Comparison of Possible Transformation Processes in the Automobile Industry

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Abstract

Established industries develop and mature along continuous trajectories defined by the underlying technological paradigm relevant to serve the value network of the industry. Technological discontinuities and/or preference shifts at the higher levels of the value network may trigger a technological transformation in the industry. The factors discussed in the literature characterizing a technological change and its impact on the industry mainly are: 1. organizational inertia (path dependence) 2. pressures on the current socio-technical regime 3. maturity of the new technology and 4. knowledge trading and spillovers. Depending on these factors, the technological transformation process may have different consequences for the industry, ranging from having a minor impact to reverting the whole maturation process, creating new structures and changing the way business is done in the future.

In today's automobile industry, the current socio-technical regime, based on the internal combustion engine and liquid fossil fuels, is under pressure due to climate change regulations and high oil price fluctuations. A technological transformation in the automobile industry can therefore be anticipated, yet high technological uncertainty still prevails and the consequences for the automakers are unknown. Here we describe three different industrial technological transformation processes, namely the Radical, Disruptive and Endogenous Transformations. The Radical and Disruptive Transformation processes have been previously described in the literature and we postulate a third transformation process, which we call Endogenous Transformation. In an Endogenous Transformation, a new technology is developed in a joint effort by most organizations in the industry to substitute the old technology, which is no longer suitable to serve the value network of the future. Using the theory outlined here and data from qualitative interviews, we have developed a system dynamics model to further analyze the conditions under which a technological change in an industry follows one of the three mentioned transformation processes. We find that industry structures (e.g. market preferences and sizes), industry business practices (e.g. knowledge sharing) as well as overlying social and regulatory forces (e.g. technology pressures) significantly influence how the transformation will unfold. Our model serves to investigate the anticipated technological change in the automobile industry and will help to clarify some of the prevailing uncertainties as well as contribute to the development of policies supporting an efficient transition towards a sustainable propulsion technology.

Keywords

Automobile Industry, Innovation, Technological Transformation, Knowledge Diffusion, Knowledge Sharing, System Dynamics

1 Introduction

Climate change regulations and high oil prices are pressurizing today's socio-technical regime in the automobile industry, which is based on the internal combustion engine (ICE) technology and liquid fossil fuels. These pressures are expected to increase in the future, anticipating important changes of the current technological paradigm in the industry. In order to better understand how different policies may influence a possible technological change in the automobile industry and how a technological change may unfold and the final industry structure it may lead to, we have developed a micro-level system dynamics model of the industry. System dynamics models have proven to be of great value for the development of policies for the management of complex systems (e.g. Forrester, 1969, 1971; Meadows *et al.*, 1972). With our research we intend to contribute to the development of effective policies that facilitate a transition towards a more sustainable propulsion technology with minimal social and economic sacrifices. In the following sections, the theoretical background and concepts that have been developed for the system dynamics modeling are described. Following that, the model is introduced and selected simulation results are presented. This work continues the work of Mathias Bosshardt (Bosshardt *et al.*, 2008; Bosshardt, 2009) done in our group and will complement the fleet dynamics model with innovation and competition dynamics present in the automobile industry.

2 Theoretical Background

An industry is formed by companies organized in a value network producing and commercializing goods or services with the quality preferences demanded by their customers. A value network is defined as a "nested commercial system" composed of supplying, manufacturing and commercializing companies, the scope and boundaries of which "is defined by the dominant technological paradigm and the corresponding technological trajectory employed at the higher levels of the network" (Christensen, 1995), i.e. proximal to the final system-of-use. In analogy to the Khunian definition of "scientific paradigm", a technological paradigm is defined as "a model and a pattern of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies" (Dosi, 1982). Technological paradigms always imply a technological trajectory, which is "the direction of advance within a technological paradigm" (Dosi, 1982) and along which technological progress can be measured as the improvement of the relevant problem solving variables defined by the underlying paradigm.

2.1 Incremental Maturation

In a competitive environment and under normal operation, companies in an industry with a stable paradigm will focus on the continuous improvement of their products along the technological trajectory relevant in the value network they are serving. In order to increase efficiency and competitiveness, successful routines providing a competitive advantage will be selected and stabilized by organizations (Nelson and Winter, 1982). This leads to a maturing process in the industry, where the initial explicitly available knowledge of organizations is continuously embedded into routines and communication channels, so becoming ever more tacit and harder to change (Henderson and Clark, 1990), consequently increasing organizational inertia (Sastry, 1997). This is a reason why the further technological development in maturing industries is path dependent and follows the technological trajectory relevant in the industries' value network.

2.2 Disruptive Transformation

Technological discontinuities[1] in an industry may cause the displacement of the existing technological paradigm by a new paradigm. With the new paradigm, new knowledge and competences become relevant for obtaining a distinctive competitive advantage, causing environmental turbulence (Tushman and Anderson, 1986) and the reversion of the continuous maturity process (Abernathy and Clark, 1984). On an industry-level, this does not happen in the form of a one-step change, but is often a complex transformation process in which the structure of the industry (number of firms, firm sizes and leading companies), as well as the valid business models may undergo significant change. During the transformation process, organizations need to make the tacit knowledge embedded into routines and communication channels explicit, before they can be updated and new, more appropriate routines and communication channels established. This organizational transformation is specially challenging and costly for established organizations, often having important competitive implications with the consequence, that they may succumb to new market entrants (Henderson and Clark, 1990). Usually, at the beginning new technologies are inferior to the prevalent technologies in existing industries, but often have or promise to have important advantageous characteristics which are demanded in market niches for specialized value networks. Therefore, new technologies tend to be developed by new companies in protected market niches without competing with the established technology and where the users are willing to pay a higher price for the exceptional features the new technology offers (Geels, 2005). As the new technology matures, it may improve along the variables which are relevant in the value network of the established industry as well, and when costs are reduced, it starts competing with the established technology. This development is further enhanced through the fast technological development of the established technology

[1] Technological discontinuities are innovations based on new technologies that solve a problem in a radically new way.

considerably beyond what the value network actually requires and what customers can exploit and are willing to pay for (Christensen, 1995). Although the new technology may still underperform the established technology, it still complies with the actual needs of the value network but at lower (unit (Adner, 2002)) costs. This results in a rapid switch [2] of the customers in the established value network to the new technology, causing a disruption in the industry where incumbent organizations, which did not foresee the technological potential of the new technology and therefore continued to focus on the further improvement of the established technology (often also as a strategic response to the threat of the new technology), are displaced by the newcomers, which were formerly confined to the specialized market niche (Christensen, 1995). It is apparent that such a disruption leads to an important transformation of the industry structure and a switch of the valid technological paradigm to the new one. But, because the new paradigm is able to comply with the relevant values demanded in the established industry (otherwise disruption would not have occurred), it does not necessarily change or redefine the technological trajectory of the industry in the following maturation process. We call the industry transformation process described above *Disruptive Transformation*, following the notation established by Clayton M. Christensen (Christensen, 1995).

2.3 Radical Transformation

Radical technological discontinuities and new paradigms may be either introduced by new market entrants or incumbent organizations in a mature industry, as did newcomers with electronic calculators in the calculators industry or incumbents like Hudson with the closed steel body in the automobile industry (Abernathy and Clark, 1984) and IBM with the Winchester design in the hard disk industry (Christensen, 1995). While the initial intention for the development and marketing of a radical technology by the innovating organization usually is to better serve the existing value network in a new and innovative way, a radical technology tends to establish a new paradigm in the value network, defining a new technological trajectory with new relevant variables for the future development. Therefore, radical and architectural innovations change the way business is done and “influence the established systems of production and marketing” (Abernathy and Clark, 1984), requiring organizations to reorient, reversing the process of industry maturity and causing industry transformation, similar to the disruptive innovations described above. A good example of this is the closed steel body in the automobile industry, which created completely new relevant values like passenger comfort, room heating and ventilation, which until then were irrelevant because of the open wooden bodies then on the market (Abernathy and Clark, 1984). The radical innovation is usually broadly adopted by the industry because it fulfills the requirements of the value network. Incumbent organizations quickly perceive the threat and react to it by reorganizing and building up the required knowledge

[2] Assuming low switching costs.

and competences to absorb and further develop the new technology in order to improve their competitiveness, as did Chevrolet and GM with the closed steel body (Abernathy and Clark, 1984). Organizational and technological challenges are the main reason for the resulting inter-organizational performance differences, which ultimately will lead to the new industry structures. Due to lower market barriers (Dosi, 1982) new organizations may enter the industry as well, posing a significant threat to incumbent organizations that need to reorganize, further accentuating inter-organizational differences. We call the industry transformation process described above, which is initiated by a radical innovation launched either by an incumbent firm or a newcomer, destined to better serve an existing value network but which will change its valid paradigm and its future technological trajectory, as *Radical Transformation*. What makes it different from the *Disruptive Transformation* is the fact that the relevant improvement variables and the technological trajectory are maintained in the *Disruptive Transformation* [3], while it is changed in the *Radical Transformation* process. What is common to both is that the transformation process is triggered by a technological discontinuity which is available and marketable from the beginning (Figure 1).

2.4 Endogenous Transformation

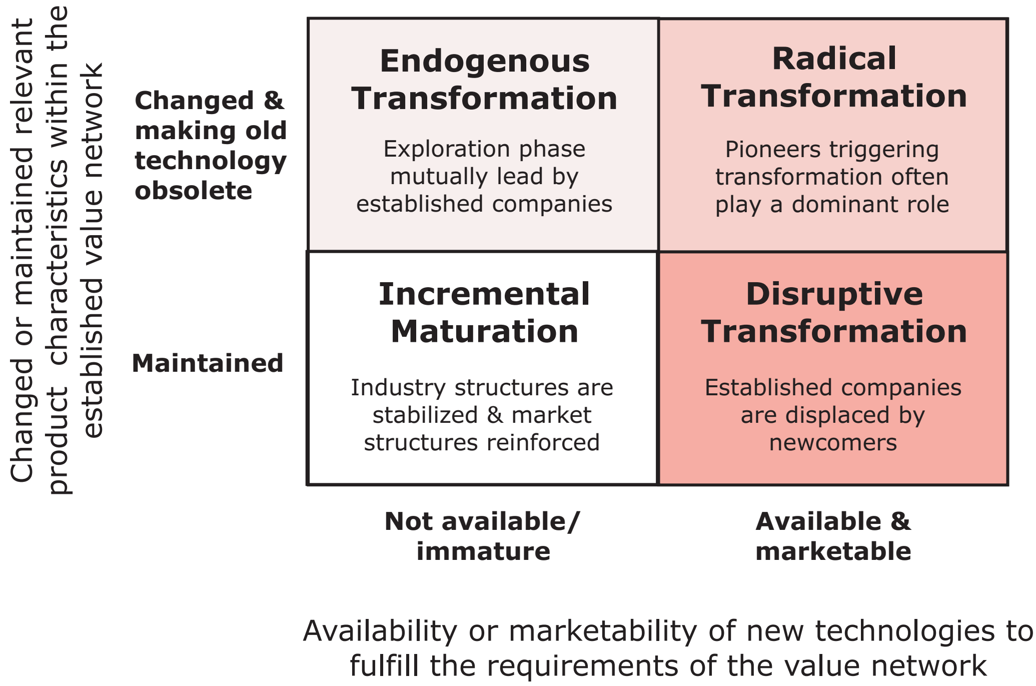
Besides the two industry transformation processes described from the literature above, we postulate a third transformation process, which we call *Endogenous Transformation* (Figure 1) and which may be evident in today's automobile industry. New climate change regulations and fluctuating fossil fuel prices are pressurizing the current paradigm of the automobile industry. These pressures are calling for new drive train technologies based on alternative fuels to primarily reduce CO_2 emissions, but also decrease the dependence on oil. As the current paradigm reaches its technological limits (e.g. thermodynamic efficiency), the industry is forced to look for new solutions based on alternative paradigms to solve the problems and serve the value network of the future. What differentiates the *Endogenous Transformation* process from the former two transformation processes is that an alternative technology to solve the pressure and problems of the current regime is not available, but needs to be developed first.

3 Methods

In order to identify important feedback loops for technological change we developed a first dynamical hypothesis (Sterman, 2006) (working paper (Bouza, 2009) available on request). Our dynamical hypothesis builds mainly on concepts from the research literature cited

[3]Actually, the new technology is adopted by the value network because it complies with its' requirements but at lower costs compared to the current technology

Figure 1: Technological Transformation Processes in Industries



Source: own creation

in the introduction (Dosi, 1982; Abernathy and Clark, 1984; Tushman and Anderson, 1986; Henderson and Clark, 1990; Christensen, 1995; Geels, 2005) and can be summarized as follows:

- During normal phases of the industry maturation process, organizations focus on continuous innovations and on improving the current technology following the technological trajectory given by the relevant paradigm in the value network.
- New technological discontinuities which could better serve the value network or pressures on the current socio-technical regime of the value network may cause organizations to change the focus from continuous innovations to develop radical innovations.
- A focus shift from continuous to radical innovations requires incumbent organizations to reorient, which is a difficult and costly organizational process.
- The industry enters a ferment exploration phase characterized by technological and market uncertainty and in which different designs are developed and marketed by different organizations; usually, this is accompanied by newcomers entering the market due to lowered market barriers.
- When a new dominant design emerges, i.e. is successfully selected by and penetrates the market, the ferment exploration phase comes to an end.

- The whole industry focuses again on the continuous improvement of the dominant design following the trajectory defined by the underlying new technological paradigm.
- Pioneering companies successfully developing and marketing the dominant design become the new leaders in the new industry era.

In order to verify the dynamical hypothesis, we have conducted qualitative interviews with automobile industry members and experts (Bouza *et al.*, 2009). From these concepts we have developed a causal-loop-diagram (Sterman, 2006) representing the most relevant factors and their interdependence. Finally, a (yet generic) system dynamics model has been created on the basis of the causal-loop-diagram to simulate technological change in industries on a micro-level. In the following we describe the results and present first simulation results obtained with the model, which are congruent with the theory of technological change outlined in the introduction.

4 Results

4.1 Interview Results

Both automobile industry members and experts confirmed in the interviews that the automobile industry's regime based on the ICE technology and liquid fossil fuels is under pressure. Mainly regulatory requirements for the reduction of green house gas emissions, which are expected to tighten in the near future, and possible fuel price fluctuations, exert the pressure on the current ICE regime. These pressures are causing a focus change from improving the ICE technology alone to also develop alternative drive train technologies for their future commercialization. It is estimated that the ICE technology will not be able to fulfill future market requirements after the next two decades and that an automobile manufacturers focusing on the improvement of the ICE technology alone will not be able to sustain a competitive advantage after the same period.

Organizational change costs (e.g. build up of new competencies in R&D and marketing teams, write-off of obsolete infrastructure and investments into new infrastructure) are not regarded as a reason to defer the development of alternative drive train technologies.

Investments into the development of alternative drive train technologies have mostly started in the last five years and are expected to increase. By the end of the next decade (2020) the share of R&D expenses for alternative drive train technologies will have reached 50% of total R&D expenses, as estimated by automobile industry members. By 2050, little, if not nothing, will be expended for the further development of the ICE technology.

Patents are effective means to protect new technological developments from the competition.

It is very usual between automobile manufactures to trade patent licenses, as is the case with Toyota's hybrid technology and Ford's diesel technology. Knowledge diffusion is high in the automobile industry, meaning that new technological developments are quickly absorbed and applied by competitors as well. But knowledge diffusion is bidirectional, meaning that an automobile manufacturer can only benefit from this knowledge diffusion if it has something to offer on its own. Other means of protecting new developments are secrecy, i.e. keeping the knowledge in-house without patenting it and not making it public. Speed to market and the image of technological leadership are key factors to obtain a competitive advantage in the highly competitive automobile industry.

The following alternative drive train technologies are regarded as having the greatest potential to have a market share of over 20% by the year 2050 (ranked by highest potential):

1. hydrogen fuel cell
2. battery electric
3. electric-gasoline hybrid
4. electric-natural gas hybrid
5. alternative liquid fuels (e.g. bio-ethanol, bio-diesel) with ICE.
6. natural gas ICE.

Here it must be noted that the technologies have been rated quite differently. This is symptomatic for the uncertainty prevalent during the exploration phase. Today it is still unknown which technology will be best suited for future marketability, i.e. fulfilling individual mobility requirements at affordable costs.

4.2 Dynamics of Technological Change

The theoretical analysis and the interview results allowed us to define the system boundaries and identify the most important variables characterizing a technological transformation process in an industry. The interdependence of the variables is shown in the causal-loop-diagram in Figure 2. Different loops characterizing the structure of the system have been identified (six reinforcing and three balancing loops).

Companies in a mature industry mainly focus on the continuous improvement of the currently dominant technology. A better technology offers a higher competitive advantage and increases current and expected future market success, as well as the dominance of the current technology

(Loop 1). With the focus on continuous innovations, organizational routines and communication networks are consolidated, leading to an increase in organizational effectiveness, but also to organizational inertia (Loop 8).

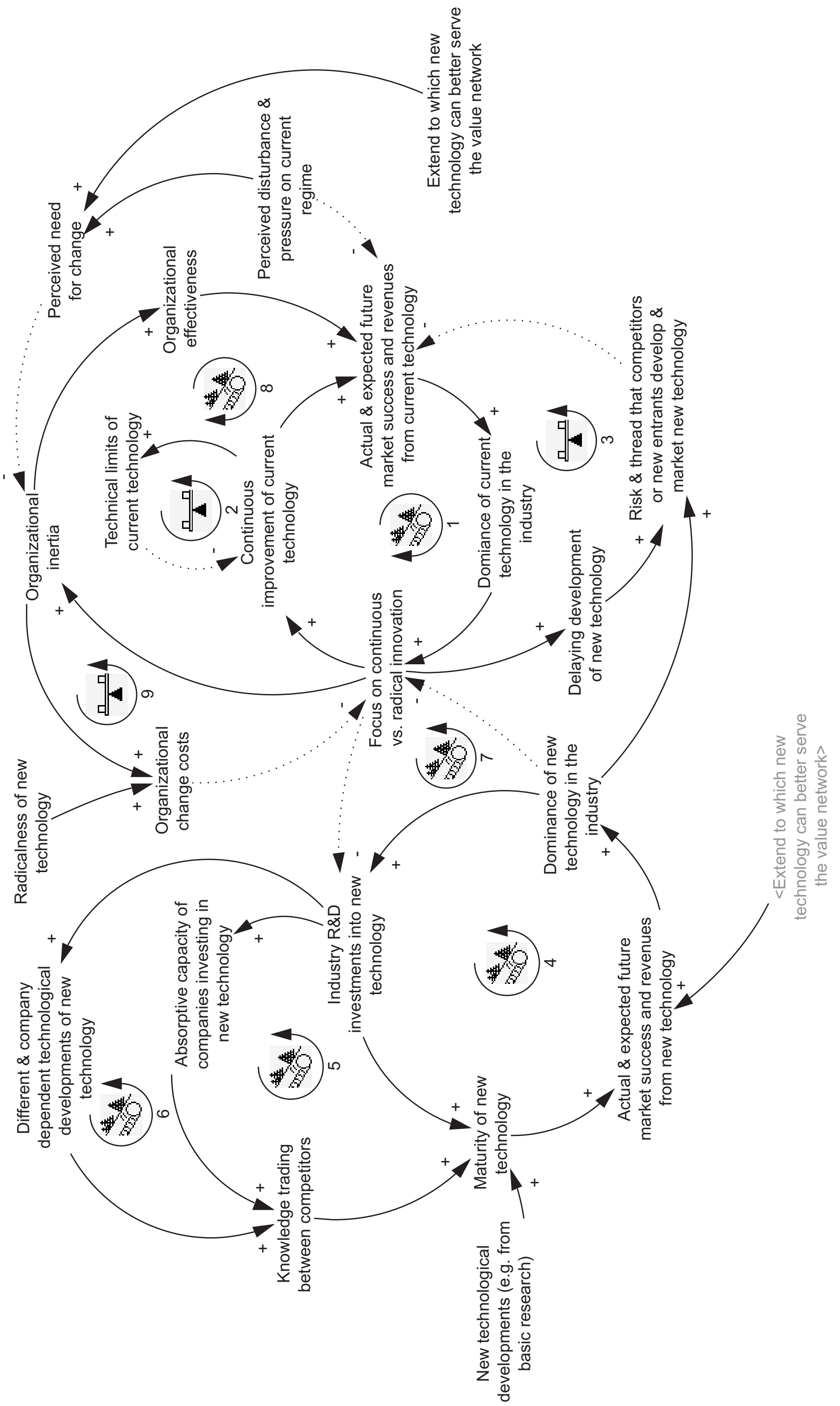
As the limits of the current technology are reached and continuous innovation becomes more and more unprofitable because of diminishing marginal improvements, the current technology begins to loose it's dominance (Loop 2). The danger or the perceived risk that competitors or new entrants may develop a new technology decreases the expected future profits that can be obtained with the current technology, making the current technology less attractive and diminishing its dominance as well (Loop 3). Both negative feedback loops (Loops 2 and 3) decrease the dominance of the current technology and favor a focus shift towards the development of new technologies (Loop 7). Investments into the research and development of new technologies increase with their technological dominance. As new technologies mature with these investments, their potential for future marketability increases, which makes them increasingly dominant, attracting further R&D investments (Loop 4). In industries where new knowledge cannot easily be copied or where it can be protected effectively (e.g. through patents), this process is further enhanced by the prospect to partake in knowledge trading with other competitors developing new technologies (Loops 5 and 6). For knowledge trading, companies need sufficient absorptive capacity (Cohen and Levinthal, 1990), otherwise they will not be able to understand and absorb the new knowledge developed by competitors. This and the necessity to posses own developments in order to be able to partake in knowledge trading at all, increases the pressure to invest into the same new technologies as the competitors do. Otherwise, a company would quickly lose its competitive position should the new technology become dominant in the future and it would be very difficult for it to catch up, because, lacking absorptive capacity and new knowledge to offer, it would not have access to the knowledge sharing process of the industry.

External pressures on the current socio-technical regime diminish future expected revenues from the current technology and increases the perceived need for change, reducing organizational inertia and organizational change costs (Loop 9) through reduced intra-organizational resistance to change. Both the radicalness of the new technology and the extend to which the new technology is expected to serve the company's value network, have an influence on the costs of organizational change.

4.3 The Model

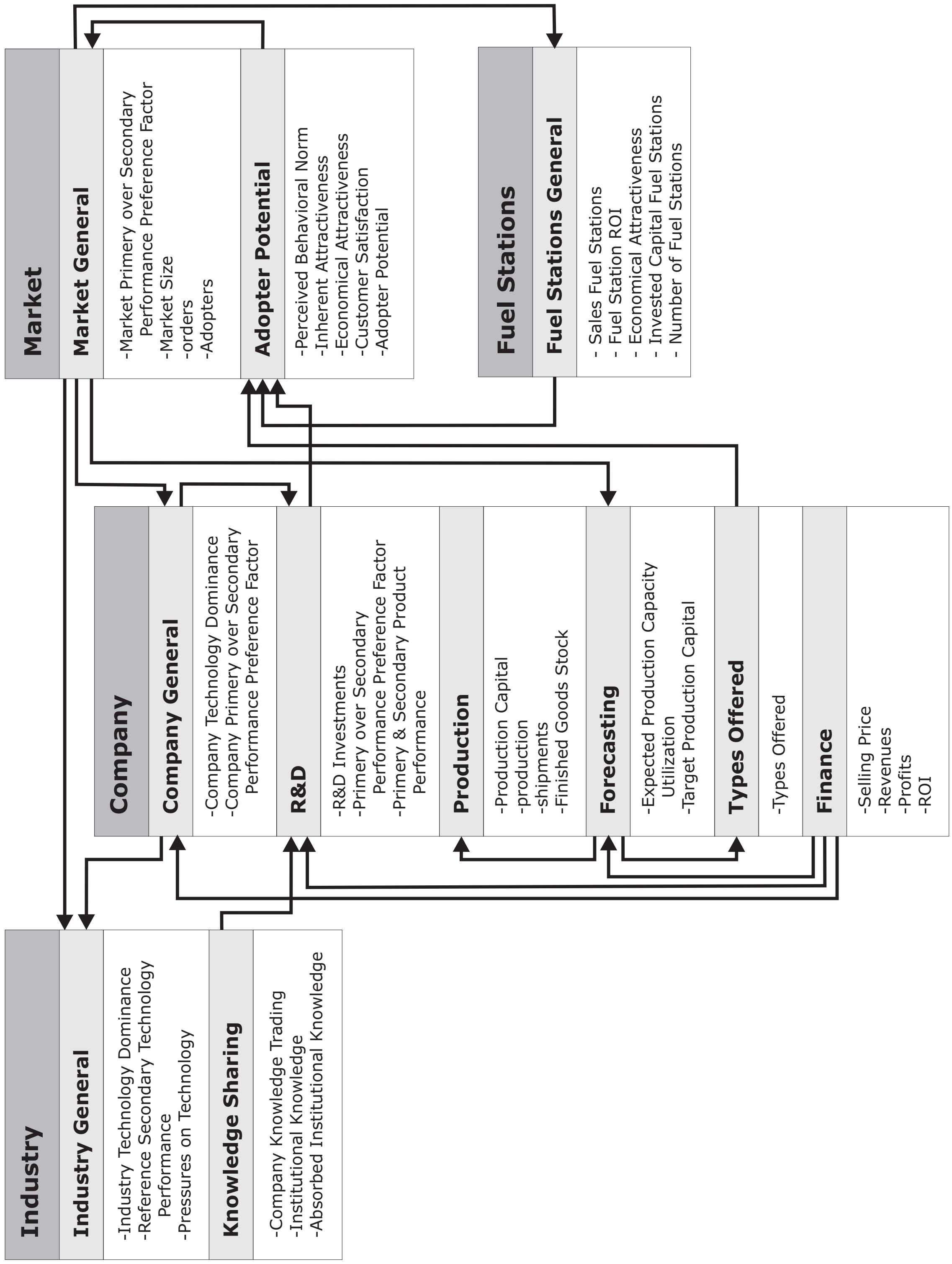
An overview of the model is given in the sector representation in Figure 3, which includes the main variables. In the model, any number of companies, technologies, fuels and markets can be defined using subscripts and without the need to change the model structure. The most relevant model sectors will be described in the following.

Figure 2: Causal-Loop-Diagram of Technological Change



Source: own creation

Figure 3: Sector Representation of the System Dynamics Model



Source: own creation

4.3.1 The Company Sector

Congruent with the purpose of modeling industrial technological change on a micro-level, the *Company* sector of the model is the most complex sector. The *Company* sector consists by itself of further complex subsections, as shown if Figure 3. The *R&D* and *Company General* sub-sectors will be described in more detail.

The R&D Sub-Sector The *R&D* sub-sector models the research and development of technologies by each company. Technologies in the model are characterized by primary and secondary performances, which could be for example power (primary) and average consumption (secondary) for drive train technologies. Research and development is based on an algorithm of local and evolutionary search described in Nelson and Winter (1982). Basically, the algorithm performs a stochastic search of new combinations of primary and secondary performances in the vicinity of the current primary and secondary performances (local) and evaluates them. If the evaluation of the new combination is higher than the evaluation of the current combination, then it is taken over (evolutionary). For the evaluation of the search results, primary and secondary performances are exponentially weighted with a company specific preference factor, as described in Adner (2002)[4], determining the inherent attractiveness of the technology. The company specific preference factor allows us to model the companies' different preferences for power or efficiency. The search area in which local search is taking place is determined by R&D investments. The higher R&D investments are, the greater the local search area will be. A greater search area increases the technological progress rate.

The Company General Sub-sector The cost of the new development, which is calculated in the *Finance* sub-sector as a function of the new technological level and the variable costs, is also considered in the evaluation of the new development. Eventually, marginal costs may become too high for further technological developments to be more attractive than the current solution. In the *Finance* sub-sector, financial data such as the cash available to the company, total R&D investments, variable and fixed costs and technology profitability are calculated. In the *Company General* sub-sector, the company specific technology dominance and the primary over secondary performance preference factor (used in the R&D process previously described) are modeled. The company specific technology dominance is used to calculate the R&D investments for each technology and company. The technology dominance is a function

[4] If p_1 and p_2 are the primary and secondary performances, respectively and f $(0 < f < 1)$ is the preference factor, then the inherent attractiveness A is given by

$$A = \begin{cases} (p_1 - p_{1,min})^f * (p_2 - p_{2,min})^{1-f} + 1 & \text{if } p_1 \geq p_{1,min} \text{ and } p_2 \geq p_{2,min} \\ 0 & \text{otherwise} \end{cases}$$

where $p_{1,min}$ and $p_{2,min}$ are the minimal primary and secondary performance required by the market, respectively.

of technology markup (or expected markup if not on the market yet), technology revenues, industry technology dominance and — to model a kind of "network effect", which leads to a preferred single technology for a company — the technology dominance itself, (the strength of the "network effect" can be modified through a parameter).

4.3.2 The Market Sector

The characteristics of the different markets, such as market size, growth rate, and market preferences, are defined in the *Market* sector. The adopter potential, i.e. the probability with which a specific company's offer is adopted, is calculated in the *Market* sector as well (Ulli-Beer *et al.*, in press). The adopter potential is a function of the behavioral norm (i.e. the social awareness of a given technology), the inherent attractiveness of the offer, the selling price, the company's image and the fuel coverage (the density of fuel stations) (Bosshardt, 2009).

4.3.3 The Industry Sector

The industry technology dominance, is a function of the behavioral norm and technology pressures. Technology pressures increase with the discrepancy between the actual and the required (exogenously given) secondary performance. Apart from making a technology less attractive for the industry, technology pressures also increase the price of the technology through a tax, which is proportional to the discrepancy of the actual and required secondary performance (similar to the future taxation of automobile manufacturers in the EU, which will be proportional to their excess (over a defined limit) of average CO_2 emissions).

The Knowledge Sharing Sub-Sector As described in section 4.1, knowledge sharing has been found to be significant in the automobile industry. Because of the high knowledge sharing intensity, the formation of a focal point of research, where most automobile manufacturers focus on the development of the same alternative drive train technology (e.g. battery-electric cars as it is evident today), can be observed (Bouza *et al.*, 2009). In the model, knowledge sharing has two effects. First, it increases the local search area (additional knowledge increases development possibility's) leading to a higher technological progress rate. Second, it increases the weight industry technology dominance has on selecting the company's technology dominance (creation of a focal point). Knowledge sharing is further based on the trust level between companies. The higher the trust level, the more intense knowledge trading is. With knowledge trading, the trust level is increased. Stochastic events between companies may cause the decrease of the trust level by a random fraction.

4.4 Simulation Results

Because of the stochastic elements in the model, the following scenarios are averaged results of 25 runs each, with different seed values used in the *R&D* and the *Knowledge Sharing* subsectors. The following assumptions apply to all scenarios:

- There are five companies in the model. Companies 1 to 4 are incumbents and Company 5 is a newcomer.
- There are 5 technologies in the model. Technology 1 is the dominant technology for all incumbents and the only technology on the market at the beginning of the simulation.
- Incumbents may develop all five technologies, while the newcomer focuses on the development and marketing of Technology 4 only.
- There are four fuels in the model. Technologies 1 and 2 both use Fuel 1, Technology 3 uses Fuel 2, Technology 4 uses Fuel 3 and Technology 5 sues Fuel 4.
- Technology 1 and 3 are the cheapest technology, while Technologies 2, 4 and 5 are more expensive (Technology 5 is more expensive than Technology 4, which is more expensive than Technology 2).
- With technological improvement, material inputs for each technology get cheaper.
- With increased primary and secondary performances, technologies get more expensive.
- Experience gain through production increases productivity (i.e. production output per production capital) and reduces production costs (e.g. wage costs).
- Fuel prices for Fuels 1 to 3 increase, while fuel prices for Fuel 4 decrease (assumed technological improvement for production of Fuel 4) during the simulation.
- All incumbents start with similar performance characteristics of Technologies 1 to 5. The newcomer has a slight advantage on Technology 4.
- Two markets exist in the simulation, Market 1 and 2.
- Market 1 is a big market (max. market size $40 \cdot 10^6$), while Market 2 is small (max. market size $3 \cdot 10^6$, respectively $2.5 \cdot 10^6$ in Scenario 3 where the market size is restricted).
- Market 2 has a higher secondary over primary performance preference than Market 1. In addition, it has a high minimum secondary performance requirement, which at the beginning of the simulation can be satisfied by Technologies 4 and 5 only.

The scenarios presented here differ in whether

- knowledge sharing
- technology pressures

are considered during the simulation and

- in the market size of Market 2.

The scenarios are described in the following and the results (adopters, i.e. the evolution of the fleet composition) are shown for each scenario in Figures 4, 5 and 6.

4.4.1 Scenario 1

In Scenario 1, both knowledge sharing and technology pressures are active. The size of Market 2 is not restricted. The simulation results in similar shares of adopters for all companies and technologies throughout the simulation. This is typical for an *Endogenous Transformation*, where most companies within an industry collectively develop new technologies. The newcomer (Company 5) starts serving Market 2 first, but is soon displaced by the incumbents. The newcomer does not manage to enter Market 1 at all. Technology 4 is selected by the market as the dominant technology. Technologies 2 and 3 in this scenario serve as bridging technologies to the point where Technology 4 reaches a critical market volume (around the year 2050, see Figure 4).

4.4.2 Scenario 2

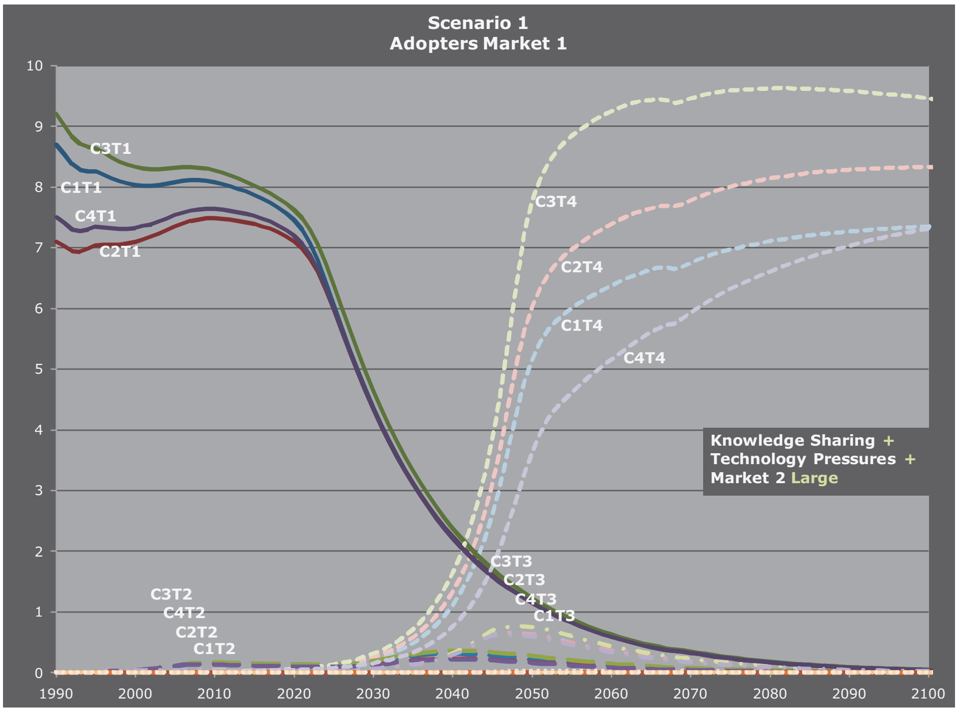
In Scenario 2, knowledge sharing is deactivated, while technology pressures are active. Without knowledge sharing, the newcomer (Company 5) is able to cause a disruption and completely displace the incumbents (Companies 1, 2, 3 and 4) from Market 1 by 2100. Compared to Scenario 1, in Scenario 2 the newcomer is able to develop it's technology in a protected market (Market 2) until it is able to compete with the established technology in Market 1. The incumbents are not able to develop an alternative technology fast enough to compete with the newcomer. This is characteristic for a *Disruptive Transformation* (see Figure 5).

4.4.3 Scenario 3

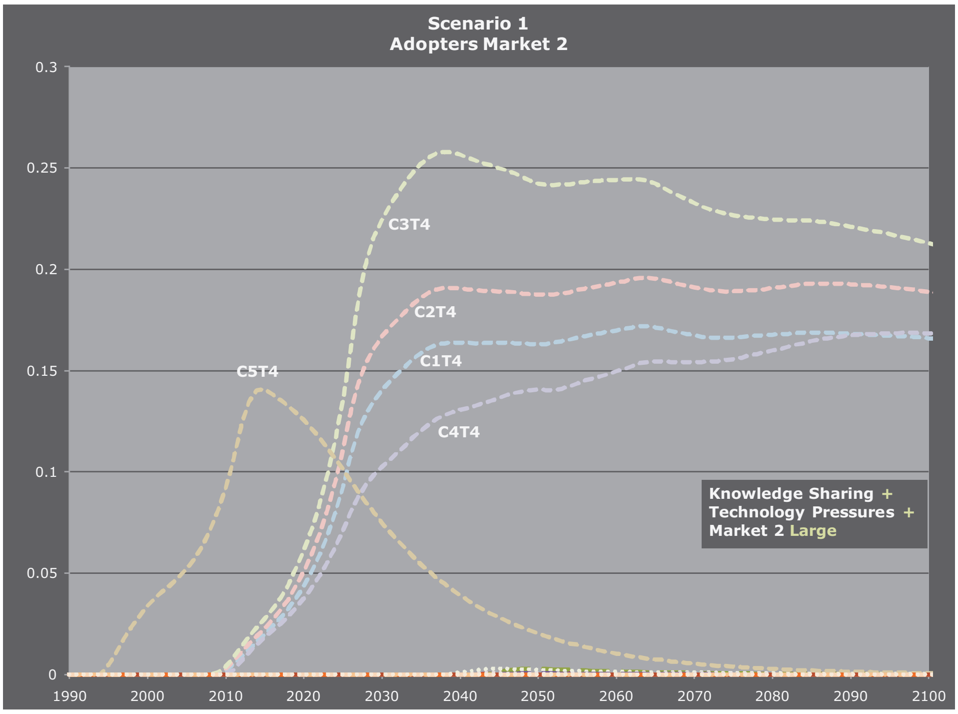
Both knowledge sharing and technology pressures are deactivated in Scenario 3. The size of Market 2 has been restricted, to deprive the newcomer of a protected large market where it can develop its technology. As a consequence, the incumbents are able to develop Technology 4 fast

Figure 4: Simulation Results or Scenario 1 — Endogenous Transformation
Companies are color coded (blue: Company 1 (C1), red: Company 2 (C2), green: Company 3(C3), purple: Company 4 (C4)). Different technologies are coded by line styles and color intensities (from Technology 1 (T1) darkest to Technology 5 (T5) brightest)

(a) Scenario 1: Adopters in Market 1



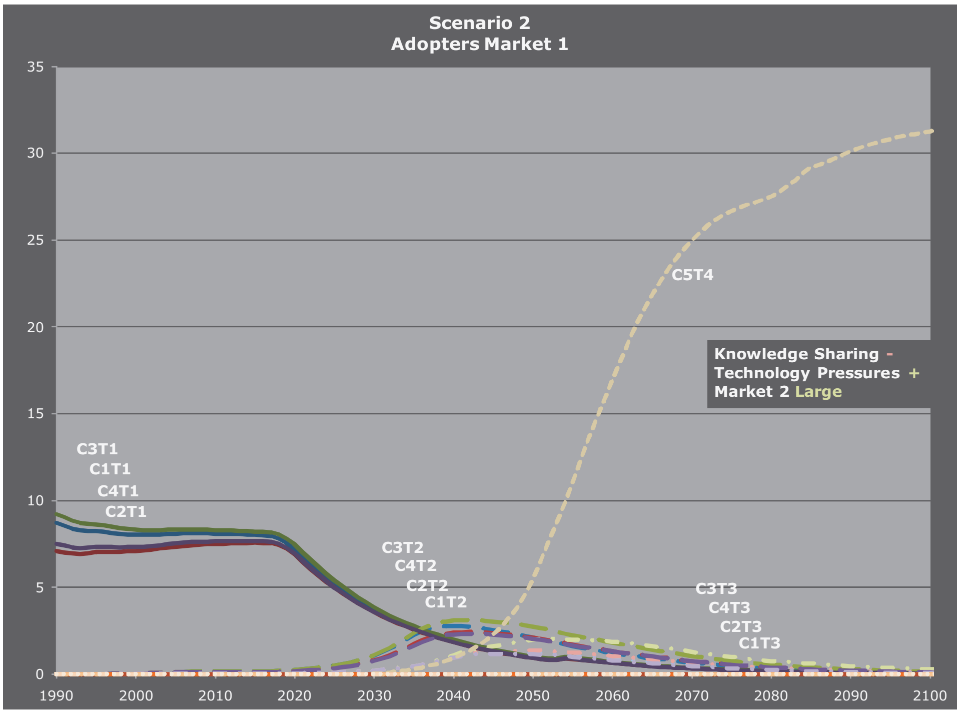
(b) Scenario 1: Adopters in Market 2



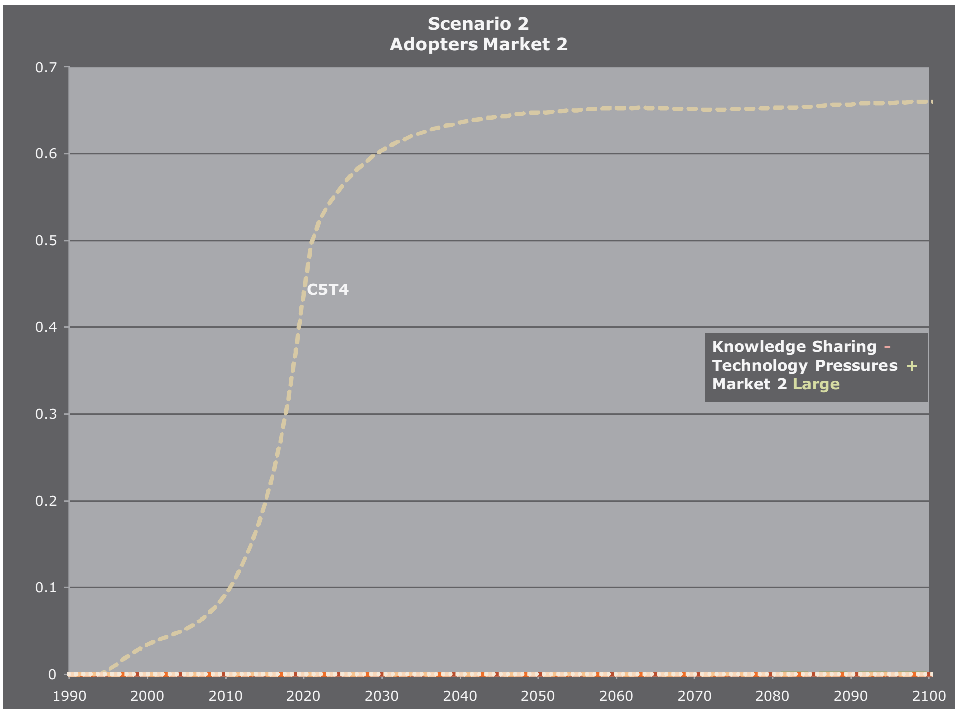
Source: own creation

Figure 5: Simulation Results or Scenario 2 — Disruptive Transformation
Companies are color coded (blue: Company 1 (C1), red: Company 2 (C2), green: Company 3(C3), purple: Company 4 (C4)). Different technologies are coded by line styles and color intensities (from Technology 1 (T1) darkest to Technology 5 (T5) brightest)

(a) Scenario 2: Adopters in Market 1



(b) Scenario 2: Adopters in Market 2



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enough and are no longer disrupted by the newcomer (compare to Scenario 2). Because of no knowledge sharing, inter-company difference of technological advancements are significant. In Scenario 3, Company 3 gains a significant advantage over Companies 2 and 4, while Company 1 does not manage to develop Technology 4 at all. This scenario represents an example of a *Radical Transformation* (see Figure 6).

5 Conclusions

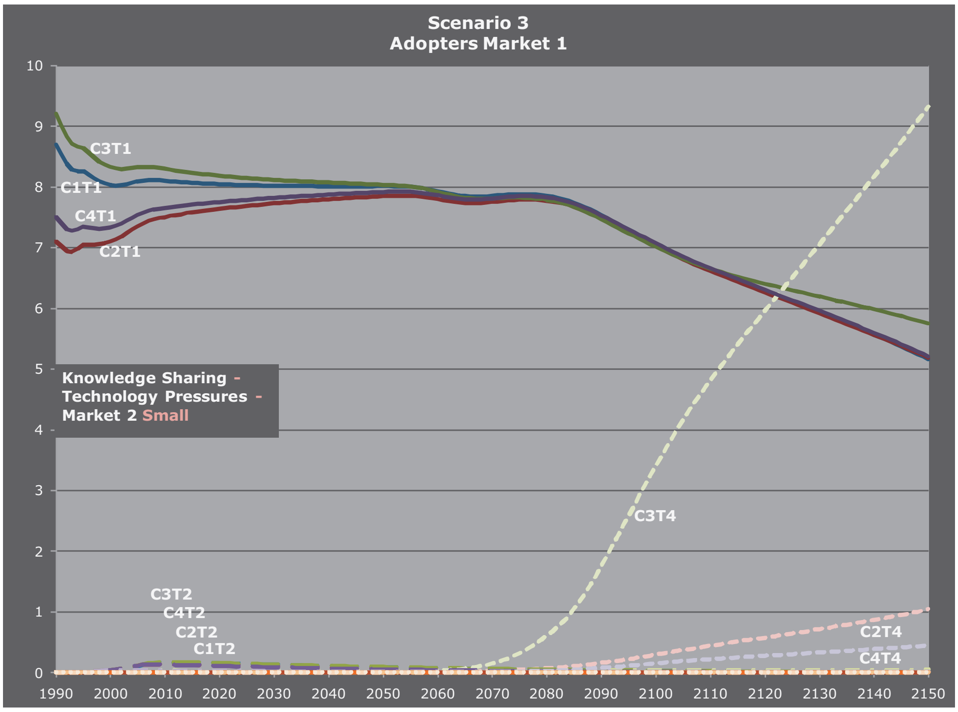
We have developed a system dynamics model for technological change with which we are able to simulate the three transformation processes described in the theory (see section 2). The Theory says that a *Disruptive Transformation* is not probable when the values of the value network change and rather suggests a *Radical* or *Endogenous Transformation* process. Despite of the active technology pressures in Scenario 2, which simulate changing values of the value network which are perceived by the companies and which diminish the dominance of the current technology, we can clearly identify a *Disruptive Transformation* under these circumstances in the model. There are two main explanations for that. First, changing values in the values network per se are not sufficient to prevent a *Disruptive Transformation*. In Scenario 2, incumbents invest into the development and commercialization of Technologies 2 and 3 as a consequence of the pressures. But Technology 4 of the newcomer proves to be the superior technology. Because of significant market losses, incumbents run out of cash and are unable to invest into the development of Technology 4 at a later stage. Second, technology pressures increases the price of Technology 1 (and to a lesser extent also of Technologies 2 and 3, which mainly use fossil fuels but have lesser CO_2 emissions). Thus, together with technological improvement and economies of scales, the newcomer is able to develop Technology 4 to become the cheapest technology and cause the disruption. Without technology pressures, the transformation process is much slower and disruption does not occur (see Figure 7).

With the simulations, knowledge sharing has been demonstrated to contribute significantly to increasing the market entry barriers. When knowledge sharing is active (Scenario 1), the newcomer is not able to enter Market 1 or maintain a sustained competitive advantage in Market 2, while without knowledge sharing disruption occurs (Scenario 2).

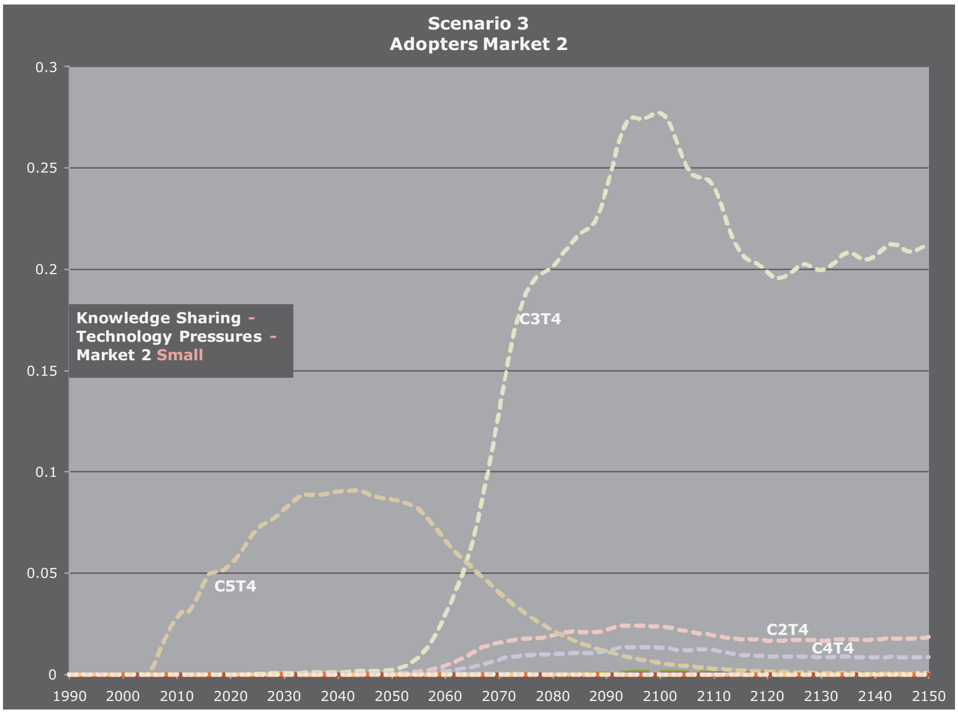
With a restricted market size of Market 2, the revenues generated by the newcomer are not sufficient to develop Technology 4 to compete with the incumbents quick enough. When both knowledge sharing and technological pressures are deactivated, the model clearly suggest a *Radical Transformation*. With technology pressures activated, incumbents more strongly align to develop an alternative technology. The result is no longer a distinct *Radical Transformation*, but rather a transformation process between a *Radical* and an *Endogenous Transformation* (see Figure 8). This accords with the understanding that perceived value changes in the value net-

Figure 6: Simulation Results or Scenario 3 — Radical Transformation
Companies are color coded (blue: Company 1 (C1), red: Company 2 (C2), green: Company 3(C3), purple: Company 4 (C4)). Different technologies are coded by line styles and color intensities (from Technology 1 (T1) darkest to Technology 5 (T5) brightest)

(a) Scenario 3: Adopters in Market 1



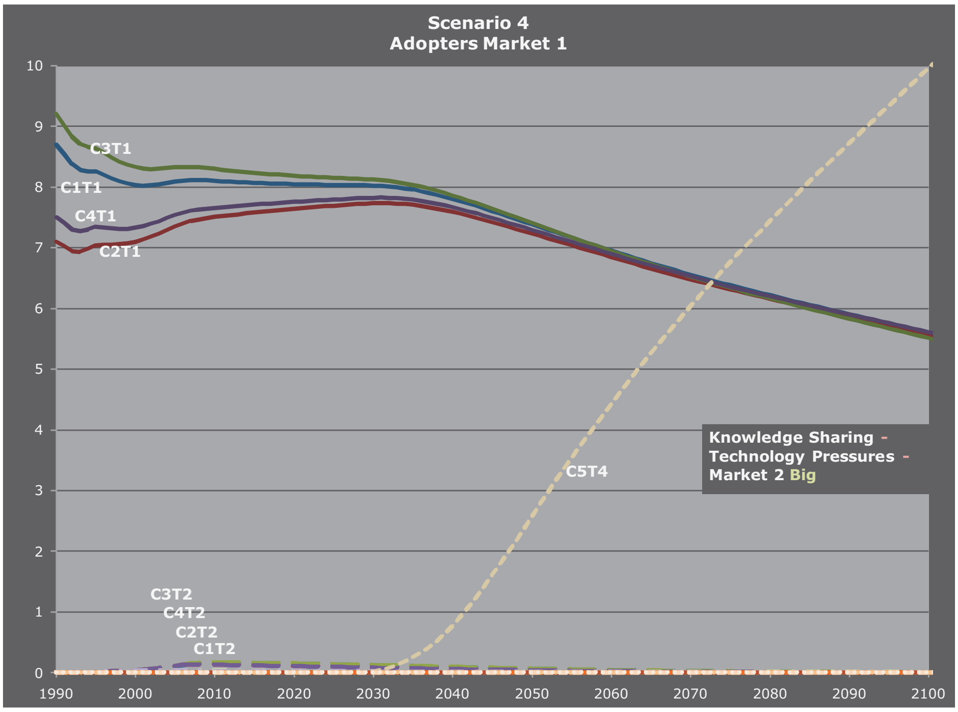
(b) Scenario 3: Adopters in Market 2



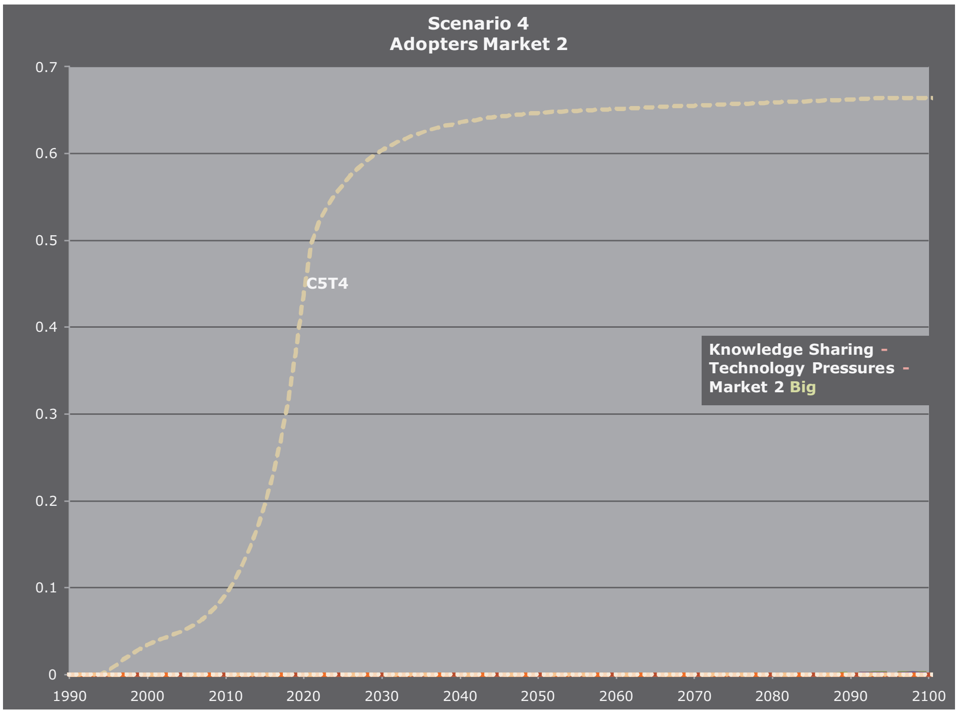
Source: own creation

Figure 7: Simulation Results or Scenario 4 — Slow transformation compared to Scenario 3 without technology pressures
Companies are color coded (blue: Company 1 (C1), red: Company 2 (C2), green: Company 3(C3), purple: Company 4 (C4)). Different technologies are coded by line styles and color intensities (from Technology 1 (T1) darkest to Technology 5 (T5) brightest)

(a) Scenario 4: Adopters in Market 1



(b) Scenario 4: Adopters in Market 2



Source: own source

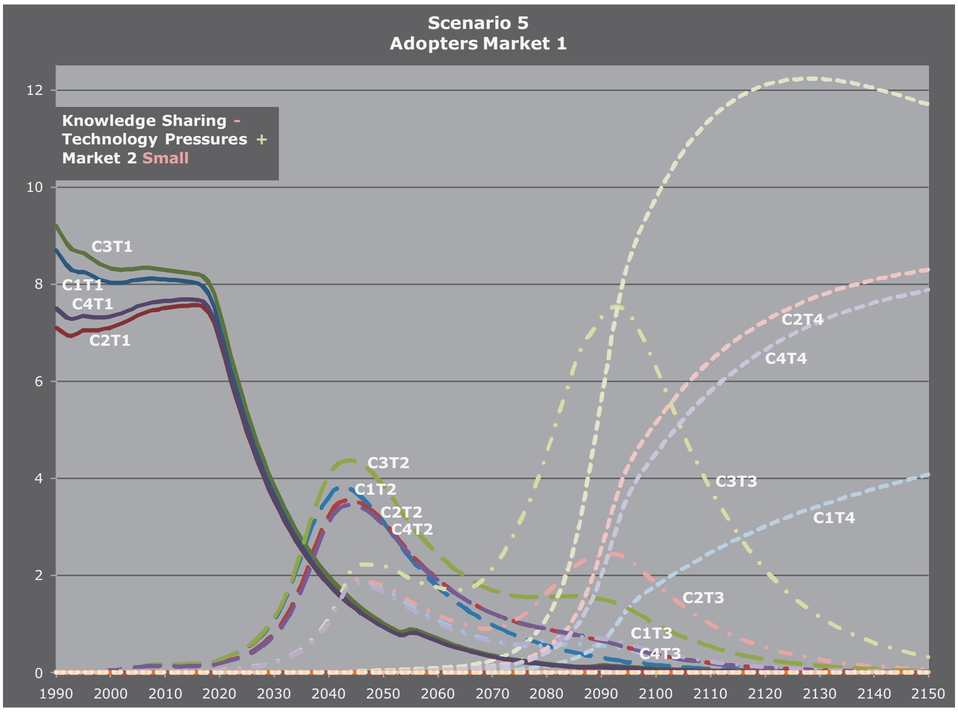
work through technology pressures make organizations aware of the required changes, reduce organizational inertia and cause a focus shift toward the development of new technologies. If knowledge symmetries between organizations persist throughout the transformation process, which is favored by knowledge sharing, an *Endogenous Transformation* is supported (compare Scenario 5 (Figure 8) and Scenario 1 (Figure 4). Without knowledge sharing, the transformation process loses the distinct characteristics of an *Endogenous Transformation* and gains typical features of a *Radical Transformation* (see 8). Furthermore, the exploration phase is longer without knowledge sharing and bridging technologies significantly penetrate the main market, which must coincide with an increased uncertainty in the market. Thus uncertainty during transformation phases can be expected to be lower in industry where knowledge sharing is dominant.

Our modeling results further suggest that not only the characteristics of new technologies (e.g. requiring new knowledge and competencies, addressing new markets), but also industry structures (e.g. market preferences and sizes), industry business practices (e.g. knowledge sharing) as well as overlying social and regulatory forces (e.g. technology pressures) importantly determine how a transformation process may unfold.

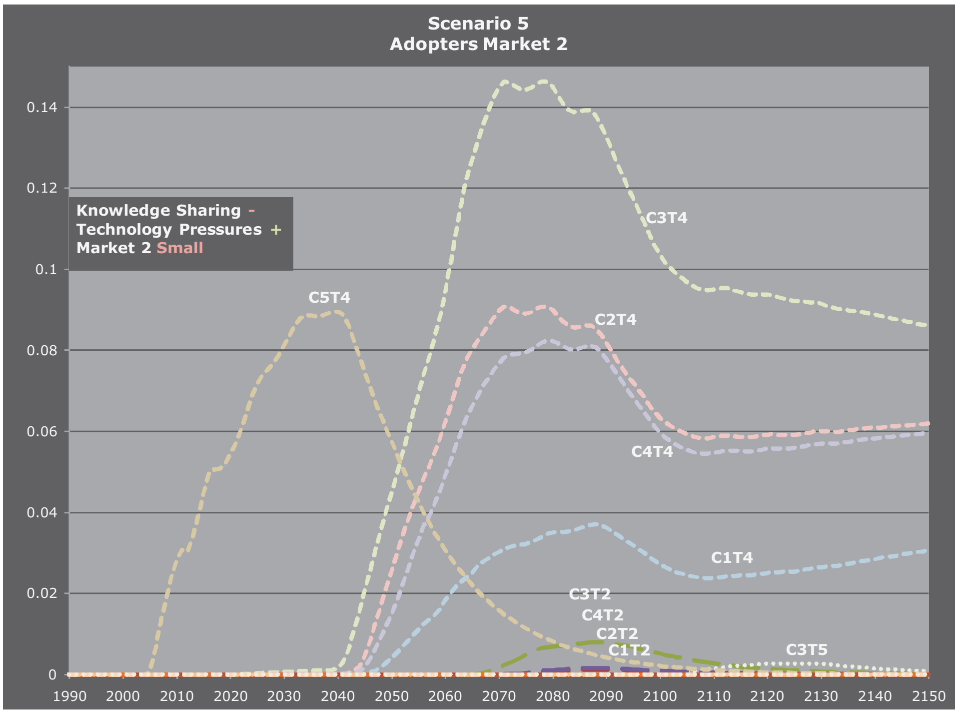
The theory outlined above helps to understand the transformation dynamics that may be found in the future automobile industry. The intensive knowledge trading between automobile makers increases the need to undertake significant R&D efforts. If a company does not research and develop new technologies, it is excluded from the knowledge trading process, increasing it's technical gap significantly with time. This may also explain why most leading automobile manufactures are investing significantly in the R&D of alternative drive train technologies today. An additional motivation for these investments may be the build up of absorptive capacity (Cohen and Levinthal, 1990) and the resulting capabilities to perceive and quickly react to technological developments and breakthroughs of competitors in alternative drive train technologies. The high risk of a car manufacturer to solely pursue the development of an alternative drive train technology, as well as the consequences of not partaking in the development of alternative drive train technologies other car manufacturers are pursuing (both excluding the car manufacturer from the knowledge trading process and increasing the technological gap) may lead to the creation of a common focal point in the industry, where the development of a selected alternative drive train technology is emphasized by all manufacturers at the same time. This may explain the congruent efforts undertaken by the leading car manufacturers to develop and commercialize battery electric cars today. Depending on how successful this commercialization will be, these efforts will be either continued and intensified or abandoned. In the latter case, this would lead to the formation of a new focal point, putting emphasis on another alternative drive train technology in the future, starting the whole process again, further prolonging the exploration phase of the transformation process.

Figure 8: Simulation Results or Scenario 5 — Transformation process with features of an Endogenous and Radical Transformation
Companies are color coded (blue: Company 1 (C1), red: Company 2 (C2), green: Company 3(C3), purple: Company 4 (C4)). Different technologies are coded by line styles and color intensities (from Technology 1 (T1) darkest to Technology 5 (T5) brightest)

(a) Scenario 5: Adopters in Market 1



(b) Scenario 5: Adopters in Market 2



Source: own source

Finally, the following requisites can be drawn as a condition for an *Endogenous Transformation* process to take place in an industry:

1. A mature, knowledge intensive and highly competitive industry with a stable socio-technical regime exists.

2. Overlying economic, sociological and/or ecological systems put pressure on the current industry's socio-technical regime, causing a shift in the values of the industry's value network.

3. Further improvements of the current technology is not a solution to solve the pressure, either because it is the cause of the problem itself (e.g. dependence on oil) or because it is reaching it's technological limits and further improvements are prohibitively expensive (e.g. thermodynamic efficiency).

4. Incumbent companies in the industry realize that, in order to solve the pressure and to fulfill future market requirements, a paradigm change is necessary (making a *Disruptive Transformation* process very unlikely).

5. No alternative technology is available to substitute the old technology and solve the pressure; possible alternative technologies exist, but are yet immature to be commercialized and need to be developed first.

6. No sudden, unexpected and radical technological breakthrough occurs, i.e. alternative technologies evolve gradually and without creating significant knowledge asymmetries between companies in the industry (otherwise the transformation process would become a *Radical Transformation*.

7. New knowledge can be effectively protected from being freely copied by the competition and is traded in the industry; this prevents significant knowledge asymmetries in the industry.

6 Outlook

The model presented here is still to be considered a generic model for technological change. Our future work will therefore focus on the parametrization of the model to represent the automobile industry. With this, we will be able to further investigate the conditions of technological change expected in the automobile industry and the consequences that may result thereof for the organizations in the industry. In addition, our work will also focus on the development of policies which sustain a rapid transformation of the industry towards a more sustainable propulsion technology with minimal social and economic losses.

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