EVOLUTION OF FLEX-FUEL TECHNOLOGY: A CASE STUDY ON VOLKSWAGEN BRAZIL

Autoria: Abraham Sin Oih Yu, Paulo Tromboni de Nascimento, Lydia Lopes Correia da Silva,
Alceu Salles Camargo Júnior, Cleber Marchetti Duranti, Carlo Borsoi Moura

ABSTRACT

This research analyzes, from a technology management perspective, the technological evolution of flex-fuel engines (capable of running on a mix of gasoline and ethanol in any proportion) in Volkswagen do Brasil (VWB) since 2003, the year the first Brazilian flex-fuel vehicle was launched by VWB. By 2009, 90% of new cars sold in Brazil were flexible-fuel vehicles, and Volkswagen has the largest share of this market. Flex-fuel technology has been under constant improvement since then and VWB has been one of the leaders in advancing the state of the art: it launched the fourth generation in 2009.

The present research tracks changes in the subsystems of VWB's flex-fuel engine by adapting the framework for dominant design proposed by Murmann and Frenken (2006). They employ the concept of pleiotropy to distinguish or classify components into core and peripheral elements. Murmann and Frenken (2006) define the technical characteristics of a product's components and subsystems as the "genotype", and the product's service features or attributes (which they compare to biological traits) as its "phenotype". The Design Structure Matrix (DSM) is a representational tool that managers can use to identify and model technical design interdependencies among subsystems and components of a complex innovation process, such as flex-fuel engine product development (Eppinger, 2001). There are several indications, but no definitive conclusion yet, that the degree of interdependence of a subsystem, as defined in a DSM, may be a reasonable proxy for pleitropy.

The data were collected through two means: 1. Review of Brazilian trade journals, specialized magazines in automotive technology and public presentation materials of VWB and other companies' managers and executives; 2. Interviews with managers and engineers of VWB, Bosch, Magneti Marelli and Delphi, who participated in the design, testing and production of these new subsystems and components. The DSMs that describe the evolution of the two VWB flex-fuel engines from 2003 to 2009 are the direct results of these interviews.

Our application of an established technology management tool - DSM - and the Murmann and Frenken (2006) framework provides an alternative method to define core and peripheral subsystems. In our approach, the degree of interdependence represents the number of affected subsystems requiring modifications and / or adjustments due to the technical alterations in one of them. It can therefore provide relevant information in planning product strategy - development and launching of products generations – and therefore properly directing organizational capabilities and investments. This paper then discusses the challenges faced by the VWB design managers in trading off engine performance, development costs and project deadlines in the last seven years in flex-fuel technology.

1. INTRODUCTION

The complexity of new product and process development is due to the difficulty of coordinating several functions within the company (Clark, Wheelwright, 1993; Gerwin, Barrowman, 2002) and understanding the latent needs of consumer markets (Urban, Hauser, Dholakia, 1987; Brown, Eisenhardt, 1995; Ulrich, Eppinger, 1995) in order to, through the use of knowledge and technology, design and launch products with superior quality and distinguishing features, that is, products with internal and external integrity (Clark, Wheelwright, 1993; Brown; Eisenhardt, 1995; Cooper, Edgett, Kleinschmidt, 2001).

One of the key aspects of the strategic management of product development is the evolution of the technologies relevant for the company's products and processes. An understanding of the dynamics or evolution of related technologies is important to executives in charge of innovation. This understanding of possible technological trajectories allows the development of technological strategies that delimit the "elbow room" for the development of new products. Additionally, as technological changes may entail changes to the industrial structure, an understanding of the consequences of technological evolution may be very important to support the company's strategic management Christensen, 1997.

The main objective of this study is to identify and understand the evolution of flex-fuel technology for automotive engines in the first seven years of its sale in Brazil. Since this flex-fuel technology has been developed only in Brazil, an understanding of its early evolution can be important to analyze its potential and the restrictions that limit its further development. This information can also be relevant for the Brazilian government's technology policy with respect to bioenergy and other green energy technologies. Furthermore, this study of the evolution of flex-fuel technology can provide data to verify, to adjust or to extend existing theories of technology evolution.

This is an empirical study of the technical evolution of the VWB (Volkswagen do Brasil) flex-fuel engine, for the period spanning 2003 to 2009. We collected data on the modifications in the subsystems and components of two main flex-fuel engine families and analyzed the patterns of these innovations using, and adapting, the framework provided by Murmann and Frenken (2006, p.925-952). These modifications reflect the decisions made by the VWB management team in these last seven years in order to improve the performance of the flex-fuel engine without a significant increase in its costs. Two aspects should be noticed in analyzing these decisions: first, flex-fuel technology has been developed solely in Brazil by the subsidiaries of foreign corporations. Consequently, these subsidiaries cannot rely on the know-how and know-why usually provided by the R&D units in their headquarters. These are decisions made by local management and engineering teams. The second aspect is that the Brazilian consumers are very price-sensitive. As a matter of fact, the so-called "popular car" (no-frills cars with engine displacement of 1 liter or less, which enjoy a special tax incentive) accounted for more than 40% of cars sold in Brazil in 2009 (ANFAVEA, 2009). Therefore, these engineering changes had to consider this important cost constrain.

This paper begins with a succinct presentation of the historical context in which the development of flex-fuel vehicles occurred in Brazil, followed with a review of the literature on product development, with particular emphasis on the characterization of dominant design, concepts such as nested hierarchy technology cycles, systems and subsystems, and the analysis tools used in the present study, such as the Design Structure Matrix (DSM). We explain the technological trajectory of Volkswagen do Brasil (VWB) by means of the aforementioned analysis tools, and then proceed to a discussion of the information obtained.

2. FLEX-FUEL ENGINE – HISTORY AND TECHNOLOGY

In the mid-1970s, with the international oil crisis and an agricultural environment favoring sugarcane growing, Brazil implemented a pioneering program for the introduction of ethanol as a fuel for automotive vehicles. The program involved several fronts, particularly the supply infrastructure, through regulations that demanded that filling stations sell ethanol fuel besides gasoline, and the development of technologies for ethanol-fueled vehicles, initially at government research centers, with technologies later being incorporated and developed by automakers operating in the country (Nigro, Szwarc, 2009; Goldemberg, Coelho, Nastari, Lucon, 2004, p.301–304; Santos, Martins, Yu, Nascimento, 2009; ANFAVEA, 2009). Fiscal incentives were also provided for the purchasing and upkeep of ethanol-fueled vehicles. The program was successful for many years, as shown by the fact that, during the 1980s, 70% of new vehicles sold in the country ran on ethanol fuel (ANFAVEA, 2009). In the early 1990s, however, when sugar reached attractive prices on the international market, plantation owners shifted from making ethanol to making sugar, which led to a countrywide ethanol fuel shortage crisis and changed consumers' perception of ethanol-fueled vehicles. The sales of these vehicles declined steeply and during the 1990s accounted for a practically negligible fraction of new car sales (ANFAVEA, 2009). The ethanol fuel distribution and sale infrastructure, however, was preserved during the 1990s, in order to serve the still-expressive existing base of ethanol-fueled vehicles.

In parallel, the 1990s saw the introduction of electronic fuel injection systems to the Brazilian market. These systems, first launched in 1967 by Bosch in Germany (Bosch, 2010), are able to precisely dose the amount of air and fuel introduced in the engine, allowing faster combustion, reduced emissions and reduced fuel consumption, an innovation that brought improvements that could hardly have been achieved with the use of carburetors. The next step was the introduction of digital fuel injection with microprocessor which provides higher flexibility, as its operation logic is software-based, facilitating the dynamic configuration of injection and ignition times, which must be optimized according to the type of fuel used.

The conjunction of these factors – ethanol-fueled vehicle technology, infrastructure for production, distribution and sale of ethanol fuel, and digital fuel injection technology – fostered the development of flex-fuel vehicles, those capable of running on a mix of gasoline and ethanol in any proportion. The flex-fuel engine dynamically recognizes or infers the characteristics of the fuel mix and adjusts fuel injection and ignition system parameters accordingly (Bosch, 2004). It was first tested in the U.S., by Bosch, in the 1980s, and the first tests in Brazil were conducted (also by Bosch) in the 1990s, using a specific sensor to detect the fuel mix. However, the parameters of the flex-fuel engine launched in Brazil in 2003 are inferred on the basis of information on the composition of exhaust gases, which are monitored by a sensor already present in the emissions control system and processed by the Engine Management System or EMS (Nascimento, Yu, Nigro, Quinello, Russo, Lima, 2009, p.110-119). The flex-fuel cars restored the image of ethanol fuel in the country by giving the vehicle owner the choice of which fuel to use at the pump for refilling, not when buying the car. In 2008, nearly 80% of new vehicles sold in Brazil were flex-fuel (ANFAVEA, 2009).

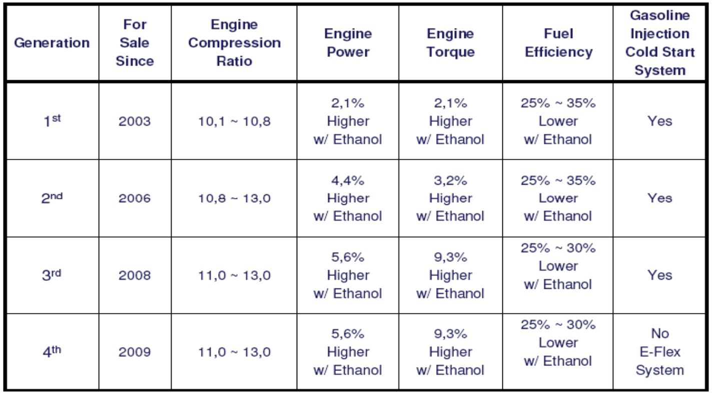
In 2003, with the launch of the first flex-fuel vehicle, and over the following years, the matter took on importance as average ethanol prices became significantly lower than those of gasoline (Goldemberg, Coelho, Nastari, Lucon, 2004, p.301–304) and the use of ethanol provided flex-fuel car users with substantial savings, even when taking into account the fact that ethanol consumption is greater per kilometer traveled due to its lower calorific power.

On the worldwide level, from the 1990s onward and particularly in recent years, there has been a growing concern with the use of fossil fuels due to the emission of CO2 into the atmosphere (Goldemberg, Coelho, Nastari, Lucon, 2004, p.301–304; Amatucci, Spers, 2009). Considering the complete cycle, from production to combustion, biofuels such as sugarcane ethanol have a zero CO2 emissions balance, as sugarcane growing sequesters CO2 from the atmosphere (Macedo, 2007). Starting in 2005, oil prices also rose to levels higher than those found during the oil crisis of the 1970s.

The flex-fuel vehicles have achieved commercial success since their 2003 launch. This dominance has motivated local automakers to develop incremental changes in the technological solution, with the yearly launch of new versions which seek to improve performance regardless of the fuel used, unlike the first versions launched in the 2003 and 2004, which were mostly concerned with system operation, i.e., “just make it work”, rather than with system optimization. While, early on, flex-fuel vehicles employed engines whose performance characteristics were close to those of gasoline-powered vehicles, regardless of the fuel used, recent versions feature technological evolutions that allow better use of the fuel chosen by the user at the pump, whether it is gasoline or ethanol.

Volkswagen Brazil has launched successive versions of flex-fuel engines that increasingly make use of the advantages of ethanol – when ethanol is used – in energy characteristics, providing better engine performance in terms of power, torque, and economy. The following table shows the improvement of the different generations of these engines.

Table 1 - Comparison of performance of several generations of VWB flex-fuel engines; percentages show change in performance as compared with using gasoline (Joseph, 2009).



Generation	For Sale Since	Engine Compression Ratio	Engine Power	Engine Torque	Fuel Efficiency	Gasoline Injection Cold Start System
1st	2003	10,1 ~ 10,8	2,1% Higher w/ Ethanol	2,1% Higher w/ Ethanol	25% ~ 35% Lower w/ Ethanol	Yes
2nd	2006	10,8 ~ 13,0	4,4% Higher w/ Ethanol	3,2% Higher w/ Ethanol	25% ~ 35% Lower w/ Ethanol	Yes
3rd	2008	11,0 ~ 13,0	5,6% Higher w/ Ethanol	9,3% Higher w/ Ethanol	25% ~ 30% Lower w/ Ethanol	Yes
4th	2009	11,0 ~ 13,0	5,6% Higher w/ Ethanol	9,3% Higher w/ Ethanol	25% ~ 30% Lower w/ Ethanol	No E-Flex System

The first generation of flex-fuel engines kept almost intact the engine originally developed for ethanol, and adjusted its compression ratio to consume gasoline (10.1:1); the engine power and torque gain with ethanol was around 2% higher, on average. It seemed that optimization of engine performance was not the concern. In the second generation, the compression ratio was made intermediate between that of engines optimized for ethanol and that of gasoline engines (from 10.8:1 up to 13:1); a power and torque enhancement of more than 4% and circa 3%, respectively, were found in ethanol operation. In the third generation, the adopted values for compression ratios (12.1:1 to 13:1) closely matched the maximum permissible rate for ethanol use; therefore, the engine power gain exceeded 5% and the ethanol torque was more than 9% superior compared with gasoline operation. In the fourth generation, an improved flex-fuel engine was developed to eliminate the need for the tiny secondary gasoline tank used for cold start of the engine, by the introduction of a subsystem responsible for warming the ethanol fuel during starting, and allowing flex-fuel vehicles to do a normal cold start at temperatures as low as -5 °C, the lowest temperature expected anywhere in the Brazilian territory (Cenbio, 2008). In March 2009, VWB launched the Polo E-Flex, the first flex-fuel Brazilian model with this subsystem which obviates the need for an auxiliary tank for cold start. This subsystem used in the Polo was developed by Bosch (Rossetti, 2009).

As the engine is a complex system, changes made to any of its subsystems in order to implement technological advances will sometimes lead to a need for adaptations in several other interacting subsystems. The key characteristic of flex-fuel engines – the ability to run on a mix of gasoline and ethanol in any proportion – entails technical difficulties to the optimization of both fuels in separate, requiring a compromise solution between better technical performance and the risk of changes. The present study seeks to identify and analyze the technological options adopted by VWB, since 2003, to permit improvements in the efficiency of the flex-fuel engine, shown in Table 1, in order to obtain maximum fuel efficiency during ethanol operation (Bauer, 1996) without, however, compromising gasoline performance. These options entail modification of many engine subsystems and components.

3. LITERATURE REVIEW AND RESEARCH METHODOLOGY

Over the years, several theories on how technologies evolve with time and which factors determine their evolutionary trajectories have been developed and subjected to empirical testing. This section describes those most relevant for the present study.

Utterback and Abernathy (1975, p.639-656) developed a dynamic model to represent the product and process innovation cycle of a given industry (such as the auto industry). The model considers the existence of an initial phase in which a large number of innovations occurs when companies are mostly seeking new product technologies or concepts. When levels of technical uncertainty decrease and a dominant project architecture starts to arise (a dominant design), manufacturing of the product begins to follow the dominant design, which organizations tend to employ on a large scale; in a second innovation cycle, these organizations begin the search for productivity and production cost improvements.

Anderson and Tushman (1990, p.604-633; 1991, p.26-31) propose a model for innovation dynamics or innovation cycles, by identifying a pattern for the evolution of technological product and process changes after studying the cement, glass, and minicomputer sectors. To these authors, the innovation cycle contains well-defined events: 1) technological discontinuity, which gives rise to the “Era of Ferment”, in which many companies begin the search for new ideas and the development of new product or process platforms in order to create and establish a new technological paradigm to supersede the old one; and 2) the appearance of a “dominant design”, which puts an end to the “Era of Ferment” and begins the incremental innovation stage, which focuses on perfecting technologies associated with the dominant design and the production process. Another technological discontinuity will start a new innovation cycle. Anderson and Tushman’s model is compatible with the more conceptual description by Dosi (1982, p.147-162), which distinguishes continuous and discontinuous innovation to the extent that continuous innovations generate advancement and improvement according to a well-known, predetermined technological trajectory. Discontinuous innovations, on the other hand, tend to break from the current trajectory, creating and establishing a new technological paradigm. Incremental innovations seek to improve the performance and functionality of product or process components or subsystems, reinforcing and sustaining the current technological trajectory and a predetermined set of competencies (Dosi, 1982, p.147-162; Anderson, Tushman, 1990, p.604-633, 1991, p.26-31; Christensen, 1997).

Christensen (1997) proposed the S-Curve model to represent technological trajectory, that is, concept changes that support current technology, or dominant technology, as it is referred to by Utterback and, Abernathy (1975, p.639-656). Christensen presented the S-Curve after studying incremental innovations which continually introduced minor improvements in the storage capacity of disk drives. “*Movement along a given S-Curve is generally the result of incremental improvements within an existing technological approach, whereas jumping onto the next technology curve implies adopting a radically new technology*” (Christensen, 1997, p. 11).

Christensen, Suárez and Utterback (1998) developed a stricter definition of the concept of “dominant design” based on product architecture, which comprises the functions of components and subsystems and their interrelations. Improvement movements, or cycles, move up and down within the product hierarchy (design hierarchy) and create an innovation dynamic (Clark, 1985, p.235-251). Clark concluded that, once the dominant design has been established, a search for refinement or improvement in subsystems, components and interrelations occurs, which can be represented as downwards movement in the "design hierarchy". Even though these improvements in subsystems farther down the design hierarchy produce major impacts on performance, they tend to maintain and support dominant design.

Murmann and Frenken (2006, p.925-952) employ the concept of pleiotropy to distinguish or classify components into core and peripheral elements. In biology, pleiotropy is the number of traits or functions that a certain gene creates or influences in an organism. These authors define the technical characteristics of a product's components and subsystems as the "genotype", and the product's service features or attributes (which they compare to biological traits) as its "phenotype".

Murmann and Frenken (2006, p.925-952) also present impact or causal relationships among technical and service characteristics in a "genotype–phenotype map", in which components and subsystems are laid out in columns, and attributes, in rows. A mark in Murmann and Frenken's map suggests that the component in a given column is important to obtaining the attribute or function in the corresponding row. They thus define the pleiotropy of a certain component or subsystem as the number of service attributes or features that may be influenced by the component. High-pleiotropy components or subsystems are known as *core* subsystems, whereas low-pleiotropy ones are termed *peripheral*.

As described in Murmann and Frenken (2006, p.925-952), the analyzed artifacts can be conceptualized as complex hierarchical systems, and it is necessary to define explicitly the levels above and below the unit of analysis in order to specify it unambiguously. Thus, the level of analysis of the engine and its subsystems needs to be defined for this study.

The Design Structure Matrix (DSM) is a representational tool that managers can use to identify and model technical design interdependencies among subsystems and components of a complex innovation process, such as flex-fuel engine product development Eppinger (2001). Many of the interactions within such engines are critical and complex, since they not only involve physically adjacent components but also transfer of materials (fuel mixture, exhaust gas, or engine oil), energy (heat or vibration) and structural forces, as well as electric signals used by the EMS (Sosa, Eppinger, Rowles, 2007). DSM is related to genotype-phenotype mapping, but is not the same (Murmann and Frenken, 2006, p.925-952).

The dominant design is not necessarily the most innovative or technologically superior one, neither is it necessarily developed by a major corporation; rather, it is the design that is the best solution when one considers the set of internal and external factors for success according to Suarez (2004, p.271-286). He proposes a stage model for the "battle" that ensues until a dominant design emerges. This five-phase model (*R&D buildup, technical feasibility, creating the market, the decisive battle,* and *post-dominance*) features four well-defined points that mark the beginning of each stage. Finally, Suarez (2004, p.271-286) identifies the success factors in order to ensure better chances of winning the battle for the dominant design.

We use and adapt the framework of Murmann and Frenken (2006, p.925-952) to analyze the evolution of VWB's engine technology since the conversion of the gasoline engine to 100% ethanol, and, then, the conversion of this to flex-fuel and its progression. More specifically, the evolution of two VWB flex-fuel engines is studied in further detail from 2003 up to 2009. In our analysis the engine is a nested hierarchy of subsystems and processes. All the technical alterations are encoded in DSMs so that the interactions among these subsystems can be revealed. A subsystem whose modification requires adjustments in many other subsystems is considered core in the engine system; otherwise, it is a peripheral subsystem. These definitions of core and peripheral subsystems differ from that of Murmann and Frenken (2006, p.925-952), which is based on pleiotropy. The option for DSM is because we find it very difficult to operationalize the genotype-phenotype map in the flex-fuel engine case. First, the impact in the service characteristics of a change in a subsystem is not binary (impact or no impact), but usually a range of impacts, which makes it difficult to determine the pleiotropy. Second, if a change in a subsystem implies alterations in other subsystems, it is even more difficult to distinguish the effects of different engineering changes on service characteristics.

There are several indications, but no definitive conclusion yet, that the degree of interdependence of a subsystem, as defined in a DSM, may be a reasonable proxy for pleitropy. We first show the similarities between these two concepts. It is known that high degree of interdependence across a technological artifact's subsystems implies higher modification costs (Murmann and Frenken, 2006, p.937); consequently it is fair to expect that once an acceptable configuration is found for this set of subsystems, the focus of innovation turns to the subsystems and components with lower degree of interdependence. Studies have demonstrated that the "risk of a net loss becomes greater for components with high pleitropy", therefore "once a design has settled on particular variants of core components, further advances are concentrated in peripheral components only" (Murmann and Frenken, 2006, p.941). From the similarities between these two concepts, it is reasonable to propose that a subsystem with high degree of interdependence has a higher chance to be a core subsystem. Another piece of evidence is the well-known interface subsystem existing in most technological artifacts. A typical interface subsystem has both high interdependence (Eppinger, 2001) and high pleitropy and therefore, once its standard is accepted, a dominant design emerges.

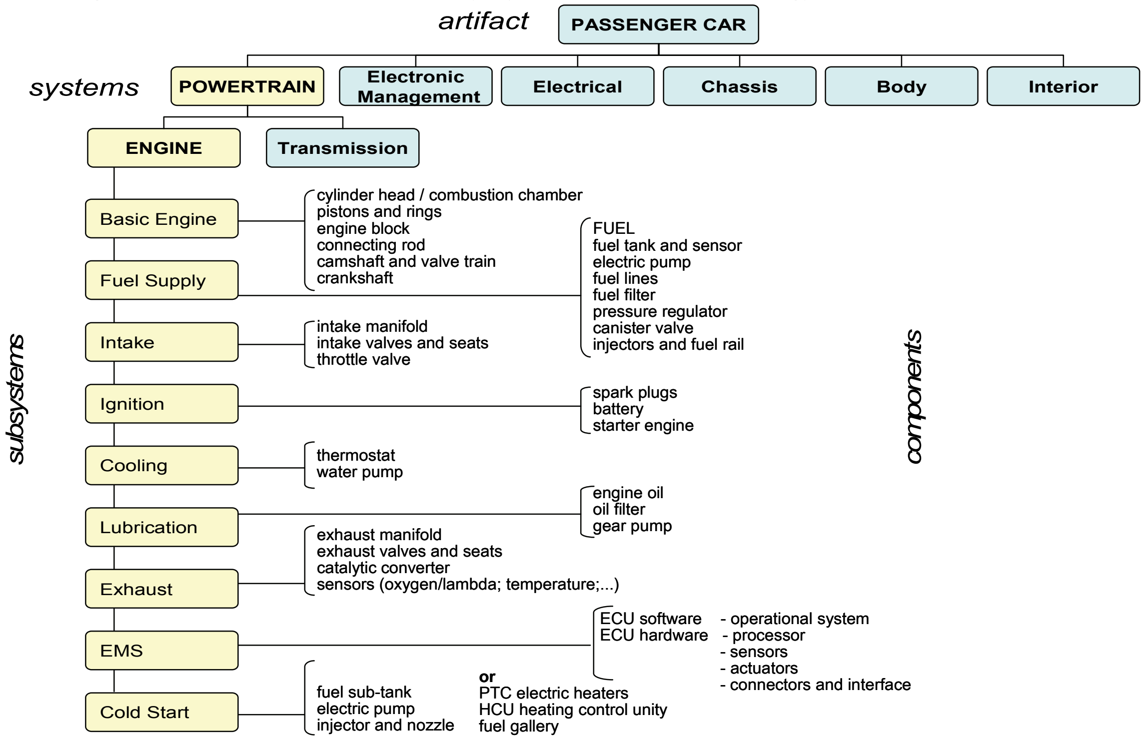
The data were collected through two means: 1. Review of Brazilian trade journals, specialized magazines in automotive technology and public presentation materials of VWB and other companies' managers and executives; 2. Interviews with managers and engineers who participated in the design, testing and production of these new subsystems and components; we interviewed managers and engineers of VWB, Bosch, Magneti Marelli and Delphi. A total of ten interviews were carried out between 2008 and 2009. Magneti Marelli and Bosch are two suppliers of EMS and other components and subsystems of flex-fuel technology to VWB. The DSMs that describe the evolution of the two VWB flex-fuel engines from 2003 to 2009 are the direct results of these interviews. Both the engineer and the manager from VWB reviewed the DSM presented in this paper. Other interviews provided the description of the contexts for the evolution of VWB flex-fuel engine technology.

4. EVOLUTION OF VWB FLEX-FUEL ENGINE TECHNOLOGIES

Studying the evolutionary change in automotive technology raises a concern about the definition of the system and its boundaries. For the purposes of this research, the vehicle product is a complex technical artifact that consists of a large number of components that work together in different nested subsystems and systems.

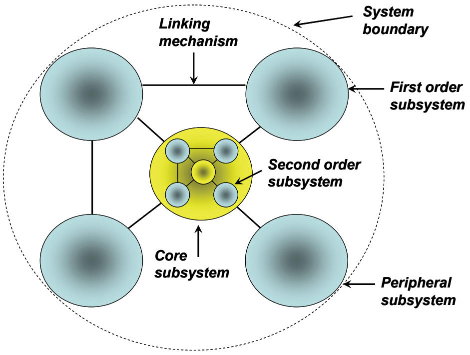
The analysis of technological changes on different levels requires a systematic approach. This study employs a hierarchical structural model. As the focus of this study is to analyze the technological evolution of flex-fuel engines, it is appropriate to consider the hierarchical structure of automotive technology suggested by Van de Wal (2007), adapted by the authors in Figure 1 as an extended version, where the artifact is a passenger car that has a propulsion system – the powertrain, consisting of an engine (main functional system) with a transmission (auxiliary functional system) and a number of nested subsystems, varying in complexity and dependency, basic components and linking mechanisms that are as crucial to the vehicle's performance as are the subsystems themselves, once these linking mechanisms may assume the important role of subsystems integrators, which are essential for the emergence of a subsequent technological shift at other levels (Lee, 2009).

Figure 1 – A structural hierarchy of automotive technology (Authors).



Interdependencies in a complex system imply that innovations in some subsystem or components, such a combustion chamber redesign, cannot be made without accompanying improvements in other subsystems such as cooling and/or lubricant components (Murmann and Frenken, 2006, p.925-952). Not all subsystems are equally important; core subsystems are those tightly coupled to other subsystems, therefore representing a strategic performance bottleneck. In contrast, peripheral subsystems are only weakly connected to other subsystems. This can be represented in the system model shown in Figure 2 (Tushman; Murmann, 2003).

Figure 2 – Nested hierarchy of a complex system (Tushman; Murmann, 2003).



Due to their high connectivity, technological changes in core subsystems have cascading effects on the other more peripheral subsystems and components. In contrast, shifts in peripheral subsystems have only minor impacts on the adjacent subsystems.

In order to analyze the evolution of technological changes made by VWB in its flex-fuel engines since their 2003 launch, six different DSMs were assembled and presented. The related technical data – modifications, substitutions and/or recalibrations of engine components – were based on extensive, in-depth interviews with the VWB engineering development team, including the manager in charge of flex-fuel technology.

The first matrix (Fig. 3) concerns the necessary modifications made over the course of twenty years, since 1980, to permit the use of ethanol (E100) in gasoline engines, followed by the main technical changes in flex-fuel engines, grouped into the basic four generations as described in Table 1 (Fig. 4, 5, 7 and 8). One additional matrix was made (Fig. 6), taking into account the changes in an important second order subsystem – a specific VWB basic engine.

Those DSMs represent the interdependencies among the engine subsystems shown in Figure 1, arranged equally in horizontal and vertical order to form a matrix of rows and columns. Reading down each column, the marks report the possible impacts (function and/or layout) caused by technical modifications of the subsystems, and its components, on the others. In other words, the potential need of component substitution and/or reconfiguration in that subsystem as cause of others subsystems' alterations is indicated across each row.

4.1 Engine modification to permit the use of ethanol fuel

Ethanol fuel has the potential to improve engine performance over that achievable with gasoline, primarily due to its higher knock resistance (octane rating), although its higher specific energy, flame speed and molar ratio of products to reactants are also significant (Turner; Peck; Pearson, 2007). The benefit of ethanol's octane increase, as with the use of hydrated ethanol (E100) or in blends in flex-fuel vehicles, has allowed car manufacturers to design engines with a higher compression ratio – optimized combustion chamber geometry, redesigned pistons and cylinder heads, besides a new camshaft profile and phase, thus promoting higher thermal efficiency. In this case, the ignition advance control must be recalibrated, optimized, for ethanol. This adaptation also requires spark plugs with colder heat range and a higher capacity battery (Stone, 1999).

Maintenance requirements are equivalent to those of a gasoline engine, with the benefit of lower carbon deposits in the engine – combustion chamber, valves seats and fuel injectors – due to ethanol's cleansing properties (Joseph, 2008). Because of lower calorific value of ethanol, a fuel supply system with higher flow capacity is required, requiring fuel injectors with larger holes and a higher flow rate fuel pump.

Alcohol fuels place particularly high demands on fuel delivery components, as acids, gums and moisture contained in the fuel pose a hazard to metals, plastics and rubber seals (Bosch, 2004). Therefore, to ensure materials compatibility with ethanol operation, manufacturers use corrosion-resistant materials in any part that may come into contact with fuel, for instance: electronic fuel injectors; fuel pump, pressure regulators, fuel tank, filter and lines with protective internal surfaces; new surface materials for the intake and exhaust valves and valve seats. Hoses, seals and connectors require resistant materials; the intake manifold and exhaust pipe demand protection on internal surfaces and a new profile (Sahu, 2007).

The engine oil may require reformulation and/or a new additive package. Special lubricants are able to maintain long term stability, despite the aggressiveness of ethanol and its combustion products. A specific catalytic converter and wash coating, closer to the exhaust manifold, may be needed, as well as a recalibrated canister for higher purge flow.

Given the lower evaporative pressure of ethanol (*vs* gasoline), when cold starting the vehicle at temperatures below 15 °C, the engine may require an auxiliary gasoline-assisted cold start system (for E85 or above) with its own temperature sensor, gasoline reservoir, extra fuel injector and fuel pump and a higher capacity battery (Nigro, 2009).

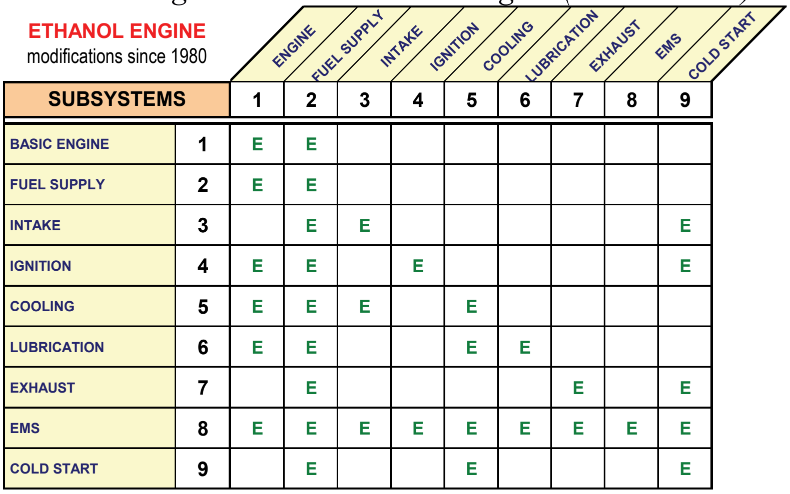
Over the last thirty years, state-of-the-art technologies have been continuously incorporated to new ethanol-fueled vehicles in Brazil with developments such as new engine designs, electronic fuel injection, electronic ignition control, engine management, catalytic converters, exhaust gas recirculation, crankcase vapor recycling, evaporative emission control, turbocharging and on-board-diagnosis. DSM of Figure 3 concerns the necessary modifications made during twenty years to permit the use of ethanol in gasoline engines.

As seen, the change from gasoline to ethanol – a modification in the "Fuel Supply" subsystem – impacts various components of all other subsystems of the engine, demanding alterations, substitutions and adjustments. Therefore, “Fuel Supply” is a core subsystem because of its high interdependence with other subsystems, as shown in the DSM of Figure 3.

The main change in the “Basic Engine” subsystem refers to the increase in compression ratio (combustion chamber and / or cylinder head redesign), an event which, in turn, triggers the need for adjustments in a wide range of subsystems, such as the ignition, cooling and lubricant subsystems. Again, the high interdependence of the “Basic Engine” subsystem characterizes it as a core subsystem.

Ethanol operation requires the installation of an auxiliary “Cold Start” subsystem, which mainly impacts the intake and exhaust subsystems, because these components require changes to receive extra components of the cold start subsystem. One would consider it core, since a major change in the subsystem itself would cause the need for adjustments in the others, although incremental changes would not significantly affect other subsystems.

Figure 3 - DSM Ethanol Engine (1980 to 2002)



ETHANOL ENGINE
modifications since 1980

SUBSYSTEMS		ENGINE 1	FUEL SUPPLY 2	INTAKE 3	IGNITION 4	COOLING 5	LUBRICATION 6	EXHAUST 7	EMS 8	COLD START 9
BASIC ENGINE	1	E	E							
FUEL SUPPLY	2	E	E							
INTAKE	3		E	E						E
IGNITION	4	E	E		E					E
COOLING	5	E	E	E		E				
LUBRICATION	6	E	E			E	E			
EXHAUST	7		E					E		E
EMS	8	E	E	E	E	E	E	E	E	E
COLD START	9		E			E				E

Modification to the EMS subsystem is required due to changes in all other subsystems. The EMS plays an important role as an integrator subsystem – the control element of the system – and can become very relevant in the incorporation of innovations throughout the system. It is essential for the promotion of successive waves of technological developments.

4.2 Technological evolution – from ethanol (E100) to flex-fuel engines

Brazilian flex-fuel engines are designed to operate indistinctly with gasoline, ethanol or any blend of them. For this to work, a fuel recognition system is required. Through electronic sensors, the EMS recognizes the fuel and automatically adjusts the engine parameters.

The EMS, processing signals from the oxygen sensor at exhaust pipe (lambda), controls the period of time the injectors stay open to ensure a stoichiometric fuel/air mixture. Based on engine speed and intake manifold temperature and pressure sensors, the EMS calculates the intake air flow as well as the fuel flow in accordance with the time the injectors stay opened.

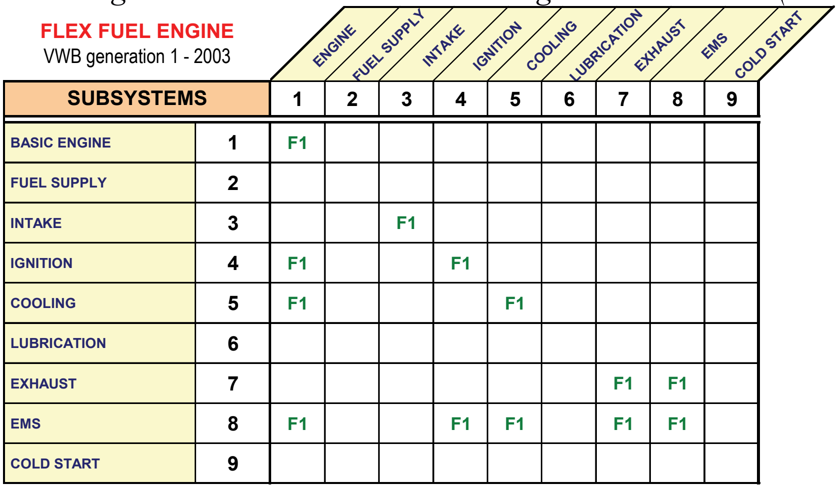
The use of EMS software to identify the composition of ethanol in the fuel based on signals from the lambda sensor is a solution created by Brazilian engineers working for tier 1 suppliers such as Bosch, Delphi and Magneti Marelli. All flex-fuel engines launched in Brazil employ this approach in designing the EMS because the different solution employed in the Bosch USA requires an additional fuel sensor which would cost around US$100 more per vehicle, which is too expensive for a price-sensitive market such as the Brazilian one.

Comparing the calculated air/fuel ratio with the theoretical values for ethanol and gasoline that were kept on the on-board computer’s memory, the EMS infers the fuel composition. Then, all pertinent engine parameters, such as sparking time, transient injection and cold start gasoline injection, are controlled accordingly (Nigro, 2009).

This study identified the modifications introduced by VWB in its two engine families: EA827 and EA111. Engine EA827 was introduced in Brazil in the 1980s, and its ethanol (E100) version was developed by VWB. It was the first VW engine adapted to flex-fuel technology, in 2003.–This engine was discontinued in 2009. The EA111 is an engine developed in Germany that later incorporated flex-fuel technology in Brazil. It is now the main VWB flex-fuel engine.

The main technical changes in VWB's flex-fuel engines, grouped into four basic generations as defined by Volkswagen (Table 1), are presented in the DSMs of Figures 4, 5, 7 and 8. One additional matrix (Figure 6) was devised, based on the changes in the second order subsystem (basic engine) of the EA111 1.0 liter flex-fuel engine that took place on the second generation of VWB fuel flex-fuel engines. This DSM shows the alterations within an important second-order subsystem. This is because this basic engine underwent the most extensive changes in the generation 2 flex-fuel engine.

Figure 4 - DSM VWB Flex-Fuel Engine Generation 1 (2003)



FLEX FUEL ENGINE
VWB generation 1 - 2003

		ENGINE	FUEL SUPPLY	INTAKE	IGNITION	COOLING	LUBRICATION	EXHAUST	EMS	COLD START
SUBSYSTEMS		1	2	3	4	5	6	7	8	9
BASIC ENGINE	1	F1								
FUEL SUPPLY	2									
INTAKE	3			F1						
IGNITION	4	F1			F1					
COOLING	5	F1				F1				
LUBRICATION	6									
EXHAUST	7							F1	F1	
EMS	8	F1			F1	F1		F1	F1	
COLD START	9									

VWB first launched the flex-fuel engine in its Gol car model, in 2003. The Gol was designed specifically for the Brazilian market, and has been one of the most popular car models in the country for many years.

As the EA287 engine was originally developed for ethanol fuel, a modification to the "Basic Engine" subsystem – a reduction of the compression ratio – was made to ensure a smooth combustion with the use of gasoline without causing detonation. Although relatively few changes were made in this subsystem, other subsystems were impacted, requiring changes in several components. Therefore, we consider the "Basic Engine" to be a core subsystem in this generation of flex-fuel engine.

Changes in the EMS subsystem were those most responsible for flex-fuel technology innovation. These changes requires extensive software modifications – an increase of approximately 20% in code lines – and almost all second order subsystems (components) of the EMS software had to be changed to incorporate the flex-fuel capability. However, these software modifications, performed by suppliers and not by VWB, had no impact on other engine subsystems. The EMS subsystem, receiving inputs from the subsystems involved in the alterations, acts as a controller of the entire engine system.

Comparing DSMs of Figures 3 and 4, note that the "density" of changes ("E" marks) in the first is much higher than that of Figure 4 ("F1" marks), probably suggesting that once an automaker masters the technologies related to ethanol fuel engines, the adoption of flex-fuel technology does not involve many technological difficulties. The main challenge lies in developing an EMS that can identify the fuel composition without requiring expensive sensors.

Figure 5 - DSM VWB Flex-Fuel Engine Generation 2 (2006)

FLEX FUEL ENGINE VWB
generation 2 - 2006

		ENGINE	FUEL SUPPLY	INTAKE	IGNITION	COOLING	LUBRICATION	EXHAUST	EMS	COLD START
SUBSYSTEMS		1	2	3	4	5	6	7	8	9
BASIC ENGINE	1	F2					F2			
FUEL SUPPLY	2		F2							
INTAKE	3	F2		F2						
IGNITION	4	F2			F2					
COOLING	5	F2				F2				
LUBRICATION	6	F2				F2	F2			
EXHAUST	7	F2						F2		
EMS	8	F2	F2	F2	F2	F2	F2	F2	F2	
COLD START	9									

Modification of the Basic Engine subsystem was based primarily on the significant increase in compression ratio (to 13:1) for the flex-fuel 1.0 liter EA111, close to the optimum value for ethanol and above usual values for gasoline. Due to this choice of a high compression ratio, favoring the optimization of ethanol operation, various changes were required in several other subsystems, such as recalibration of the ignition advance control, new camshaft phase (intake and exhaust valves), engine oil reformulation and recalibration of the thermostatic cooling valve. The broader impacts generated on the other subsystems reinforce its position as a core subsystem.

It is important to note that 2nd generation innovations were launched three years after commercial introduction of the flex-fuel car in the market by VWB whose product development team had enough time to monitor first generation engine performance, to consider different options for engine redesign and make decisions for the new configuration of the basic engine to obtain increase in performance. These changes in the Basic Engine are detailed in the next DSM (Figure 6). Modifications required in all subsystems have a direct impact on the EMS, which in turn adjusts the parameters of these other subsystems.

This matrix illustrates the impacts on a lower level subsystem (basic engine, as opposed to engine seen in the other maps) that occurred with the 2nd generation of flex-fuel engines (2006), in which major changes were introduced. A significant increase in compression ratio, allowed by redesigning the combustion chamber and cylinder head geometry and resizing the connecting rods, led to higher combustion pressures, which in turn impacted the pistons, piston rings and crankshaft, which required appropriate adjustments. Seeking a more stable combustion process in the combustion chamber, there was a need for a new camshaft profile and phase, which also influenced a change in timing belt material.

Figure 6 – DSM VWB Flex-Fuel Engine Generation 2 (2006)

FUEL FLEX ENGINE
SUBSYSTEM: Basic Engine
VWB generation 2 - 2006

		Cylinder head	Combust. chamber	Pistons	Piston rings	Engine block	Camshaft	Connect. rods	Crankshaft	Timing belt
COMPONENTS		1	2	3	4	5	6	7	8	9
Cylinder head	1	F2								
Combustion chamber	2	F2	F2							
Pistons	3		F2	F2						
Piston rings	4		F2	F2	F2					
Engine block	5									
Valve train / Camshaft	6		F2				F2			F2
Connecting rods	7		F2					F2		
Crankshaft	8		F2					F2	F2	F2
Timing belt	9						F2		F2	F2

Figure 7 - DSM VWB Flex-Fuel Engine Generation 3 (2008)

FLEX FUEL ENGINE
VWB generation 3 - 2008

		ENGINE	FUEL SUPPLY	INTAKE	IGNITION	COOLING	LUBRICATION	EXHAUST	EMS	COLD START
SUBSYSTEMS		1	2	3	4	5	6	7	8	9
BASIC ENGINE	1	F3								
FUEL SUPPLY	2									
INTAKE	3			F3						
IGNITION	4									
COOLING	5					F3		F3		
LUBRICATION	6	F3					F3			
EXHAUST	7							F3		
EMS	8	F3		F3		F3		F3	F3	
COLD START	9									

The innovations introduced in generation 3 comprised a set of changes that provide continuity to the alterations initiated in generation 2 (2006). Modifications to the Basic Engine subsystem referred to the increase in compression ratio also for the engine EA111 1.6 (to 12.1), requiring changes mainly in the Cooling subsystem.

There was a more refined improvement in the Intake subsystem, in order to enhance engine performance (high torque) at low engine speeds; changes were carried out in the camshaft phase diagram, as well as a redesign of the intake manifold and of other components. The impact of such changes was limited to the subsystem itself, besides the required alterations in the EMS subsystem, therefore highlighting its position as peripheral.

Modification to the Cooling subsystem was necessary, since increasing compression ratio and torque increased the working temperature of the engine block, mandating additional engine oil injectors for cooling the pistons, and reset the phase control of the valve thermostat. Again, the impact was restricted to the subsystem itself, making it a peripheral subsystem.

Modification to the Exhaust subsystem was also required due to the implementation of more stringent emission standards (PROCONVE L5 emission standards for light-duty vehicles): adjustments were necessary in the exhaust manifold, which also underwent a change in material and a new catalytic converter. The influences of these changes were restricted to the subsystem itself, thus classified as peripheral.

Figure 8 - DSM VWB Flex-Fuel Engine Generation 4 (2009)

FLEX FUEL ENGINE
VWB generation 4 - 2009

		ENGINE	FUEL SUPPLY	INTAKE	IGNITION	COOLING	LUBRICATION	EXHAUST	EMS	COLD START
SUBSYSTEMS		1	2	3	4	5	6	7	8	9
BASIC ENGINE	1									
FUEL SUPPLY	2									
INTAKE	3			F4						F4
IGNITION	4				F4					F4
COOLING	5									
LUBRICATION	6									
EXHAUST	7							F4		F4
EMS	8			F4	F4			F4	F4	F4
COLD START	9									F4

The introduction of a new Cold Start subsystem, developed by Bosch, was the key innovation of the 4th generation of VWB flex-fuel engines. This innovation did not affect technical performance in terms of fuel efficiency, engine power and torque (Table 1), but greatly simplified operation of the car: the driver no longer needs to fill up an auxiliary gasoline tank when the main tank is filled with ethanol. According to our interview with the engineers at Bosch, the innovation of the cold start subsystem involved very complex technologies. This is probably the reason why a fourth-generation flex-fuel engine was launched in the Polo model, a more expensive car than the Gol. This is a different technology, which makes it possible to start the engine on ethanol at low ambient temperatures by heating the fuel mixture, waiving auxiliary fuel injection in these operating conditions. The system operates by means of electric heater thermistors (PTC) located in small holes in the fuel gallery, which are controlled by the on-board computer (ECU) and an exclusive heating control unit (HCU). According to the ethanol content in the tank and weather temperature, the ECU / HCU determines whether to warm up the PTC heaters until the fuel reaches appropriate conditions (Joseph, 2009).

As discussed in the DSM of Figure 3 (ethanol engine), a major change in this subsystem causes the need for adjustments in the others, such as a redesign and material change of the intake manifold, a switch to a higher-capacity battery and spark plugs with new specifications. The extent of the impact on other subsystems makes the cold start a core subsystem.

5. DISCUSSION AND CONCLUSIONS

This paper analyzed the changes implemented in the two families of VWB flex-fuel engines between 2003 and 2009. Four generations of flex-fuel engines are identified, and the main modifications and their interdependences with other subsystems described. The results of this research are summarized in the six Design Structure Matrices (DSM) based on the framework proposed by Murmann and Frenken (2006, p.925-952). This section analyzes three aspects based on these DSMs and the context under which these modifications were made: first, a discussion of VWB’s managerial decision making regarding these modifications; second, a discussion of dominant design of the flex-fuel engine; and third, a discussion of the application of the framework to this study. Much of the information about the context is based on papers produced by our colleagues (Nascimento et al, 2009, p.110-119; Yu et al, 2009).

With respect to VWB’s underlying managerial rationale in implementing these engineering changes over the last seven years, we can analyze the innovations in each generation of the flex-fuel engines. The key innovation in the first generation of VWB flex-fuel engine was the EMS developed by Magneti Marelli (for the Gol car model) and Bosch (for the Polo car model). The modifications in other engine subsystems were relatively minor (DSM of Figure 4) compared with the modifications required for a gasoline engine to run on ethanol (DSM of Figure 3). In order to understand why VWB decided not to carry out more extensive changes in other engine subsystems, we need to look at the context of this decision. Although the technology (flex-fuel engine) was available and the price of ethanol was favorable, our interviews show that VWB managers were quite uncertain about the market acceptance of this technology before its launch in 2003. This uncertainty probably influenced the managerial decision for the first generation of flex-fuel engine. In other words, VWB management adopted a real option approach in launching the first flex-fuel engine: pay a minimum premium so that it would have the option to improve the engine later on, if the market really took off, reducing the risk in case the flex-fuel car did not sell well.

Another managerial insight in comparing the DSMs of Figures 3 and 4 concerns the delay of automakers that have not dominated ethanol engine technology. These companies, such as Citroën, Honda, Kia, etc., entered the Brazilian market in the mid 1990s, when the demand for ethanol-powered cars was at its lowest point. In order to introduce flex-fuel cars after 2003, these companies had to carry out modifications presented in both DSMs of Figures 3 and 4 simultaneously; therefore, these automakers had to overcome a much higher barrier to market entry. We are not excluding other factors that may also have played a role in this delay for these companies (e.g., the importance of the Brazilian market for the headquarter), but only pointing out the usefulness in understanding the detailed technological evolution.

The second generation of flex-fuel engine, introduced in 2006, incorporated major modifications in the basic engine, as described in the DSM of Figure 6, and their impacts on other engine subsystems, as shown in the DSM of Figure 5. Note that between the first and the second generation of flex-fuel engine, three years had passed. Sales for flex-fuel cars had exploded, and VWB was able to design and test engineering changes that provided much better performance (Table 1). The main alteration was in the basic engine (DSM of Figure 5), more specifically in the combustion chamber (DSM of Figure 6). These modifications entail adjustments in almost all other engine subsystems, such as ignition, cooling and lubrication.

The third generation flex-fuel engine, introduced two years after the second, involved mostly incremental changes, although a new government regulation on emissions was responsible for a change in the exhaust subsystem of the generation 3 engine.

The first three generations focused on improving the basic engine, and required modifications in other subsystems. Therefore, these three generations of innovations are concerned with the performance of the flex-fuel engine, on aspects such as power, torque and fuel efficiency (Table 1). The fourth generation departed from this trajectory; it is concerned with the driver's convenience. The key innovation is the new cold start subsystem provided by Bosch. With this new subsystem, from the drivers' perspective, a flex-fuel car is the same as a gasoline-powered car in the winter. However, because of its complexity (DSM of Figure 8), VWB launched this new cold start subsystem only in more expensive cars, such as the Polo, in 2009. Higher production volumes will probably drive the cost down in the future.

A second relevant aspect for analysis is to speculate on the emergence of dominant design in Brazilian flex-fuel engines based on the observed trajectory of technical changes in this study. We use the word "speculate" because the concept of dominant design is defined for an industry. In our case, it should be defined for the Brazilian auto industry. However, this study analyzed technical changes in the flex-fuel engine of one automaker – VWB. Therefore, we can only speculate on the emergence, or not, of dominant design based on a single case and the framework proposed by Murmann and Frenken (2006, p.925-952). As shown by them, once an industry has settled on a dominant design for a technological class, further innovations are concentrated on peripheral components. In our analysis of VWB's flex-fuel engine, we concluded that two subsystems are core: basic engine and cold start, because these two subsystems affect many other subsystems. However, the main focuses of innovations in VWB's flex-fuel engines over the past seven years focused exactly on these cores, not on peripheral subsystems such as ignition and cooling. Therefore, we can tentatively conclude that the Brazilian auto industry has not yet reached a dominant design for the local flex-fuel engine, being still in the so-called "era of ferment" in the evolution of the Brazilian flex-fuel engine. A more definitive conclusion will only be possible if future studies can replicate this one for other companies' flex-fuel engines.

On the other hand, it seems that the EMS subsystem of the Brazilian flex-fuel engine has long been the dominant design – since 2003. This is because all EMS models, from different suppliers, are employing the same approach to detect fuel composition. However, since this study is focused on the evolution of the VWB's flex-fuel engines, we have therefore not analyzed second-order subsystems within all EMS models to draw a definitive conclusion. This can be another interesting topic for future research.

Finally, some reflections on using the Murmann and Frenken (2006, p.925-952) framework in this research are in order. We found the framework truly useful for our research. It provides a common language for communication among authors and a structure for data collection. Although they mentioned that the DSM is related to the genotype-phenotype map, they did not elaborate further on it. However, even though one of the authors of this paper holds a PhD in engine technology, we found genotype-phenotype mapping more difficult to use, as it requires a much deeper understanding of the relations between genotype and phenotype. On the other hand, the DSM is very useful as a tool to collect data on the design process, particularly on the interaction among different subsystems or components.

Our application of an established technology management tool - DSM - and the Murmann and Frenken (2006, p.925-952) framework provides an alternative method to define core and peripheral subsystems. In our approach, the degree of interdependence represents the number of affected subsystems requiring modifications and / or adjustments due to the technical alterations in one of them. It can therefore provide relevant information in planning product strategy - development and launching of products generations – and therefore properly directing organizational capabilities and investments. However, the relationship between the degree of interdependence and the pleitropy of a subsystem has not been established conclusively by scholars of innovation. Therefore, this is another research topic worth the attention of researchers interested in understanding the evolution of technology.

Our study of changes in the VWB flex-fuel engine shows that every modification in any subsystem results in an adjustment in the EMS software. Fortunately, these adjustments usually only involved changes in DSM parameters; there was no need to rewrite the software. The only exception is probably the new cold start subsystem. Therefore, the costs of DSM adjustments are relatively low. The EMS is obviously a control structure, but in the case of flex-fuel engines, it plays a very unique role: it is flexible enough to accommodate changes in other subsystems, and this kind of control system has not been discussed by Murmann and Frenken (2006, p.925-952) in terms of its impact on technological evolution.

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