard interfaces between subsystems and components defined by design rules. In contrast, products with integral architectures are defined by complex relationships and tightly coupled physical interfaces.

integral architecture, the economic exercise of an option which has not been foreseen initially in the design process can be very difficult and even impossible. This built-in-flexibility potential of modular systems refers to the advantages, put forth by Merton (1973), of holding a « *portfolio of options* » (modular system) rather than an « *option on a portfolio of assets* » (option on a system).

Modularization of technical systems entails however a cost which increases with the complexity of the system and which must be compared to the option value of modularity. Considering increasing costs of modularity and the difficulties to break interdependencies, an alternative strategy may consist in preserving options inside the integral system to create operational flexibility within the limits of foreseeable changes that may affect the integral system during its deployment or operational life (Gil, 2007). It should be noted however that such preservation can also require major investments in order to confer to the integral system a certain level of dynamic flexibility. For an integral architecture, a first phase can consist in comparing the costs and benefits of modularization with the costs and benefits of option preservation.

Focusing more particularly on option preservation strategies Gil (2007) shows that preservation increases the value of the technical system within which these options are incorporated since it reduces the cost of exercising them in the future, provided that the design and preservation strategies remain robust with the passage of time. However, the investments made to preserve an option, i.e. to keep the option open within the system also increases the initial cost of acquiring the option. This initial cost corresponds to the irreversible investments committed for preservation and indicates the unrecoverable costs that could be borne if the option is not exercised. The essential trade-off associated to preservation concerns here the relation between the cost of acquiring the option and the cost of exercising the option, knowing that an increase of the former diminishes the latter in the future. The critical question is then the following: should the system pay more during its deployment phase by investing in the preservation of an option or should it pay when the option has to be exercised in some distant future? As argued by Gil (2007), the attractiveness of built-in flexibility increases when the perceived uncertainty that the option will be exercised, is low.

These two configurations (integral system *versus* modular system) relate to two possible extreme states towards which the deployment path might evolve. At the same time they correspond to two possible structures of a given technical system: the first based on a concentrated structure and the second, a more decentralized one organized around independent firms. In a technical system aiming to preserve as much as is economically feasible the diversity developed during the de-realignment path, modularity can help to value the heterogeneity and the variety of innovative resources (inputs) available as well as the heterogeneity and variety of demand and markets (outputs). This double objective of keeping both the heterogeneity of innovative resources and markets increases the value of built-in-flexibility, the option value of modularity and the attractiveness of preserving options. Such a perspective motivates in fact the flexibility of operational combinations between the different components and subsystems of a technical system in order to diversify the possible configurations and acquire the adaptive capability according to the evolution of the environment and the evolution of the broader landscape within which the system is embedded.

4. Conclusion

Our paper used the real option perspective to stress the influence of investment strategies on technological transition dynamics in the presence of uncertainty and irreversibility. The will to preserve flexibility, when firms are confronted with high uncertainty and irreversibility, can in fact induce strategies which are different from those promoted by traditional investment rules based on the net present value calculus. From the real option perspective investment strategies are not limited to a binary choice between “investing” and “not investing”. Rather, decisions are guided by the strategic exploitation of flexibilities and irreversibilities which characterize the sequential logic of past and future investments. Investment strategies do not simply reflect the will of firms to maintain flexibility but also to manage and create irreversibilities to come in a strategic way. It is this tension between flexibility and irreversibility that shapes firms’ investment strategies. As shown by the literature on « standard wars » and on network industries, the trade-off between these two dimensions is a key determinant of firms’ investment strategies (Shapiro & Varian, 1999; Suarez, 2004). From a real options point of view an investment strategy is a dynamic portfolio of options by which actors manage in a proactive way the sequentiality and temporality of their decisions. It is the importance given by real options reasoning to this

sequential logic that allows an enriched analysis of investment strategies by highlighting some determinants – such as the trade-off between learning by exploitation and exploration, the will to shape and influence in a strategic way the competition and industry rules of the game as they evolve (e.g. by favoring indecision through flexibility or by creating irreversibility), the endogeneity of uncertainty etc. – which are poorly considered by traditional investment rules.

As we have shown, the analysis of transition dynamics via real options brings a more qualified vision on investment decisions depending on the pathway considered. Insofar as the dominant sources of uncertainty and irreversibility change from one pathway to another it becomes important to explicit more precisely the impact of these changes on investment strategies of firms. It seems also crucial to better understand the differentiated impact of different factors on the value of options according to the pathway considered. In fact, a given uncertainty factor (e.g. the need for or the absence of an infrastructure, the need for complementary technologies, the presence of rival technologies) may affect differently the value of an option along the transition process. If some of the uncertainty factors considered above may well have a negative impact on the positioning option value during the transformation pathway and discourage consequently holding growth options and prolong the term of deferral options, the same uncertainty factors might have a positive impact on growth options during e.g. the de-realignment pathway and create cascading effects.

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