1. Introduction

If it is certain that in the long term new technological solutions should be deployed in the automotive sector to reduce significantly greenhouse gases to mitigate climate change risks and to respond to problems related to oil dependency and security of supply, the range of uncertainties is still quite high as to the solutions that will be adopted and the technological configurations that will dominate our future transport system. These uncertainties do not only pertain to the future state of the transport system for the time horizon 2050 or 2100, they also bear upon the transition process itself and the way it will unfold, its duration, the policies that will punctuate it, the nature of competitive forces that will shape it, the industrial strategies that will be adopted, the technological trajectories that will be determinant and the degree of diversity that will possibly be maintained. This paper deals with the effect of such uncertainties on the choice of investment modes by firms in the automotive sector during the transition process in order to better understand the evolution of system innovations.

Several contributions dealing with the evolution and development of large technical systems (Hughes, 1987; Gökalp, 1992; Davies, 1996; Walker, 2000; Markard & Truffer, 2006) have contributed 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 such phenomena as 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.

Our contribution both builds upon and departs from the literature on socio-technical transition processes (Geels, 2002; Geels & Schot, 2007). It builds upon the socio-technical
transition approach in that it 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 adopts a real options reasoning perspective 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 in a proactive way the sequence and temporality of their decisions. 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 punctuating the transition process – explicit through the dynamic composition of option portfolios – between flexibility and irreversibility - whose form and importance varies along the transition process - structures investment strategies and regulates the possible evolutions of system innovations.

Our approach combines two complementary approaches to analyze the transition dynamics of technical systems in presence of uncertainty and irreversibility: on the one hand a conceptual approach based on real options reasoning and on the other hand scenario building in order to consider likely futures with respect to the evolution of the technological systems concerning clean and efficient vehicles.

Section 2 presents our analytical framework integrating both the socio-technical transition approach based on the multi-level perspective 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 applies our theoretical insights on transition dynamics to the issue of alternative engines and fuels in the automotive sector by using a scenario building approach.
2. Integrating socio-technical transition dynamics and real options

2.1. Real options reasoning

The real options approach (Dixit & Pindyck, 1994; Trigeorgis, 1996) constitutes a fruitful framework to better understand investment decisions in presence of uncertainty. Contrasting with traditional investment rules based on the net present value (NPV), the real options perspective takes into account the capability of managers to react flexibly to environmental changes and stresses the importance of varying uncertainty levels and sources between the different stages of a project in explaining investment modes and decisions. When investments are at least partially irreversible, NPV does in fact not consider the benefits of sequentially organizing decisions in presence of uncertainty in order to better integrate into the decision process useful 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 that might be generated through flexibility.

Several types of options have been generally highlighted in the literature, including the option to wait, the option to stage, the option to expand, the option to abandon, the option to switch, the option 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, the formation or participation in joint ventures, or positioning within a new market. Whereas put options may concern the flexibility to contract the production scale or the possibility to exit 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 born to create flexibility in order to reduce the costs of adjustment 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 acquire in order to realize the project on which an option is hold; (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 the life of the option.

Notice that when there is no volatility, there is no reason to adopt an option strategy since flexibility has no value. By contrast, for a given level of irreversibility, the value of options (of flexibility) increases with volatility. Since an option strategy 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 buy (call) for instance allows to benefit from risky events when uncertainty gets resolved in favor of the investment under consideration by giving a preferential right to the option holder to take actions in order to exercise the option. If on the contrary, conditions end up unfavorably, the investment is not realized.
(the option is not exercised) and the only cost born is the one of holding the option (assumed to be largely inferior to the total investment cost).

Whereas earlier contributions on real options have mainly insisted on the value associated to the option to wait or to defer in presence of uncertainty (McDonald & Siegel, 1986), more recently several contributions have stressed the importance of more proactive option investment strategies such as the option to grow giving firms a competitive advantage and helping them to benefit from early market positioning if uncertainty is resolved in favor of the decisions engaged (Kulatilaka & Perotti, 1998). Even if the logic that underlies both waiting and growth options integrates the value of flexibility in presence of uncertainty, this value does not derive from the same source for each of the options. The option to wait stresses the value to delay investment in order to benefit from the arrival of new information. By contrast the option to grow insists on the value associated with early investment in order to develop the capabilities necessary to facilitate preferential access to future opportunities (Bowman & Hurry, 1993; Kogut & Kulatilaka, 2001).

Both type of options (growth and deferral) advocate to behave in the opposite way if we take the NPV as the reference point. An investment which could be justified according to the NPV rule (NPV>0) may not be engaged if firms behave according to the logic of the deferral option. According to this option, a firm will invest only 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 shifts from a flexible to an irreversible position. In the case of growth options, an investment can be initiated even if the NPV rule advocates to not invest (NPV<0). In this case, expenses may be engaged and 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 the price of entry to create the opportunity to participate to the sequence of expected projects to come.

This ambiguity about the investment behavior of firms under uncertainty compels to have a closer look on uncertainty sources and to differentiate the role of different contingencies which characterize the competitive environment of firms during the different decision stages in order to better understand the evolution of option strategies (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. Such a dynamic perspective is for instance adopted by Bowman & Hurry (1993). They stress the sequential character of discovering, holding and exercising options through the option chain. Also for Nootenboom (2000) the development of an option strategy for firms is a challenging one. It forces them to act under real and radical uncertainty which only gets resolved as firms take actions allowing them to structure progressively their option portfolio strategy (Nootenboom, 2000).

In fact, unlike traditional investment models where projects are evaluated independently and where their values are considered additively, real option models insist on the importance of interactions between the investments of a firm (Trigeorgis, 1996; McGrath & Nerkar, 2004). Taking into account these interactions and their nature leads to consider
options as a means to connect a chain of interlinked projects. In most cases the acquisition of an option is the key for opening other options. Furthermore, since options interact, the choice of an option is likely to affect the value of pre-existing options and the latter may influence the value and the choice of new options. Options can be independent from one another, but they are also often substitutable or complementary among themselves. Similarly, since options within a portfolio are not necessarily additive and since the opening of each option has a cost, the addition of options to a portfolio does not necessarily increase the portfolio value. This leads to consider an option portfolio strategy as a trade-off between different types of options according to the uncertainties actors prioritize (firm-specific uncertainty, technological, market, competitive and/or policy uncertainty). We can thus consider that an option strategy in the socio-technical transition perspective will consist to trade-off in a dynamic way between different combined and/or cascading option types according to the priorities regime actors give to the uncertainties they are confronted with during the transition process.

Before developing further our main arguments on socio-technical transition processes through the real option lens, it is useful to insist on some key points which are at the heart of the debates on the applicability frontier of real options (Adner & Levinthal, 2004; McGrath et al., 2004). These debates stem from the assumptions that underpin financial and real option models. For Adner & Levinthal (2004), although the development of real option models has been greatly inspired by the theory of financial options, in a context where firms can endogenize uncertainty through strategic actions, the validity of the real options methodology to evaluate appropriately investment opportunities can be seriously questioned.

Three assumptions are for Adner & Levinthal (2004), 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 change the intrinsic characteristics of the asset. But, contrary to financial options, the holder of a real option can act endogenously, i.e. can shape the markets and the technologies that influence the option value. Firms do not hold options passively. Rather the decision to hold an option motivates a firm to improve its value by trying to influence 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, on their strategic positioning and on their competitive context. It is thus an endogenous choice. The threat of preemption by competitors has a key role in determining the duration of real options. In term of assessment, longer option durations lead to increase the value of real options and create the risk of overevaluating them. 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. Other authors, on the contrary, stress the importance of taking into account endogenous actions in evaluation models in order to manage uncertainty proactively and account for the strategic behavior of firms (Kogut & Kulatilaka, 2004; McGrath et al., 2004).
We would argue that, the violation of these assumptions, if it complicates the application of option theory to ‘real’ investments, it contributes at the same time to better take into account 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 create value by generating future decisions rights. They act according to the value they attach to the preservation of their future decision rights to realize investment choices. This strategic rationality might thus be the source of option traps (Adner & Levinthal, 2004) since such a rationality may bias decisions in favor of abandoning options (tendency to disqualify valuable opportunities) or maintaining them (tendency to overestimate opportunities). In a collective decision process, optional thinking can thus create decision dilemmas and lead to indecision. In fact the value of an option depends on the specific uncertainty and knowledge profiles of each firm. A corollary is that the value sources of an option are not necessarily the same between firms and 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. To the extent that options concern future investment choices, their value results from the convergence of actors’ expectations and the flexibility of their interpretative schemes concerning their potential in terms of opportunities. In this sense the value of an option is a question of interpreting problems (and solutions) and of competition between possible interpretations and world visions. These perceptions influence in turn the recognition of opportunities and selection pressures, the responses to provide and actors’ adaptation strategies.

The possibility offered by real options reasoning to highlight actors’ strategic rationality in presence of uncertainty allows to integrate into the analysis agency, governance and power issues. In fact holding an option confers the right to participate to the bargaining dynamics within system innovations and to the transition governance process. Holding, abandoning or striking options can here be interpreted as strategies to shape the ability of actors to orient trajectories and to weigh up over the balance of selection criteria during the transition process. The real options approach gives thus an alternative interpretation of the investment behavior of firms to the debate on ‘investment barriers’. Whereas the presence of investment barriers refers to market imperfections, the real option lens insists on the strategic rationality of firms to explain investment behaviors.

2.2. Transition processes, real options and flexibility

We will in this section present our conceptual and 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 to the interactions between the socio-technical landscape, the socio-technical regime and technological niches. These interactions are considered according to their timing as well as their nature. The timing of interactions refers to the synchronic or a-synchronic development of the macro, meso and micro levels. The nature of interactions between these levels can be either stabilizing or disruptive. The interactions according to the combination between these two dimension leads to distinguish different transition pathways and dynamics:
(a) Reproduction pathway of the existing regime

This pathway is characterized by the absence of pressure from the landscape and the 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 in niches. Progressively, the incremental innovations develop and build up internally to improve the performance of the regime.

(b) Transformation pathway of the existing regime

The pressure from the landscape is assumed to be moderate and niche innovations are still not sufficiently developed to respond to these pressures. Regime actors feel thus the necessity to change internally their innovation activities to respond to these pressures. Faced with changes in their selection environment, the regime uses its adaptive capability to reorient its development trajectories. The propagation of these technical developments modifies the regime from the interior. Regime actors might during this pathway import competencies developed by niches if they are not too distant from the regimes’ competencies.

(c) Reconfiguration pathway of the existing regime

Innovations are essentially developed by 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 unchanged its rules. But these innovations can also progressively trigger more profound adjustments within the regime as regime actors begin to experiment new combinations between existing and new competencies and increase their knowledge on new technologies. This process can lead to technical changes or changes in practices, in perceptions and research heuristics by opening up new spaces for the broader adoption of niche innovations. Innovation sequences within niches can thus progressively influence the nature of pressures exercised by the landscape and trigger significant changes in the regime.

(d) De-realignment pathway

In a context where the socio-technical landscape changes abruptly and divergently, the regime is confronted with increasing difficulties and actors lose faith on the ability of the incumbent regime to respond appropriately to these changes. This leads to the de-alignment of the regime and its progressive erosion. The pressure exercised by the landscape creates an uncertainty with respect to the way to allocate innovation efforts and the domains to prioritize. This uncertainty is particularly high when there are no immediate substitutes to the regime. 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 pathway is thus characterized by a prolonged period of co-existence, of experimentation and competition for limited resources. Eventually one of the innovations becomes dominant to trigger the adoption and the institutionalization of a new regime.
(e) Deployment pathway of a new regime

This pathway is also characterized by a strong landscape pressure, but as opposed to the preceding pathway, niche innovations are here sufficiently developed and have the capacity to replace the existing regime. This strong pressure opens up for niche actors windows of opportunities to diffuse their innovations through a process of niche accumulation. When the innovation penetrates the main markets, incumbent regime actors can take defensive actions to improve the performance of the existing régime (sailing ship effect). Such competition ends up by the substitution of the incumbent regime by an innovation initially developed within a niche.

Figure 1

Timing and nature of interactions between the landscape, the regime and niches

![Nature of interactions between the regime and the landscape]

Disruptive

Synchronic

A-synchronic

Deployment → De-realignment

Reconfiguration ← Transformation

Reconfiguration ← Transformation

Source: Geels & Schot (2007)

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, 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 as to 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 fallow is not determined by a beforehand future given system and 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 the transition process, for the reasons just mentioned above, to structure transition dynamics has recently been stressed by Frenken et al. (2007). In order to give a dynamic real option perspective on investments sustaining the transition process, 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 and dominate specific pathways of the transition process (Cf. Figure 4).

**Figure 2**

*Real Options, flexibility and transition processes*

<table>
<thead>
<tr>
<th>Options on the future system</th>
<th>Option to wait</th>
<th>Option to position and to develop capabilities</th>
<th>Option to grow and to diversify</th>
<th>Built-in flexibility option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Options on the incumbent system</td>
<td>Option to keep</td>
<td>Option to switch</td>
<td>Option to combine</td>
<td>Option to abandon</td>
</tr>
</tbody>
</table>

**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 actors to choose, initiate and exercise different types of real options during the transition process. This strategic capacity corresponds also to the capability of actors 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 actors to manage a portfolio of options both parallely (during a given pathway) 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 (substitutable or complementary) can be an additional way to illuminate investment strategies pursued by actors. Such a strategy reflects also the trade-off engaged 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 actors 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 actors. 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 actors and among technologies. If in a situation of uncertainty and incomplete knowledge some mimicry can be observed among actors, this mimicry creates at the same time opportunities to strengthen 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 actors can always keep options on the preceding pathway and others engage option strategies that announce future pathways. Furthermore, actors may not only have different perceptions on the timing of holding options but also on the timing of exercising or abandoning them.

Organizational or 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 (organizational flexibility of the incumbent system) and the deployment pathway through which a new system emerges (repertoire of routines defining the organizational 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 actors to adapt the structure of 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 new repertoires of routines. Structural flexibility may develop gradually through exploration activities and the co-existence of several technical systems. The objective is to create variety with respect to operational flexibility forms and to select the most appropriate operational flexibility form according to the landscape characteristics that might prevail.

Notice that in our framework flexibility management can concern the incumbent technical system as well as the future system to come. 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 in the following option strategies both to the existing technical system as well as 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 have the ambition to prepare and to build up ex ante the structural and operational flexibilities of the system to come.
3. Strategic options and regulation of transition pathways

3.1. Options regulating the reproduction path

During this pathway the uncertainties that characterize the future technical regime orient investments towards traditional technologies and discourage investments on disruptive solutions. Two types of options dominate actors’ strategies and reinforce each other in order to manage the uncertainties they are confronted with.

The first is the option to wait. When the new technical system to come is uncertain and when the investments required are irreversible, waiting is considered to be economically more beneficial than immediate investment. The higher the uncertainty, the higher also will be the value of the option to wait which represents the value of flexibility. Immediate investment, i.e. the abdication of the option to wait (or the option to invest once more useful information is revealed) creates an opportunity cost which is here included to the cost of immediately investing. The option to wait indicates that although the NPV of a project might be positive, it is beneficial to not exercise the option to invest. In other words, the adoption of an investment strategy based on the option value of a project taking into account the uncertainty of the environment increases the threshold value of the investment. In presence of uncertainty, actors invest only if the NPV of a project exceeds its cost by an amount equal to the value of the option to defer (McDonald and Siegel, 1986).

Beside the deferral option, another type of option on the incumbent system can extend the reproduction path. A characteristic of this path is that uncertainty on the future system creates a value for the option to keep the existing system. Delaying exit even if the NPV of a project becomes negative may thus be a rational reaction to uncertainty and irreversibility. The option to keep the existing system may be justified because of the uncertainty on the potential to improve the incumbent system as well as the uncertainty on future alternatives. As suggested by Kogut & Kulatilaka (2001), when organizational change is disruptive, regime actors may hesitate to change radically the system, hoping that future states of the world will allow the incumbent regime to become more attractive. Consequently, in a very volatile environment and when change is costly, the exploitation of the incumbent regime is 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 actors and conduces them to exploit it more intensively until the cost of such learning becomes higher than the benefits expected. Thus, investments on the incumbent regime may continue until the economic losses exceed the option value to keep the incumbent system. In fact, the more important are uncertainties on future technological alternatives and their adoption costs, the more regime actors will rationally choose, before becoming confident on future developments, to persist on technologies that might reveal 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 regime actors are rationally hesitant to support the cost of change towards competencies which might become obsolete if the
environment returns back to its precedent state or because of the risk to choose the wrong alternative.

Notice that in presence of several alternative technologies, the value of the option to keep will also be higher since the value of waiting for one specific technology will depend on the value of waiting for all other available alternative technologies. Therefore, the decision to invest in a new regime might depend on the technological system possessing the highest threshold value. In fact, when several technological options compete, their option value to wait may differ. Thus, the return necessary to trigger an immediate investment on a new technology may depend not only on the value of waiting for this technology but also on the value of waiting for the other technologies. Technologies may thus behave as a hedge for each other and increase the value of waiting compared to the case where they are considered separately.

A real options reasoning provides also a reason for the hysteresis phenomenon (Dixit, 1992): 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 investment in the new technical system 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.

Before concluding our analysis of the reproduction pathway in terms of real options, it is important to insist on the perception actors have on the uncertainty they are confronted with and which play a key role with respect to the type of options they choose and their investment strategies. Environmental uncertainty can be perceived as exogenous or endogenous by actors (Folta, 1998). While exogenous uncertainty is principally resolved by the passage of time through the arrival of new information, endogenous uncertainty can be reduced through strategic investments and allow actors to influence the evolution of the environment in their favor (Sanchez & Mahoney, 1996). Although both types of uncertainty increase the value of real options, they create, as we already stressed, opposing pressures on investment decisions. The uncertainty on the new technical system, which is perceived as exogenous during the reproduction path, induces actors to wait until such uncertainty reaches an acceptable level before engaging investments. We can, at this level, distinguish exogenous uncertainty specific to an industry (or regime) and exogenous uncertainty specific to a firm (or project). When exogenous uncertainty shifts from the local (firm or project) to the global level (industry or technological domain), actors defer more investments. As opposed to exogenous uncertainty, endogenous uncertainty creates learning opportunities and thus can encourage firms to invest. The endogenous uncertainty which characterizes the reproduction trajectory justifies the option to keep and exploit the incumbent system even if ex ante the projects considered can have a negative NPV.

Notice also that, even if in our case, the option to wait dominates actors’ strategies during the entire reproduction pathway, 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 of the option strategies pursued by firms because of changing landscape conditions affecting uncertainty. The transition issue leads in fact
to insist on the sequential logic of investments. Therefore, the waiting option in isolation does not allow for taking into account other possible options such as e.g. the options to position, to grow or to abandon. According to the type of uncertainty considered, the option to wait may have a different cost and all investments may not have the same degree of irreversibility if actors have the opportunity to abandon or to switch technologies. In the following we assume that the increasing endogeneity of uncertainty during the transition process confers an increasing strategic importance to learning capabilities and to proactive irreversibility management by actors. If actors perceive uncertainty as endogenous it becomes more appropriate to consider option strategies sequentially. The sequentiality of the transition process allows in fact to diversify option strategies. It also suggests that investment decisions should not be evaluated according to the efficiency of a single action but rather by considering the efficiency of a set of sequential actions and through the path dependency effects created by the transition process.

3.2. Options regulating the transformation path

As for the reproduction pathway, the transformation and reconfiguration trajectories aim to foster from the interior the ‘breathing spaces’ of the existing regime. Nevertheless, if the reproduction path exploits the organizational flexibility of the incumbent system, the objective of the transformation and reconfiguration pathways is to increase the structural flexibility of the incumbent system.

Option strategies during the transformation pathway result mainly from the will to trade-off between exploitation and exploration activities. Even if actors develop strategies related to their existing competences, they at the same time enlarge their competences on alternative niche technologies to improve their long term capabilities. The regime as an adaptive system cultivates on the one hand essentially new technologies that do not put into question systemic competences developed in the past and on the other hand adopts a search strategy for new emerging solutions. The principal feature of this trajectory consists in initiating a proactive behavior (and which becomes stronger in the following paths) on emerging solutions in order to direct risk and to benefit from it rather than to suffer it. Efforts on emerging solutions which are far from being stabilized allow actors to discover 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.

We can within this path again distinguish two types of investment options. A first strategy called switching option consists in minimizing the distance between existing competences and those new to be acquired and to be mobilized in the mid-term. The aim is to smooth the transition process and to avoid disruptive changes. The strategy consists thus to invest in new technological options based on their switching value. This involves investments in technologies which increase the value of switching towards new

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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 which is close. The second definition refers to options mentioned in section 3.4 and concerns changes within the same technological system of production modes (in terms of inputs, resources, processes or outputs). We dedicate the term transition to the passage from one technological system to another which is profoundly different.
competences by at the same minimizing the switching costs through an innovation and learning logic on the perimeter of the incumbent system. Such an option corresponds to the will to exploit the potential of structural flexibility of the existing regime. Here again, it is mainly the uncertainty affecting the long term evolution of future technologies which determines actors’ propensity to hold and exercise switching options.

The second strategy is related to the **positioning option** (McGrath, 1997). Positioning or capability investments constitute a first step towards holding options on the long term and which give to actors the right but not the obligation to adopt new technologies. Such investments catch the importance to invest in opportunities which might be critical to the future growth and success of regime actors. This corresponds for actors to strengthen their absorption capabilities for technologies developed in niches and to possess competences that might reveal to be critical in the future. As noticed by Kogut & Kulatilaka (2001), the radicalness of an innovation is less linked to the newness of a technology than to its conformity with existing knowledge within the regime and more particularly with the way work is organized, knowledge and power are distributed among regime actors and those engaged in niches and in technology creation. The essential purpose of positioning options consists thus to become familiarized with this new organizational context and the knowledge that shapes it. We assume here that such positioning options allow firms to acquire decision rights on following pathways and on other type of options during the transition process.

As for the option to wait, the value of positioning options increases with uncertainty but, contrary to the option to wait, causes an active commitment by the actors. It turns out to be useful to invest for instance in R&D even if *ex ante* the NPV of a project is negative. The higher the uncertainty, the higher will be the incentive to realize positioning investments. Projects with higher uncertainty have also a wider range of potential consequences and thus include also more growth opportunities. Since the value of the option to position is increasing with the importance of opportunities that it can generate (Kogut & Kulatilaka, 1994), the tendency of the regime during this pathway might be to invest in options having a wider range of “opportunity windows”. An investment involving a multiplicity of applications will for instance have a higher value than an investment with a narrow set of potential applications. Positioning investments will thus in this context have the tendency to focus on generic or transverse technologies. The strategy pursued by actors will be to develop a generalist competence profile which better corresponds to a wider set of environmental outcomes likely to occur. It is also possible that during this pathway some actors, particularly in niches but also within the incumbent regime adopt more targeted and specialized positioning options either to differentiate themselves from others and to accelerate the transformation path or to position themselves as leaders in the transition process by preempting following paths.
Positioning options may be assimilated to a trial-error process. Since alternative technologies are emergent and their scientific and technical proprieties are not completely established, positioning investments may have a high rate of failure. The transformation path can therefore be dominated by a high rate of abandon of explorative activities already engaged. It is thus important that actors integrate in their option strategy, the abandonment risk of projects because of unforeseen negative events. This should be the more so when the options considered involve high cost R&D activities. Positioning options may thus lead either to abandoning projects on which options are held (when uncertainty is resolved unfavorably) or motivate additional resource commitments (when uncertainty is resolved favorably). Such a strategy refers to the sequential investment logic of combined options. For instance, investments in generic technologies, as opposed to investments in specific technologies may be considered as resulting from a combination of the option to wait, the option to position, the option to abandon and the option to grow (Cf. Figure 3). Whilst granting to regime actors the right for flexibility to commit additional resources to opportunities created in case these might reveal promising (option to grow), generic technologies increase the value of the option to abandon since the resources committed to a failed project can be transferred more easily to other more profitable projects by minimizing the losses attached to the costs of maintaining the positioning option. In fact, during the transformation pathway, 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 phase) since the value of the option to abandon makes up part of the value of the option to position. It is the possibility to abandon and the possibility to act sequentially that confers to the option to position its attractiveness.

It is in this phase that the propensity of actors developing option traps might be the strongest. Actors’ perception of emerging technologies and their evaluation of options may during this path be highly dependent on their beliefs, their motivations, their opportunity set and their vision which are often biased by their past experience. The capability and the will of actors to influence strategically technological uncertainties in a context characterized by technical controversies, may thus motivate them to try to shape
contingencies in their interest either by favoring the abandonment of some options or by supporting others in order to orient future trajectories. The incentives of actors involved in technological niches might for instance prevent the appropriate and timely abandonment of emerging options because of the importance they attach to these options, the higher potential they associate to them and the stakes these options represent for them, even though learning outcomes reveal to be disappointing. As for regime actors their behavior may be biased towards abandoning real opportunities.

As shown by McGrath (1997), the value of positioning options does not only depend on factors specific to the technology itself (cost of technology development which determines the option price) but also on the uncertain environment within which it might be deployed and which determines the stream of revenues and the costs of its commercialization (the value and the cost of the underlying assets). Revenue streams may be influenced by several uncertainty sources such as the structure of demand, the adoption speed of the technology, blocking strategies by incumbent actors, expropriation strategies, the existence of substitute technologies, and imitation by competitors. Commercialization cost uncertainties can concern the access to or the development of infrastructures, the development of complementary technologies. Some contingent factors, such as infrastructural requirements and the need for complementary technologies can have particularly during the transformation path a negative impact on the value of positioning options. Although actors may develop strategies – through amplifying pre-investments - to influence and endogenize favorably the uncertainties affecting these factors, it is likely that the need for a new infrastructure or complementary technologies demotivates during this pathway additional resource commitments (delaying growth options and thus following paths) and rather favors a wait and see posture prolonging the reproduction path. Notice however that, the impact of these factors on the option value may be different according to the pathway considered. In fact, the need for infrastructure or complementary technologies may well influence positively the value of growth options during the de-realignement path since investing quickly in network assets and on complementary technologies might have a vital strategic effect during this path on the selection process between technologies and the adoption behavior of users. In this case the uncertainty which dominates is relative to the competition outcome among technologies and should positively influence the value of the growth option and reduce the critical threshold level to strike it. Additionally, the intensity of network and complementarity effects should enhance strategic growth options (Lin & Kulatilaka, 2007). A similar effect should also be observed for built-in flexibility options during the deployment pathway.

### 3.3. Options regulating the reconfiguration path

During the reproduction and transformation pathways the regime changes from within and regime improvements are supported by internal resources. Furthermore, emerging technologies evolve independently from dominant technologies even if regime actors adopt positioning strategies. The attention given to emerging technologies in the configuration path is however not of the same nature as in the preceding phase where actors develop essentially their absorption capacity of peripheral technologies without necessarily establishing links with incumbent technologies. By contrast, during the reconfiguration path, the progress of these new technologies and which often have generic qualities attract increasingly the attention of actors because of their potential to improve the incumbent
system. In fact, the principal and distinctive feature of the reconfiguration path is the intensity of interactions between existing and alternative technologies even though these are not able to compete directly with and substitute mature technologies.

Pistorius & Utterback (1997) define technological interactions by examining the nature of mechanisms through which a given technology can improve or inhibit the growth rate of another technology. Their contribution goes beyond the simple vision of inter-technology competition in order to analyze the strategic options that may be deployed in a multi-mode interaction context between emerging and dominant technologies (of which competition, symbiosis and predator-prey interactions are three possible modes) and in a dynamic framework considering the transition from one mode of interaction to another.

We will assume that symbiosis or hybridization between the existing and the emerging regime represents the distinctive trait of the reconfiguration pathway. Such symbiosis aims at strengthening the structural flexibility of the incumbent regime by intensifying its interactions with alternative technologies. These links create, in addition, a self-enforcing diversification dynamic since without fundamentally questioning the incumbent technological system, hybridization with emerging technologies increases the resilience of the dominant system.

Hybridization consists in coupling technologies developed in niches with existing technologies. It is intended to link the innovation developed outside the regime to a specific problem within the dominant regime in order to overcome its performance limits. Such a technological coupling can generate a variety of relations in order to offer either better or new functionalities. For the emergent technology coupling is often necessary in order to favor its market growth rate, whereas for the incumbent technology coupling can be justified by the need for optimization and the need to integrate new functionalities. The technologies generated through hybridization are characterized by mutual interdependencies which determine their respective survival. The emerging technology can at the beginning be integrated as an additional element or auxiliary device into the incumbent technology in order to improve its performance and become after a period of more sophisticated hybridization, the core element of the system. The advantage of such hybridization is to escape direct competition with the incumbent system (Islas, 1997; Raven 2007).

The large scale use of an emerging technology during its hybridization phase can lead to important cost reductions, improvements in reliability and performance and to better knowledge and acceptance of the technology by users. In fact, hybridization between the new and the existing technologies, introduces a qualitative jump in the learning environment of both technologies which have an a-synchronous position within the learning process going from experimental exploration to commercial exploitation (Llerena & Schenk, 2005). Due to the fact that each phase of the learning process is subject to decreasing returns, the appropriate management of the different learning phases can be a crucial element for the success of a technology. This leads us 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 an alternative technology, hybridization avoids to prolong beyond the time necessary some costly exploration activities and to better manage the transition from exploration to exploitation. In the case of the mature
technology, its combination with the emerging technology may set in motion a new period of intensive exploration in order to optimize the hybrid configuration.

Notice, however, that hybrids are transition technologies which may not survive in this form forever. Often hybridization is not a long term solution since the coupling of different technologies may be a source of inefficiency and create suboptimal situations. In this sense hybridization is typically a transitional strategy. Furthermore since, hybridization introduces some flexibility into the incumbent system by forging links with new technologies, lock-in situations may be developed through such links, when a short term solution, easier to implement, hinders the accomplishment of long term objectives by blocking the breakthrough of more radical technologies. This may put radical technologies in a difficult situation since they have to face an improved incumbent system (sailing ship effect).

This framework can be combined with real options reasoning in order to analyze more precisely the reconfiguration pathway. We use the analytical approach suggested by Luehrman (1998a, 1998b) in order to consider the hybridization strategy from the real option perspective. In the figure below (Cf. Figure 4), the options’ space is defined according to two metrics to evaluate option values: on the one hand the Value-to Cost ratio of technological assets to be developed which also includes the value of flexibility and on the other hand, the Cumulated Volatility ($\sigma \sqrt{t}$) with $\sigma$ the volatility per period of the technological assets’ returns and $t$ the expiration date of the option. The option value of the technology increases when, on the figure, one moves towards the South-East. Notice that applying NPV, one would accept all projects situated within regions 1 and 2 and reject all other projects. Luehrman shows that a real option reasoning refines the strategic space of actors since through such a reasoning one does not only take into account the current position of projects but also their possible positions in the future. The decisional space thus is not limited to a binary choice between « invest » and « do not invest » (regions 1 and 6) but taking into account uncertainty leads to better qualify the decision space.

**Figure 4**

*Option value of mature (M), emergent (E) and combined (C) technologies: Symbiosis*

Source: Luehrman (1998a, 1998b) and authors
Figure 4 applies this reasoning to the interaction case between emerging and mature technologies. We assume that the mature technology achieves 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 actors hesitate between two options: abandoning or keeping the technology. The combination with the emerging technology changes however the perspective on the mature system. The hybridization with the new system introduces a new phase in the perception that actors have on the incumbent system since they associate new opportunities to the incumbent technology even if these are considered to be uncertain. As shown in Figure 4 hybridization favors the option to keep the mature technology (shift down-right), in other words it increases uncertainty with respect to its future and its expected Value/Cost ratio (Region 2). A similar evolution takes place for the emerging technology. Its hybridization with the mature technology shifts it from the regions « 5 or 4 » towards the right (regions 4 or 3) since it increases its positioning and/or growth option value and reduces the option value of abandoning or waiting. 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 (we have here a case where M is the predator and E the prey). Another scenario could progressively lead to the domination of the emerging technology by abandoning the mature technology (E becoming the predator and M the prey).

It is possible to characterize the three pathways that we analyzed by the opposition between two distinct innovation approaches that might influence the perception of options on emerging technologies: on the one hand the logic of large technical systems (existing regime) and on the other hand the logic of large projects on emerging technologies (niches). The different perspectives and incentives of actors following the two different innovation logics and the nature of allocation of resources which underlie them correspond to two different strategic visions of the options held on the new emerging system. Whereas for the regime actors the initiatives engaged within niches 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) express this contrast through the difference between « holding the option » and « being the option ». The de-realignment and deployment pathways through a tighter interaction between niches and the existing regime should lead progressively to a convergence of these opposite innovation logics and perceptions.

### 3.4. Options regulating the de-realignment or diversification path

The main difference between the pathways already analyzed and those of de-realignment and deployment rests upon the following argument: whereas the first three pathways aim to exploit the ex post flexibility potential of the incumbent regime, the last two pathways aim to preserve ex ante the flexibility of future technical systems. Furthermore, a difference distinguishes the de-realignment pathway from the deployment pathway. It concerns the way flexibility is maintained during each of the pathways. During the de-realignment phase the organizational 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 absence of a dominant system. Flexibility is thus maintained in order to respond to the emergence of a dominant design in a context where different technologies co-exist in a competitive tension. Such technological co-existence is mainly motivated by the complexity of technological systems (Nair & Ahlstrom, 2003). For such systems, the evolution of the whole system often depends on the evolution of its sub-systems. A continuous innovation flow within sub-systems may in fact allow the whole system to survive by narrowing the gap between rival technologies and prevent a given system to have an overwhelming advantage on others. Furthermore, the interactions and complementarities progressively developed between technologies may influence firms’ investment modes and contribute to better understand and intensify the links between competitive technologies. Equally, regulatory and policy measures may influence these interactions and delay the adoption of a dominant design and prevent the exclusion of losers. This path can also be characterized by the importance of what Nair & Ahlstrom (2003) call meta-technologies which by impacting positively several rival systems can enhance their survival chance and delay the emergence of a dominant system.

During this path the comparative assessment of the merits and limits of each technology, in presence of multiple evaluation criteria, can also delay the definitive selection of a technology. In fact, rival technologies can be evaluated according to several dimensions. The difficulty to hierarchize preferences in an uncertain environment can thus introduce a technological indecision where no solution dominates others according to all the criteria considered. Furthermore, even if some technologies do not achieve a level of complete parity in term of global performance, they can achieve the level of parity required to avoid their extinction (Nair & Ahlstrom, 2003). The institutional framework, the social, economic, strategic and political context, influencing practices, bargaining and power relationships can also blur differences between technologies. This explains why some ‘sufficiently good’ options can be preserved during the selection process. During this path, actors may well assess, perceive and understand differently the factors that determine the benefits and risks of each technological system, and support according to their experience and history, a different system in order to respond to the same objective. In other words we may characterize this diversification path by the concept of equifinality where the final state is likely to be achieved by starting from different points and through different trajectories.

Beyond technological uncertainty, actors’ strategies take progressively also into account during this path market uncertainty. Such uncertainty derives from demand volatility as well as from changing user needs. Uncertainty bears also upon the combination of technological attributes (functionalities) that the market will definitely select. Issues relate in this framework on the possible evolution of market segments and the applications considered as being attractive on those emerging segments in order to create and to capture commercial opportunities when partitioning the market between rival technologies.

Market uncertainty may be managed by strategic investments in niches (Kemp et al., 1998). In fact, inter-technological competition and diversity create during this path, opportunities for developing more focused segmentation strategies allowing technologies
to occupy segments in a differentiated way. Such differentiation mitigates failure risks and reduces also the intensity of inter-technology competition for the same resources. Actors explore during this path different segments by trying to exploit specific demand attributes. Strategic niche accumulation offers here 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 diversity instead of prematurely selecting markets (Raven, 2007).

The main options during this path are options to grow and options to diversify. The importance of growth options is justified by the competition intensity among firms whose investments affect and shape 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 the deferral and positioning options increases with uncertainty, the value of growth options increases more (Kulatilaka & Perotti, 1998; Folta & O’Brian, 2004) in a context where the uncertainty about the timing of adoption and deployment of technologies are exacerbated and where there exist competitive advantages to early entry in the market. In fact, early investment does not only affect production costs but also the strike price of the growth option since it influences competitors’ decision – inducing them to behave less aggressively – and consequently the growth option value.

If some uncertainty sources (market competition) favor growth opportunities, other uncertainties (technological competition) motivate the development of diversification opportunities – switching options – because of the unstable nature of the pathway. The tension between commitment and flexibility is less expressed during this path by the choice between deferral and growth options but rather by the trade-off between growth and switching (diversification) options. Whereas growth options commit early on market opportunities, switching options focus on structural flexibility to control technological uncertainty. Thus, the value of the option portfolio depends during this path on the tension to be managed between the growth potential of each underlying asset and the possibility to switch assets (Anand et al., 2007) and to preserve structural flexibility. Unlike the transformation path where the possibility to choose between several technologies valued the option to wait and to position, here technological uncertainty and competition value switching options.

In order to better grasp the dynamics of strategic investments during the de-realignment path and its specificity compared to preceding transition paths we will in the following adopt an option portfolio approach and insist on portfolio effects (Bowman & Hurry, 1993; MacMillan & McGrath, 2002; Anand et al., 2007). The nature of interactions between investment options and between underlying assets (complementary and substitutable), and their effects on the value of the portfolio can in fact be critical in shaping the evolution of the transition process since each strategic investment alters the investment conditions on other strategic options (e.g. the impact of striking an option on other options in the portfolio). It is therefore no more sufficient to take decisions on each option individually but to take into account these interactions in the management of options in order to determine the effective configuration of the portfolio. A portfolio effect may be

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2 The option to switch through diversification refers here to the ability of firms to respond to the technological selection process by adopting a hedging strategy broadening the variety of technologies developed.
observed each time when the value of an option is contingent on the value of other options in the portfolio. Such portfolio effects induce non-additivity: the portfolio value differs from the value obtained by adding linearly the different options. There may for instance arise dynamic substitution effects between investments in case for instance of a dominant technology emerging in the long term. Complementarity effects can also emerge when the adoption of a technology makes other technologies more or less attractive.

In presence of a portfolio effect, the analysis cannot in fact consider only the volatility (\(\sigma\)) of underlying assets but should, as shown by Anand et al. (2007), also consider the correlation (\(\rho\)) between expected gains of underlying assets and the exercise constraints on options (as when there is a capacity constraint that limits the ability to pursue different investments 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 e.g. new growth options to the portfolio decreases the marginal value of each additional option (Vassolo et al., 2005). This is due to the fact that the portfolio value depends \(\text{in fine}\) on the number of options that can be exercised and each new option added has a lower probability to be exercised. The expectations of actors on these exercise constraints constitute consequently a natural limit to diversification. Correlation between assets has also complex effects on the portfolio value. Not taking into account these effects can for instance lead to underestimate the option value to diversify and of complementary investments. Whereas the option value to diversify (to switch) increases with a negative correlation (mutually exclusive technologies), a positive correlation, which can be assimilated to a complementary relationship between underlying assets increases the value of growth options. Thus, different correlation choices can impact differently the value of growth and switching options. For instance, even if the marginal contribution of a growth option is very low, firms may add new options because of their positive impact on the option value to diversify (Anand et al. 2007).

It is important to better grasp the opportunities attached to different types of options and the possible interaction effects among them by reconsidering the distinction between technological and market uncertainty already presented. This should allow us to better analyze the option portfolio strategies and the trade-off between different types of options according to the different paths of the transition process. One important reason to distinguish between both types of uncertainty is that they affect the value of options differently. As argued by Anand et al. (2007) whereas in the presence of a technological uncertainty the value of the option to diversify dominates firms’ investment strategies, in presence of a market uncertainty it is the growth option value (or more generally the commitment option value) that dominates.

**Technological uncertainty** refers to a situation where firms must decide to choose among alternative technologies for a given market. Two aspects are here worth emphasizing: (1) the first mover advantages which will allow one or several technologies to survive and (2) the negative correlation between the values of rival technologies. The first aspect improves the value of commitment. As we already stressed uncertainty created by technological rivalry increases the option value to wait, but it also increases the value of positioning (transformation path), hybridization (reconfiguration path) and growth options. Particularly, during the de-realignment path the waiting option can have
detrimental effects. A greater uncertainty during this path because of greater technical diversity and competition can increase the value of commitment more than the option value to wait and to abandon. Unlike the option to wait, in the case of commitment options, uncertainty motivates actors to be technological leaders in order to orient the emerging technological regime.

The second aspect relates to switching options. Under negative correlation between assets (rival technologies) as one technology emerges progressively as the dominant design, the value of other technologies will drop significantly since only one technology is likely to survive in the long term (mutually exclusive technologies or perfectly substitutable solutions). In this case, an option to diversify (hedging strategy) 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). Lint & Pennings (2002) show however that if a negative correlation between two technologies favors diversification, the value of flexibility is only attractive if the investments committed to keep both options open are relatively modest. In case these costs exceed a certain threshold, only one technology is developed. A second possible factor affecting the diversification strategy is that as only or some technologies will succeed, a severe exercise constraint (m low) will strengthen the negative correlation effect on the portfolio value. In other words firms will be motivated to hold growth options on alternative technologies which will be profoundly different or distant.

These explanations converge to suggest that a firm facing technological uncertainty will be motivated to invest into a large portfolio of negatively correlated assets (commitment options) even in the presence of severe exercise constraints (Anand et al., 2007). Because of the important negative correlation among the underlying assets, the value created by the option to diversify should be greater than the loss induced by the decreased probability to exercise commitment options. In other words, a firm facing technological uncertainty should be more motivated to hedge against the risk of lockout even if the value of the growth option is negligible. The portfolio will thus be characterized by a large ratio n/m. Option portfolios in presence of technological uncertainty will be structured around assets negatively correlated (-1≤ρ<0) and will be relatively extended in comparison to the capacity to exercise the options acquired.

The situation in presence of market uncertainty will be different concerning the correlation choice among assets and the interdependencies between options Anand et al. (2007). First, the choice between different markets on which growth options are hold will likely be positively correlated (positively correlated growth rates) or at least will be uncorrelated in order to exploit the growth potential of demand. Furthermore, with a positive or zero correlation, the potential value of diversification will be low, so that it will be preferable to choose so many commitment options as it is possible to exercise and not more (i.e. convergence towards a ratio n/m=1) because of the decreasing marginal value of an additional commitment option on the portfolio value. In presence however of a low positive correlation (or zero correlation), it can still be optimal to increase portfolios’ breadth in order to preserve flexibility (n/m≥1). Nevertheless, this ratio will always be inferior compared to the case of technological uncertainty characterized by a situation where only one technology could win the competition.
By adopting a sequential and dynamic approach we can put forward the following proposal: if technological uncertainty dominates option portfolio strategies during the transition phase between the transformation and the de-realignment paths, market uncertainty dominates portfolio strategies during the transition phase between the de-realignment and the deployment paths. Furthermore, once technological uncertainty is reduced, technological options will also have the tendency to be focused on positively correlated assets (i.e. on complementary ones) reinforcing each other mutually. 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 (Cf. Figure 5).

**Figure 5**

*Option portfolios (OP) according to technological and market uncertainties*

![Option portfolios diagram](image)

Source: MacMillan & McGrath (2002); Anand et al. (2001), adapted and completed by the authors

### 3.5. Options regulating the deployment path

The main difference between the de-realignment path and this pathway in terms of flexibility management is the following: whereas the former creates technological diversity to maintain flexibility, the latter is based on *built-in flexibility* within investments made. The organizational flexibility is preserved through options incorporated within the new technical system. Such a built-in-flexibility can reduce path dependency and can help to avoid lock-in into undesirable sub-optimal solutions by supporting the introduction of new innovations in the technical system (e.g. successive technological generations). Notice that the more the built-in-flexibility is perceived as critical, the more the value of growth options on alternative technologies will be high during the de-realignment pathway. We thus observe once again a portfolio effect because of the sequential interdependency between the different transition pathways.
This path is generally characterized by the commitment of heavy investments since the aim is not only to invest in the development of technological knowledge but also to deploy resources and assets to develop the infrastructures and to introduce the technologies on the market. These infrastructures are often complex (transport system, production system, energy supply system) and require years to be deployed and are generally conceived to operate during decades despite the uncertainties over future states of the world under which they will be exploited. The new technical system can be assimilated to a set of complex product systems, and of capital, engineering and information and technology intensive physical networks (Hobday, 2000). These complex technical systems are characterized by high uncertainty during their design phase and by long construction processes. They manifest also long operational life-cycles, frequent interactions between operation, development and design phases long after the end of the project. Several technical systems can co-exist but what defines mainly this pathway is the strengthening of the interdependencies between the components of the new regime. Such a regime should for instance have the tendency to evolve towards integrated architectures made of interconnected components and sub-systems. The replacement or the suppression of an element within the system may thus affect other elements and the operational and performance features of the whole system. Such systems will also be characterized by different types of standards including technical social norms and dedicated organizational practices. These standards and practices will have the tendency to co-evolve with the system and will allow for compatibility, interoperability between the components of the system.

In presence of uncertainty, investing in a new technical system or in a new infrastructure is always a complex decision. The real options approach can allow here to bring some insights on the design, development and investment strategies by insisting on the potential to preserve the flexibility of the technical system and of the infrastructure during the deployment pathway. The option strategies during this phase will consist to avoid irreversible commitments concerning the design of infrastructures for future generations. The aim should thus be to think about the openness and the regenerative capacity (redundancy) of technical systems and infrastructures in order to allow them to economically adapt to the evolution of the environment. In the extreme case where such flexibility is not taken into account, the technical system may be confronted to premature obsolescence. Whenever the evolution of the environment is difficult to predict, it may be critical, as early as the design or the development phases of the technical system to think about how to organize the operational flexibility of the new system and of the infrastructure. The incorporation of options into the definition of the technical system should make the latter more apt to economically adapt to operational changes resulting from technology or industry evolution. Since deployment options (built-in-flexibility options) imply generally the substitution or the addition of critical functional elements within the technical system, a problem during the set-up of a portfolio strategy in presence of budget constraints and limited information on the value of each option should be to determine the outlays to commit in order to incorporate the appropriate options from the very design phase of the technical system. In fact, the more one invests in one option, the less it will be possible to invest in other options. Several types of options can during this path be incorporated within the technical system in order to maintain flexibility in the face of a volatile environment (Trigeorgis, 1996; Gil, 2007):
**Options to expand** are those which built-in flexibility in order to engage at the appropriate moment the changes required to increase the capacity of the system in response to future events justifying economically its expansion. These options may also concern projects whose aim is to develop dynamic **technological platforms** as in the case of complementary technologies and in the case of substitution between successive technological generations.

**Stage or time-to-build options** spread the development of projects supporting the technical system over several stages. The completion of each stage represents an option on the next stage. Actors have here the option to abandon the execution of future stages if uncertainty resolves unfavorably. The option to stage may limit investment costs by at the same time accelerating the moment from which the invested capital may generate revenues. Such an option may also restrict capacity if the expected growth does not materialize or if environmental conditions deteriorate.

**Switching options** reflect the will of actors to pay a certain premium in order to adopt a flexible technology, rather than a rigid one, which can modify its operational mode by switching inputs, production processes or outputs. Such options built in operational flexibility.

One of the difficulties concerning the management of options during this path comes from the fact that once the technical system is in place, it can be very difficult and costly, because of path-dependency and multiple 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. It is useful to consider here the very architecture of the technical systems by referring to the modularity of their components. In fact, it is possible to assume that the emerging technical system may take two possible architectural forms. It may either evolve towards a **modular system** or an **integrated system**. These two extreme architectural forms highlight the differences in terms of option management and built-in-flexibility during the deployment path.

The literature on the design of modular products (Ulrich, 1995; Baldwin and Clark, 2000; Schilling & Steensma; 2001) 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. Baldwin and Clark (2000) stress the advantages of modular systems by insisting on their capacity and their potential to facilitate the creation and the exercise of options. They justify investments in modularization by mainly the three advantage it provides: (1) it makes complexity easier to manage; (2) it opens the possibility to pursue exploration activities on several modules in parallel, and (3) it allows a higher tolerance towards uncertainty in the sense that particular elements of a modular system may be renewed after an unpredictable event as long as the design rules established at the very beginning in order to maintain the coherence of the system are respected. In other words, modular systems have a built-in-
flexibility capacity which is not given as such for non modular systems. In fact in presence of an 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. Figure 6, illustrates the way the option structure of a system changes by evolving from an integral to a modular architecture. Such modularity can be key to exercise switching or stage options or to develop technological platforms. This built-in-flexibility potential of modular systems refers to the advantages, put forth by Merton (1973) more generally, of holding a «portfolio of options» (modular system) rather than an «option on a portfolio of assets» (option on a system).

The degree of modularity of the technical system during its deployment should not only have, as we have already stressed, an impact on the value of growth options during the de-realignment pathway but should also contribute to loosen the constraints restraining the exercise of these options and thus increase diversity during the deployment pathway. Such modularity should also favor the longer co-existence of competing technologies by supporting the extension of the learning processes necessary to the maturation of less advanced technical solutions.

**Figure 6**

*Potential of option creation and strike of integrated and modular systems*

An initial integral technical system can be modularized in order to improve its built-in-flexibility. Modularization entails however a cost which is increasing with the complexity of the system and which must be compared to the option value of modularity (Cf. Figure 7). Considering the increasing costs of modularity with complexity and the difficulties to break interdependencies, an alternative strategy can consist to preserve in advance options within the integral system (Gil, 2007). In other words, in presence of an integral architecture a first phase can consist in comparing the costs and benefits of modularization with the costs and benefits of option preservation for a given level of complexity of the technical system. Gil (2007) focuses on the key role of option preservation during the definition and design phases of integral technical systems in order to more easily exercise them if uncertainty resolves in their favor. The main objective of preservation is to make the definition of the technical system resilient and to create operational flexibility within the limits of foreseeable changes that may affect the integral system during its deployment or operational life. Notice however that such preservation...
can require major investments in order to confer to the integral system a certain form of dynamic flexibility. Thus, when the technical system is integral, its long operational life may motivate to keep options open in order to allow the system to adapt to environmental changes and to technological evolution. The value of preservation will be to improve the incorporation of options into the definition of the new technical system.

**Figure 7**

*Trade-off between modularization and option preservation in the case of an integrated system*

![Graph showing trade-off between modularization and option preservation](image)

As shown by Gil (2007), preservation increases the strategic value of options. It also increases the value of the technical system within which these options are incorporated since it reduces the cost of exercising these options in the future, provided that the design which have motivated preservation still holds with the passage of time. However, the investment 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 born 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 than the following: should the system pay more during its emergence 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 preservation increases when the perceived uncertainty, that the option will be exercised, is low (high chance that the option will be exercised). A low uncertainty will often be associated to options that will likely be exercised in the short term. On the other hand, the likelihood that the future differs from initially expected scenarios should increase with the distance of time. In a context where budgets are limited and where information on the future is incomplete the propensity to preserve short term options rather than more risky long term options should be grater. The contribution of Gil (2007) distinguishes furthermore two types of preservation: passive and active. Passive preservation relates essentially to the design effort made in order to keep the space necessary to allow the system to exercise some options in the future. Active preservation includes beyond the design effort, physical investments to preserve such options and is thus more costly.
The decision to preserve each option within a portfolio depends mainly on two factors (Gil, 2007): (1) the assumed uncertainty if yes or not the option will be exercised in the future, and (2) the degree of modularity of the technical system within which the option should be incorporated. The attractiveness of preservation decreases with increasing uncertainty of exercising options and with increasing system modularity. However, for an integral system, even if a high uncertainty may exclude active preservation in order to avoid high irrecoverable costs, it may still motivate passive preservation. In fact, although uncertainty may be high, in presence of an integral architecture, it may still pay to invest in passive preservation in order to keep the possibility to incorporate options that might be exercised in the future (which however does not exclude a significant cost increase of exercising these options). But, an active preservation can also be motivated when the cost of exercising an option without such preservation is perceived to be exorbitant. By contrast, in presence of a highly modular system, even if uncertainty is high, preservation becomes unnecessary. This result relates to mutually exclusive investments since investment in modularization helps to control the cost of exercising options without requiring preservation. Thus, in the case of an integral system facing a low uncertainty, investments in active preservation should be promoted in order to increase the value of options and to reduce their exercising costs. But, such preservation should become less attractive with both high uncertainty and high modularity, two factors which in themselves have also a positive impact on the value of options.

These two configurations (integral system versus modular system) relate to two possible extreme states towards which the deployment path might evolve. They at the same correspond to two possible structures of a given industry: the first based on a concentrated structure and the second, a more decentralized one organized around independent actors. In a technical system aiming to preserve as much as economically feasible the diversity developed during the de-realignment path, modularity can help to value the heterogeneity and the variety of resources (inputs) available as well as the heterogeneity and variety of demand and markets (outputs). This double objective of preserving both the heterogeneity of resources and market segments 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 switching capability according to the evolution of the environment and the evolution of the broader landscape within which the system is embedded and to which it must adapt.

4. Transition scenarios in the automotive sector

4.1. Transition dynamics and characterization of technological systems

We combine in this section the real option perspective to analyze investment strategies along the transition process with scenario planning (Miller & Waller, 2003) in order to give a more precise vision of the contingencies, uncertainties, policy trends, and opportunities that might shape transition dynamics and strategies in the field of alternative vehicles and fuels. Our approach consists in providing for each path and the options regulating it the technological systems and investment modes that are likely to prevail and dominate. We
proceed first to a plausible characterization of each path synthesized by the following Table (Cf. Table 1).

Table 1

**Characterization of socio-technical pathways in the automotive sector**

<table>
<thead>
<tr>
<th>Pathways</th>
<th>Technological systems likely to dominate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reproduction</strong></td>
<td>Extension of the fossil paradigm</td>
</tr>
<tr>
<td><strong>Key assumptions:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Traditional engine improvements, progressive downsizing.</td>
</tr>
<tr>
<td></td>
<td>Emergence and adoption of new diesel and gasoline engines.</td>
</tr>
<tr>
<td></td>
<td>First generation bio-fuels.</td>
</tr>
<tr>
<td></td>
<td>Existing infrastructure.</td>
</tr>
<tr>
<td></td>
<td>Efficiency improvements.</td>
</tr>
<tr>
<td></td>
<td>Demand shifts towards more efficient and less consuming vehicles.</td>
</tr>
<tr>
<td><strong>Transformation</strong></td>
<td>In-depth transformation of the fossil paradigm</td>
</tr>
<tr>
<td><strong>Key assumptions:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diversification of fossil resources in the automotive sector (Coal to Liquid, Gas to Liquid).</td>
</tr>
<tr>
<td></td>
<td>Existing infrastructure with massive investments in production plants.</td>
</tr>
<tr>
<td></td>
<td>Availability of carbon capture and storage (CCS).</td>
</tr>
<tr>
<td><strong>Reconfiguration</strong></td>
<td>Generalized diffusion of hybrid systems</td>
</tr>
<tr>
<td><strong>Key assumptions:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diffusion of hybrid vehicles and introduction of plug-in hybrids.</td>
</tr>
<tr>
<td></td>
<td>Increasing role of hydrogen (H2) in the production of fossil fuels and on-board reforming of H2 for vehicles.</td>
</tr>
<tr>
<td></td>
<td>Deployment of second generation bio-fuels.</td>
</tr>
<tr>
<td></td>
<td>Optimization of complementarities between traditional and renewable energies.</td>
</tr>
<tr>
<td></td>
<td>Emergence of 1st generation smart grids.</td>
</tr>
<tr>
<td><strong>De-realignment</strong></td>
<td>Diversification of alternative systems</td>
</tr>
<tr>
<td><strong>Key assumptions:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Breakthroughs in electricity storage, in H2 production and storage and in the performance/price of fuel cells.</td>
</tr>
<tr>
<td></td>
<td>Adoption of CCS.</td>
</tr>
<tr>
<td></td>
<td>Introduction of technologies favoring resource diversification (natural gas, biomass, coal, renewable energies,...) and energy vector diversification (electricity, synfuels, H2,...).</td>
</tr>
<tr>
<td></td>
<td>Deployment of 1st generation smart grids.</td>
</tr>
<tr>
<td></td>
<td>High market segmentation.</td>
</tr>
<tr>
<td><strong>Deployment</strong></td>
<td>Flexibility and modularization of alternative systems</td>
</tr>
<tr>
<td><strong>Key assumptions:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H2 economy and/or electrification of the automotive sector.</td>
</tr>
<tr>
<td></td>
<td>Development of management mechanisms for built-in flexibility and/or for energy system diversity.</td>
</tr>
<tr>
<td></td>
<td>Centralized versus decentralized infrastructure deployment.</td>
</tr>
<tr>
<td></td>
<td>Development of 2nd generation smart grids.</td>
</tr>
</tbody>
</table>

4.2. **Transition scenarios under different political and technological assumptions**

Using this characterization, we work out several plausible scenarios contingent principally on the policy landscape and the technological systems that could critically influence the transition process.

The **evolution of technological systems** is mainly taken into account through a certain number of technologies that we assume as key - that is possessing the potential to carry a
heavy weight over the orientation and bifurcation of pathways. Among these technologies we notably insist on synfuels (using coal, natural gas and second generation biomass), nuclear electricity, integrated gasification combined cycle using coal, carbon capture and storage, fuel cells, hydrogen production and storage technologies, hybrid systems and renewable energies. We also focus on the key role that might play infrastructure development strategies in the transition process through e.g. the use of smart grids.

As for the policy landscape, it refers essentially to the intensity, the scope and the timing of environmental policies (reduction of greenhouse gases) and of energy security policies\(^3\) (IEA, 2005 & 2007). The real options lens stresses the importance of taking explicitly into account, during the elaboration of these policies, the impacts of uncertainty and risk on the investment decisions of firms when these are irreversible. If we adopt a real options reasoning, the activation of investments in low emitting technologies may in fact require a stronger policy than expected or generally assumed. Such reasoning may also explain why certain policies aimed to stimulate investments can turn out to be ineffective. Also, the same source of uncertainty may affect different technologies diversely and lead to technological evolutions hardly predictable (IEA, 2007). Furthermore, according to the situations and pathways considered, it may be in the interest of policy makers either to increase or decrease the level of uncertainty to stimulate investments.

Notice that, these two major policy orientations (environmental and energy security) are confronted with two other forms of major irreversibility and uncertainty. The one relates to climate warming / change and the other to the depletion of fossil reserves and their economic impacts. Inspired by the seminal works of Arrow & Fisher (1974) and of Henry (1974) on the risk of irreversible environmental impacts of investments committed and the option value of preserving the environment, several contributions have extended this approach by considering the opposite and conflicting effects of uncertainties and irreversibilities which hang over the climate issue on the one hand and the investments required to reduce greenhouse gas emissions on the other hand. The dilemma bears here upon on the trade-off between two option values or two forms of irreversibility: one of creating irreversibility by investing rapidly in order to preserve the option to protect ourselves from possible environmental impacts which may in the future turn out to be catastrophic or one of waiting or slowing down investments in order to preserve the right to take more informed decisions in the future with the risk of worsening environmental irreversibilities (Pindyck, 2002; Fisher & Narain, 2003).

The elaboration of our scenarios leans on principally the distinction between these two major policy orientations: the one centered on voluntarily trying to contain climate warming supported by international cooperation among actors and the other centered on the priority given to energy security issues. The major technological uncertainties considered concern the adoption or not of carbon capture and storage technologies (CCS) and breakthroughs on electricity storage on the one hand and hydrogen and fuel cell technologies on the other hand. The scenarios are established according both to the socio-technical systems that are likely to dominate the final state of the transition process and the impacts of different policies and different technologies on the transition process. We define transition dynamics according to the impact that different policy assumptions and

\(^3\) The political uncertainty may also concern policies supporting the diffusion of alternative technologies and taxation and subsidy policies.
technologies might have on the duration of each pathway. In fact, policy decisions and the evolution of technologies may either extend or shorten each pathway considered and even hinder or block the transition towards an alternative technological system. Consequently, according to the assumptions adopted the transition towards a new technological system may become longer or shorter and may even not take place at all when the combination of different assumptions leads to the lock-in within a given pathway.

Beyond our analytical framework, the elaboration of our scenarios draws inspiration from a certain number of documents and reports worked out in a prospective way and insisting on the role of policy making in the energy field and the position several alternative technologies might occupy in the future (IEA, 2001; IEA, 2005; WBCSD, 2004; WEC, 2007; Hyways, 2008; Plouchart & His, 2001; Bauquis, 2006).

The Figures below *(Cf. Figure 8 and Figure 9)* give an outline of the different scenarios likely to structure the transition process according to the policy and technological uncertainties faced by the energy system. Each scenario is characterized by the acronym (RTRDD) and summarizes the five pathways used to describe the transition process and the technological systems which we assume is likely to dominate each pathway *(Cf. Table 1)*: Reproduction (R), Transformation (T), Reconfiguration (R), De-realignment (D) and Deployment (D). To each pathway we associate a positive (+) or negative (−) sign indicating that a set of assumptions may either extend or shorten the given pathway. A cross (x) signifies the blocking of the technological system on the preceding pathway or by passing a pathway.
Figure 8
Different transition scenarios under different political and technological assumptions

(Case: Climate change policy)
Figure 9
Different transition scenarios under different political and technological assumptions

(Case: Energy security policy)
5. Conclusion

Our paper uses the real option perspective and reasoning in order to stress the influence of investment strategies on transition dynamics in presence of uncertainty and irreversibility. We show that the will to preserve flexibility when firms are confronted with high uncertainty and irreversibility induces investment strategies which are different from traditional investment rules based on the net present value calculus. In fact, contrary to the traditional approach, 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. It is also important to insist on the fact that investment strategies do not only reflect the will of actors to maintain flexibility but also to manage and create in a strategic way irreversibilities to come. It is this tension between flexibility and irreversibility that shapes the investment strategies of actors. 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 (Garud & Kumaraswamy, 1993; Shapiro & Varian, 1999; Suarez, 2004). From the real options lens 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 permits to enrich the 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 not taken into account by the traditional approach.

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. Thus, if some of the uncertainty factors considered above may well have a negative impact on the positioning option value during the transformation pathway and demotivate 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.

By combining real options reasoning and scenario building we finally provided a prospective view on the possible transition dynamics and trajectories that might structure the emergence and deployment of alternative engines and fuels in the automotive sector.
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