An architectural analysis of green vehicles – possibilities of technological, architectural and firm diversity

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Abstract: This paper applies the analytical framework of *product architectures* and *design-based comparative advantages* to the case of *green vehicles*, or low carbon automobiles which has potentials for capturing significant portions of the future market. First, the paper explains concepts of architectures, capabilities and their fits. Second, this framework is applied to the case of futuristic products, including green vehicles, which have to overcome their weaknesses in *critical functions, critical components* and *critical links* among them for future market acceptance. Third, we provide a preliminary analysis on architectural patterns of eight types of potential green vehicles. The results indicate their *architectural diversity* caused partly by their *technological diversity*. Finally, based on the hypothesis of *architecture-capability fit*, we predict that the architectural diversity of green vehicles may in turn result in diversity across firms or countries which take leading roles in different types of green vehicles, causing their *intra-industrial trade*.

Keywords: green vehicle, product architecture, design-based comparative advantage, *critical functions*, technological/architectural/firm diversity.

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1 Architectures and competitiveness of 'green vehicles'

1.1 Technological and architectural diversity of green vehicles

Green vehicles and their potential

This paper explores the architectural aspects of *green vehicles*, or environmentally friendly low carbon vehicles of the next generation, including advanced internal combustion engine vehicles (ICEVs), parallel hybrid (or parallel-series hybrid) vehicles (HEVs), plug-in hybrid vehicles (PHEVs), secondary battery electric vehicles (BEVs), range extender electric vehicles (or series hybrid vehicles; REVs), and fuel cell vehicles (FCVs). A hybrid vehicle (HEV, PHEV, REV) is usually a vehicle whose power train is a combination of an electric motor and an internal combustion engine (ICE), but in fact there can be other types of combinations [e.g., REVs with secondary batteries and fuel cells (FC)]. Some of these vehicles are seen as relatively incremental innovations compared to traditional ICEVs, while others are regarded as relatively radical (technologically discontinuous) or even disruptive (industrially discontinuous) innovations (Schumpeter, 1934; Abernathy and Utterback, 1978; Christensen, 1997; Chararon and Teske, 2007; Freyssenet, 2011; Dijk, 2014).

It is known that each type of the above-mentioned green vehicles has various strengths and weaknesses in terms of friendliness toward the environment, as well as customers and producers. Some are environmentally more attractive but more expensive and/or less user-friendly. Others are less expensive but more energy-consuming. Moreover, their impact on global warming may vary depending on how electricity is generated in each region. Thus, none of the above types of green vehicles seems to be able to take over the world's automobile market in the next few decades. On the contrary, the author foresees that the first half of the 21st century will most likely be characterised by diversity in power train types, including most of the aforementioned types of vehicles, each occupying a market niche or a larger segment with different characteristics (Fujimoto, 2014).

Hypothesis on architectural diversity

If the above prediction about the technological diversity of green vehicles holds true, it may also be reasonable to infer that there will be a variety of product architectures. Generally speaking, *technology* refers to knowledge or information about concrete causal relations between an artefact's structures and functions, whereas *architecture* refers to correspondences in the abstract between the same artefact's functional and structural elements (Ulrich, 1995; Fujimoto, 2007). Following the definition of *design* from the theory of axiomatic design (Suh, 1990), technology and architecture can be seen respectively as substantial and formal knowledge about an artefact, or as the vocabulary and grammar of design, as it were.

Thus, the question here is whether the technological diversity of the so-called green vehicles is accompanied by their architectural diversity. On the one hand, it seems reasonable to examine the hypothesis that the two diversities might tend to go together because technology and architecture are two sides of the same coin called design. On the other hand, it is logically possible and empirically observed that different technologies share similar architectures and vice versa (Henderson and Clark, 1990).

Since there are still significant technological and commercial uncertainties regarding the future of green vehicles, it might be too early to conduct rigorous empirical studies addressing this research question, but it is a good time to focus on exploratory studies based on a research framework for measuring and analysing architectural varieties of potential future product types.

1.2 Intra-industry and intra-firm trade of green vehicles

Who makes which type?

Measuring and forecasting the architectural varieties of future products seem to be important not only for researchers but also for industrial practitioners and policy makers, because such architectural differences are likely to affect the industrial performance of firms, regions and countries which are endowed with different types of organisational capabilities, according to the logic of *design-based comparative advantages* (Fujimoto, 2007, 2012, 2014).

In other words, the variety of green vehicle architectures may result in a variety of firms, regions or countries developing and/or producing them, each of which may have competitive advantages in different types of energy-saving automotive technologies. For example, firms or regions with relatively strong coordination capabilities in design and manufacturing may turn out to be competitive in certain types of futuristic vehicles with relatively integral architectures (Womack et al., 1990; Clark and Fujimoto, 1991; Fujimoto, 1999), whereas those with ecosystem-managing or interface-managing capabilities may become strong competitors in products with open-modular architectures (Baldwin and Clark, 2000; Gawer and Cusumano, 2002; Iansiti and Lavien, 2004; Teece, 2007; Sanchez, 2013).

Besides, diversity in development-production locations may, in turn, bring about product-line differentiation among both incumbent automobile firms and new entrants, as well as intra-industry trade among countries with different endowments in terms of development-production capabilities.

The literature has often discussed whether incumbent firms, or new entrants, or both will be the winners in the global competition for green (lower carbon) vehicles in the future (Freyssenet, 2011).

Mutual trade of green vehicles?

As mentioned above, considering the technological and architectural varieties of green vehicles, the question may arise as to which countries or regions are more likely to have comparative advantages in which types of green vehicles. This question is closely related to one of the stylised facts of the current global economy – *intra-industry trade*. Whereas David Ricardo (Ricardo, 1817), who established the theory of comparative advantage in the 19th century, described and analysed inter-industry trade between two countries with different characteristics (e.g., wines exported from country E and textiles from country P), in more recent years economists have predicted that similar products within a given category (e.g., motor vehicles) will increasingly be imported and exported between two countries at the same time – i.e., intra-industry trade of the 21st century. In this paper, we will argue that this prediction may be applied to the case of future green vehicles too.

This may also imply *intra-firm trade* of green vehicles within a global automobile manufacturer (e.g., Toyota, VW, GM), since such multinational firms are likely to develop and produce more than one type of green vehicle to avoid the risk of technological misprediction and obsolescence.

The literature on the competitiveness of green vehicles, however, has tended to focus only on technological and economic comparisons among their different types (ICEVs, HEVs, PHEVs, REVs, BEVs, FCVs, etc.). The question as to which regions or firms, with which kinds of resources and capabilities, are more likely to be competitive in which types of green vehicles has not been discussed extensively in research thus far.

Outlines

Against this background, this paper will attempt to explore the above-mentioned research question: which regions or firms are more likely to be relatively competitive in which types of green vehicles? The framework of *design-based comparative advantages* (Fujimoto, 2007, 2012), which predicts a fit between a product's architecture and a region's (or a firm's) endowment of certain organisational capabilities, will be adopted to answer the research question. That is, we will discuss the relative technological characteristics of the various types of green vehicles, the relative integrality or modularity of their architectures in particular, as well as the types of firms which may enjoy competitiveness in different types of green vehicles.

Section 2 will briefly illustrate the basic framework of design-based comparative advantages. In Section 3, we will first make some predictions or hypotheses regarding diversity across the technologies and architectures of green vehicles, as well as the firms/regions/countries which develop and produce them. We will then propose a modified framework for analysing architectures of futuristic products and apply it to the cases of eight green vehicle types. As an overview, we will plot the architectural position of each vehicle type along the integrality/modularity spectrum to determine whether architectural diversity is actually observed. We will also provide some preliminary remarks on the types of firms and regions which may enjoy competitive advantages in each green vehicle type.

Note that the purpose of this exploratory paper is not so much to present accurate measurements of automotive product architectures, but rather to propose a possible method for empirical architectural analysis that may be applied to certain futuristic products, and to make first-cut predictions on technological diversity, architectural diversity, as well as on the diversity of firms, regions and countries that may be competitive in different types of green vehicles.

2 The framework of design-based comparative advantage

2.1 Global competition and the role of design

Globalisation and intra-industrial trade

The concept of comparative advantage of industries, both Ricardian and neo-classical, continues to be key in understanding the freer trade systems of the 21st century. Newer approaches, such as the product lifecycle (flying geese) theory, the new trade theory and the new-new trade theory, certainly provide additional explanatory tools to understand today's trade phenomena which involve emerging nations, foreign direct investment, product differentiation and economies of scale (Akamatsu, 1962; Vernon, 1966; Helpman and Krugman, 1985; Melitz, 2003). Without introducing the concept of *design* of traded goods and services, however, we may not be able to capture the essential characteristics of today's international trade – *intra-industrial trade at minute levels*, such as sheet steel for the automobile's inner body panels exported from Korea to Japan and sheet steel for the outer panels exported from Japan to Korea.

The end of the 'Post-Cold-War' era

Some 20 years after the end of the Cold War and abrupt entrance of gigantic low-wage countries like China into the global market, the average wage in emerging countries has finally started to rise, as the period of 'unlimited supply of labour' (Lewis, 1954) has come to an end. Thus, this may be a good time to introduce a dynamic and field-based version of the Ricardian-Sraffian trade theory to analyse how international differences in productivity and wage increase between advanced and emerging countries affect changes in global trade structures (Ricardo, 1817; Sraffa, 1960; Shiozawa, 2007; Fujimoto and Shiozawa, 2011).

Against this background, this paper sketches out an evolutionary framework to analyse industrial performance by introducing concepts like *manufacturing* (monozukuri) *as design information flow*, genba *as value-creating site, evolution of organisational capabilities, evolution of product-process architectures, dynamic fit of capabilities and architectures*, and multi-layer concepts of industrial performance (see Fujimoto, 2007, 2012 for details).

2.2 Capability, architecture and performance

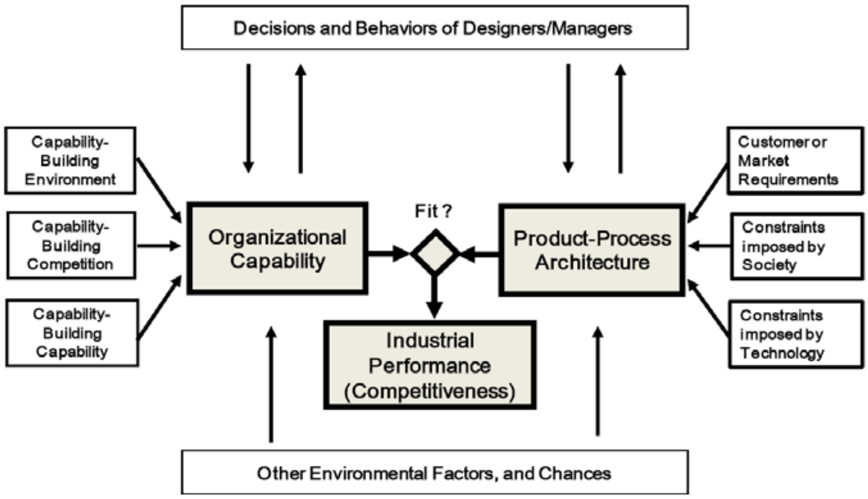
Design-based comparative advantage

Let us first illustrate the basic logic of *design-based comparative advantage* (Fujimoto, 2007, 2012), which is as follows: the dynamic fit between a certain type of genba's organisational capability having emerged in a country on the one hand and a certain type of product architecture having evolved over time on the other hand tends to result in higher competitive performance of the design locations in terms of comparative design costs (Figure 1).

Here *organisational capability* in manufacturing is defined as a system of organisational routines which collectively control and improve the flow of design information to customers (Nelson and Winter, 1982; Clark and Fujimoto, 1991; Fujimoto, 1999). To the extent that an organisation is a system of coordinated activities (Barnard, 1938), the key dimensions of its capability will naturally include degrees and types of *coordination*. The evolutionary logic is also introduced here to explain why different types of organisational capabilities are unevenly accumulated in different countries and regions (Fujimoto, 1999, 2007).

On the other hand, the concept of *architecture* is defined as a formal pattern for coordinating the functional and structural design elements of an artefact, including a product and a process (Suh, 1990; Ulrich, 1995; Fujimoto, 2007). A product/process with integral architecture is coordination-intensive, whereas a product/process with modular architecture is coordination-saving.

Figure 1 Design-based comparative advantage (see online version for colours)



It follows from the above argument that a country's patterns of comparative advantage in design may be influenced by a certain fit between the *coordination capabilities* of its manufacturing sites (genba) and the *coordination intensities* of the architectures of its products/processes, both of which evolve over time. Specifically, a country whose industrial sites are relatively rich in continuous coordination capabilities due to certain evolutionary reasons, such as post-war Japan, might have a comparative advantage in design for what concerns relatively coordination-intensive products or those with integral architectures.

Conversely, a country whose industrial sites have historically emphasised specialisation-standardisation-simplification of their products, processes, components and their interfaces – such as the USA, whose industries historically grew with a massive inflow of immigrants – might have a comparative advantage in designing relatively coordination-saving products or those with modular architectures. In addition, firms and regions endowed with capabilities for creating and managing standardised inter-component interfaces at the earlier stages of product development tend to take on a leading role in modular (in particular, open-modular) products (Ulrich, 1995; Baldwin and Clark, 2000; Teece, 2007; Sanchez, 2013).

Evolutionary view

Thus, both capabilities and architectures are treated as endogenous and dynamic here. This paper assumes that a certain evolutionary process results in the uneven distribution of certain types of organisational capabilities across countries and firms. History matters.

The view of design-based comparative advantage also assumes that organisational capabilities are more difficult to move across borders than capital, goods and services, even in the age of globalisation, and that they tend to become country-specific. A country's capability-building environment (e.g., scarcity of resources), the intensity of its industry's capability-building competition and its firms' capability-building capability (i.e., evolutionary capability; Fujimoto, 1999) all affect the prevalent nature of the capabilities of its manufacturing sites or genba.

The evolutionary view of architectures also argues that a product's overall (macro) architecture is selected ex-post by markets and society, whereas its micro architecture is generated ex-ante by engineers (Fujimoto, 2012). When a product faces demanding functional requirements and/or strict constraints (e.g., safety and environmental regulations), its macro architecture tends to become integral, other things being equal. By contrast, when the requirements and constraints are less strict, it tends to become more modular. Thus, a product's architecture is not a given – it evolves through micro-macro loops between design selection by engineers and by markets.

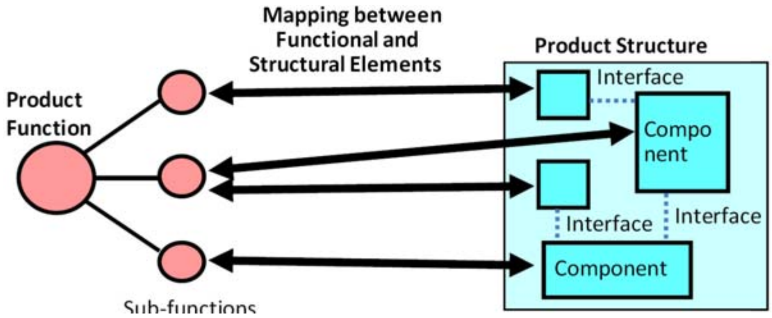
Accordingly, the framework of design-based comparative advantage may explain why similar products (e.g., various types of green vehicles) within the same product category (e.g., automobiles) are imported or exported at the same time – the intra-industry trade of architecturally differentiated products. In this paper, we will make some preliminary predictions regarding competitive advantages of different types of firms or regions in different types of green vehicles.

2.3 *Product-process architecture*

Definition

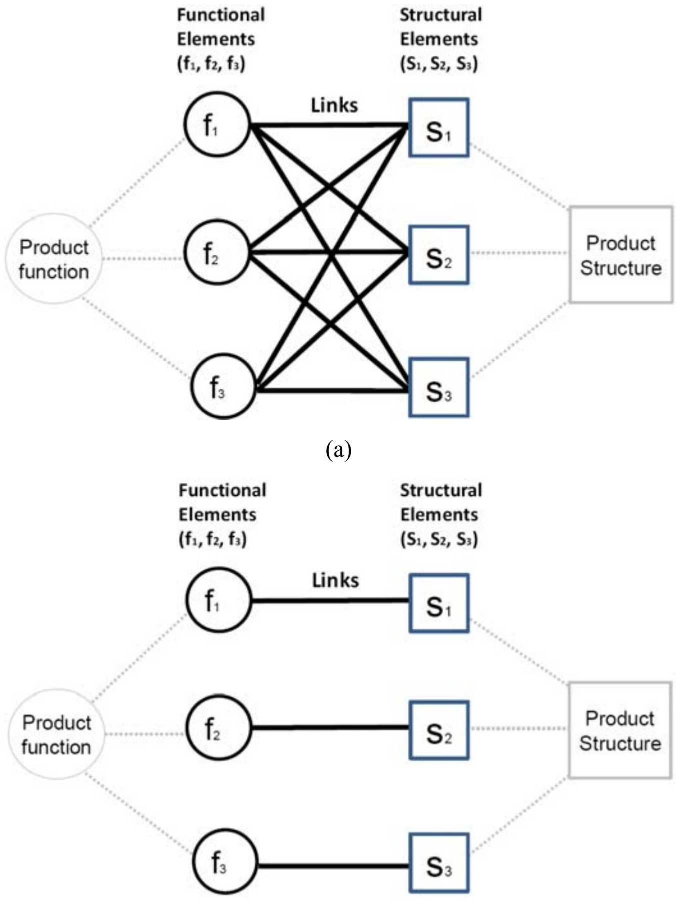
Having illustrated the basic model of the capability-architecture fit, let us now turn to more operational definitions of architectures. Architecture is defined for any given artificial system (Simon, 1969), including a product, use system, production process or business model. It refers to a formal pattern for linking an artificial system's functional elements to its structural elements (Figure 2; Langlois and Roberstson, 1992; Ulrich, 1995).

Figure 2 Product architecture (see online version for colours)



Thus, *product architecture* implies the basic way of thinking in the minds of engineers when they design the functions and structures of a new product. A product's designers may start from its overall concept or overall function, and then decompose it into a set of sub-functions or functional elements. They then conceive the product's components or structural elements and map those functional elements in relation to the structural elements. Thus, a product's architecture refers to a formal pattern of correspondence (or links) between its functional and structural elements. It can be graphically represented by a bipartite graph with n functional elements and m structural elements (Figure 3).

Figure 3 Bipartite graph between functional and structural elements, (a) integral architecture (many-to-many correspondence) (b) modular architecture (one-to-one correspondence) (see online version for colours)



(a)

(b)

Note: A case of three functional and three structural elements.

Likewise, *process architecture* refers to the correspondence between the functional or structural elements of a product and its production process factors. The concept of process architecture is important particularly in non-assembly type industries, such as the chemical and steel industries and other goods from process industries, whose products are monolithic and difficult to deconstruct into discrete components.

Since this paper analyses mechanical products, let us focus on product architectures from here on.

Basic types

There are certain basic types of architectures: modular versus integral, and open versus closed (Ulrich, 1995; Fine, 1998; Baldwin and Clark, 2000; Fujimoto, 2007). *Modular architecture*, in its pure form, represents a one-to-one correspondence between functional and structural elements [Figure 3(b)]. The parameters for components or production processes can be designed and operated relatively independently from one another with less coordination between them. The i*nterfaces* between such components can be simplified and standardised, so the 'mix and match' of structural elements can generate variety within the total system (e.g., product) without sacrificing functionality (Ulrich, 1995; Sanchez and Mahoney, 1996; Baldwin and Clark, 2000). In other words, a modular product is *coordination-saving*.

Integral architecture, by contrast, represents a many-to-many correspondence between the product's functional and structural elements [Figure 3(a)]. The designs of the components and their interfaces tend to be specific to each variation of the product. Such components must be optimised for the complete product through mutual adjustments of functional-structural design parameters. In other words, an integral product is *coordination-intensive*. 'Mix and match' is difficult, and so is the use of many common components without sacrificing the functionality and integrity of the whole product (Fujimoto, 2007).

We can illustrate purely modular and purely integral cases by using the framework of axiomatic design (Suh, 1990). In this context, the design process is described as the design engineers' effort to identify and solve a simultaneous equation of functional and structural variables, $\mathbf{Ax} = \mathbf{y}$, where $\mathbf{y}$ is a vector of functional requirements, $\mathbf{x}$ refers to structural design parameters, and $\mathbf{A}$ is a matrix representing causal relations between $\mathbf{x}$ and $\mathbf{y}$. Engineers identify functional requirements $\mathbf{y}^*$ given by customers and try to acquire causal knowledge $\mathbf{A}$ by learning from existing systems, accessing the scientific knowledge-base, or conducting physical or virtual simulations. They then try to find the best-effort solution $\mathbf{x}^*$ by combining existing components or creating new types of parts.

In this axiomatic design framework, a new product's architecture is summarised by the content of matrix $\mathbf{A}$, which represents causal relations, where a_{ij} is a non-zero coefficient (Fujimoto, 2007).

Modular Architecture Integral Architecture

$$\mathbf{A} = \begin{bmatrix} a_{11} & 0 & \cdots & 0 \\ 0 & a_{22} & & \\ \vdots & & \ddots & \\ 0 & & & a_{mm} \end{bmatrix} \qquad \mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & & \\ \vdots & & \ddots & \\ a_{m1} & & & a_{mm} \end{bmatrix}$$

On the other hand, open and closed architectures are defined in relation to inter-firm openness or intra-firm closedness of the *interfaces* between a product's components. *Open architecture* refers to a type of modular architecture in which mix and match of component designs is technically and commercially feasible not only within a firm but also across firms because of such open interfaces. *Closed architecture*, conversely, is the case where interfaces are either firm-specific or product-specific, so that mix and match of components which are independently designed by different firms is impossible. As mentioned below, closed architecture is either modular or integral.

By combining the modular-integral axis and the open-closed axis described above, we can identify three basic types of product architectures (Figure 4).

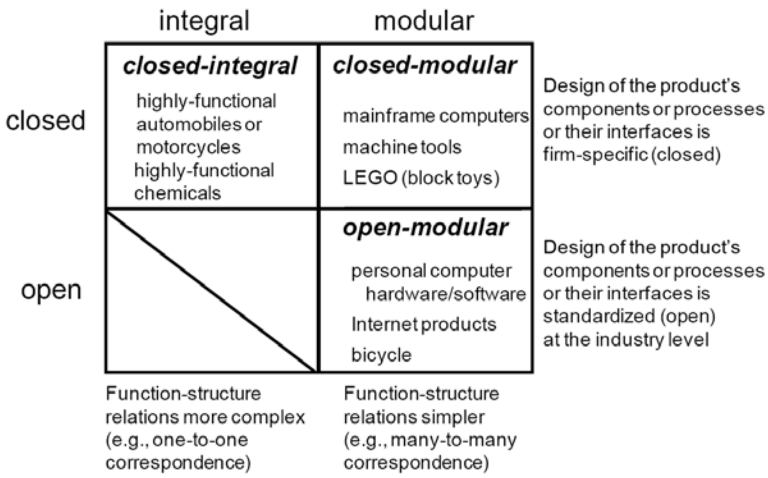
1 *open-modular* (open)

2 *closed-modular*

3 *closed-integral* (integral).

Generally speaking, open-modular products tend to consist of industry-standard (open) components and/or interfaces; closed-modular products are characterised by firm-specific common components and/or interfaces; lastly, closed-integral products include product-specific or custom-designed components and/or interfaces.

Figure 4 Basic types of product/process architecture



2.4 Design-based comparative advantage

Coordination capability and intensity

To sum up, the framework of *design-based comparative advantage* predicts that the dynamic fit between a certain type of manufacturing site's (genba's) organisational capability having emerged in a country, on the one hand, and a certain type of product architecture having evolved over time, on the other hand, tends to result in higher competitive performance of design locations in terms of comparative design costs (Fujimoto, 2007, 2012).

Note again that *organisational capability* in manufacturing is defined as a system of organisational routines which collectively control and improve the flow of design information to customers (Nelson and Winter, 1982; Clark and Fujimoto, 1991; Fujimoto, 1999). To the extent that an organisation is a system of coordinated activities (Barnard, 1938), the key dimensions of its capability will naturally include degrees and types of coordination.

The concept of *architecture* is also defined as a formal pattern for coordinating the functional and structural design elements of an artefact, including product and process (Ulrich, 1995; Fujimoto, 2007). A product/process with integral architecture is coordination-intensive, whereas a product/process with modular architecture is coordination-saving, as mentioned earlier.

It follows from the above argument that a country's patterns of comparative advantage in design may be influenced by a certain fit between the *coordination* *capabilities* of its manufacturing sites (genba) and the *coordination intensities* of products and processes, both of which evolve over time.

General predictions

Thus, our basic hypotheses regarding design-based comparative advantage are as follows (Fujimoto, 2007):

1 the countries, regions, or firms whose manufacturing sites have higher *coordination capability* (e.g., teamwork of multi-skilled workers and engineers) tend to enjoy comparative design cost advantages in the types of products (and/or their components) with *coordination-intensive* design forms, that is, *integral architectures*

2 the countries, regions, or firms which are endowed with *specific technological capability* (e.g., individual skills of highly specialised workers and engineers) tend to enjoy comparative design cost advantages in the types of products (and/or their components) with *coordination-saving* design forms that is *modular architectures*.

Specifically, a country whose industrial sites are relatively rich in coordination capabilities due to evolutionary reasons, such as post-war Japan or some parts of the European continent, may have comparative advantages in designing relatively integral (or coordination-intensive) architectures. On the contrary, a country whose industrial sites have historically emphasised specialisation, standardisation and simplification of products, processes, components and their interfaces – such as the USA, whose industries rapidly grew with a massive inflow of immigrants – may have comparative advantages in designing relatively modular (or coordination-saving) products.

3 Functions and architectures of green vehicles: an application

3.1 Predictions about the varieties of architectures and manufacturers of future green vehicles

Technological, architectural, and firm diversity

Having explained the general framework of design approach to manufacturing, genba's organisational capabilities, product architectures and design-based comparative advantages, let us now try to apply this framework to the specific case of 'green vehicles' of different technological types, including electric vehicles, FCVs, advanced internal combustion engines vehicles (IVEVs), and various hybrid vehicles.

Since the purpose of the present paper is not to rigorously test hypotheses on the relations between architecture, capability and competitiveness of existing products, but to carry out a preliminary comparative analysis of potentially competitive product types for the future, what we can do at this point is to make preparations for more solid empirical research in the future. This involves putting forward some predictions about possible future product types as well as performing preliminary empirical analyses.

Based on our current knowledge of present and future technological progress, market needs, social values, and environmental-energy constraints, this paper proposes the following three predictions. To be realistic, our analysis will be limited to the early part of the 21st century (e.g., 2010s~2020s).

- *Prediction 1 (technological diversity):* a variety of technologically different green vehicles will survive or gain significantly large market segments. None of them will dominate the world automobile market.

As the following function-structure analysis indicates, none of the current contenders aspiring to become future green vehicles is superior to its rivals in all of the main functional requirements for general-purpose personal transportation. In other words, all of these vehicle types will have both strengths and weaknesses in relation to different aspects of product functions.

- *Prediction 2 (architectural diversity):* given the possibility of diversity in technological types of future green vehicles, we may also predict that there will be a variety of architectural integrality/modularity.

Although technological variety in a certain product category does not always result in a variety of product architectures, it may be reasonable to predict great architectural diversity when we observe that different technological types face critical functional challenges of different natures. Note here that future products are more likely to differ from one another in their architectural integrality/modularity when the critical functions that they have to deal with are different.

- *Prediction 3 (firm/regional diversity):* given the possibility of technological and architectural diversity, we may predict that firms, regions, or countries with different organisational capability profiles will be characterised by competitive advantages in different types of green vehicles.

To the extent that future green vehicles show diversity in their core technologies and product architectures, and to the extent that the above-mentioned theory of design-based comparative advantages holds true, it may be reasonable to predict that firms, regions, or countries endowed with different degrees of coordination capability will tend to demonstrate their competitive advantages in developing and producing corresponding types of green vehicles. It is almost self-evident that areas and firms with richer resources and greater expertise in a certain technological field will tend to outperform their rivals in the vehicle types which intensively use that particular technology, but our additional prediction is that the coordination capabilities of development/production sites matter in predicting which areas or firms may take a leading role in each type of green vehicle.

In the present paper, we assume that Prediction 1 (technological diversity) will hold true in the foreseeable future (e.g., 2010s~2020s) as far as most vehicle types analysed in this paper are concerned – IVEVs, including gasoline, diesel, LNG and bio-fuels; BEVs; fuel-cell vehicles (FCVs); parallel or HEVs; PHEVs; and series hybrid vehicles or range extenders (REVs).

Technological diversity as main assumption

These vehicle types have been capturing either a significant or a niche portion of the world automobile market with or without government subsidies, following serious continuous efforts to develop marketable products by firms and governments for at least a few decades. However, given the current market evaluations of the above-mentioned vehicle types, all of which have both strengths and weaknesses, none of them is likely to quickly become a dominant design within the next few decades.

Note also that this discussion does not include some other types of potentially green vehicles – stirling engine vehicles, gas-turbine vehicles, nuclear-power vehicles, and so on – which were considered when the oil crises of the 1970s triggered a series of debates around the 're-invention of automobiles' mainly in the US under the Carter Administration (Abernathy et al., 1983). In other words, this paper regards the above-mentioned types of vehicles (ICEVs, BEVs, FCVs, HEVs, PHEVs, REVs) as the 'survivors' of the techno-economic selection process for green vehicles up to the present time.

For the above reasons, Prediction 1 about the technological diversity of green vehicles in the automobile market of the foreseeable future is treated as the main assumption of the present analysis.

Architectural diversity as hypothesis

Given the assumption that future green vehicles will display technological diversity, our next question is whether this will be accompanied by architectural diversity. As mentioned earlier, it does not always hold true that technological differences across products will necessarily result in architectural differences.

Generally speaking, the theories of design and architecture predict that a product will tend to become more integral when several difficult functional problems must be solved in order for it to achieve market acceptance (i.e., 'critical functions', discussed later) and when the problematic functions are related to 'global performance' aspects, such as the size and weight of the total product (Ulrich, 1995).

If the problematic functions are related to 'local performance' aspects (Ulrich, 1995), each of which may be solved by improving the structural design of certain corresponding components (i.e., 'critical components', discussed later), the architecture of the whole product consisting of said components will tend to be more modular in terms of its internal design, or 'modular-inside', other things being equal. This also means that a component itself will tend to be more 'modular-outside,' or functionally more independent of the other (outside) components of the product in question.

Moreover, to the extent that the functional problems that this 'modular-inside' product faces are difficult to solve, the architecture of its 'modular-outside' critical component itself will tend to be more 'integral-inside'. For example, if a certain green vehicle (e.g., REV), whose product architecture is relatively modular for some technological reasons, faces a difficult energy-related problem, and if the vehicle's power generation unit turns out to be the critical component corresponding to it, this component's architecture will tend toward 'modular-outside, integral-inside' (Fujimoto 2007, 2012), other things being equal.

In any case, despite the above predictions based on the theories of design and architecture (Simon, 1969; Sue, 1990; Ulrich, 1995; etc.), it is difficult to draw any ex-ante conclusions on whether or to what extent the technological variety of green vehicles will result in their architectural diversity. This paper will therefore treat Prediction 2 about the architectural diversity of green vehicles as a hypothesis and attempt a preliminary empirical analysis based on the knowledge available regarding current state-of-the-art technologies in this field.

Firm and region/county diversity for future research

If this paper finds some evidence of architectural diversity across green vehicles in terms of their integrality/modularity, the next question is whether such architectural diversity will lead to diversity among the manufacturers developing and producing green vehicles competitively.

The theory of design-based comparative advantages lets us infer that the firms, regions, or countries endowed with strong coordination capabilities are more likely to display competitive performance in relatively integral (i.e., coordination-intensive) vehicle types, whereas the firms, regions, or countries which are weaker in coordination capabilities but have specific technological capabilities may demonstrate design-based comparative advantages in relatively modular green vehicles, which rely on those particular technologies for their critical functions and components.

However, it is obviously too early to conduct full-scale empirical research on this topic. We should also avoid technological determinism and any prophecies about who will take the lead in certain types of green vehicles in the future. Competing firms can always make their own capability-building efforts and chose their strategies accordingly. In this paper, we simply argue that the companies and regions/countries which are endowed with certain coordination or technological capabilities will tend to outperform their rivals more easily than those which do not possess the capabilities required for the development of certain types of green vehicles.

We will therefore carry out only a preliminary analysis of the types of firms and regions/countries which are currently taking leading roles in certain types of green vehicles, such as leading Japanese firms in HEVs, a US incumbent firm and a European start-up firm in REVs, a US new entrant in BEVs, and so on. More systematic research may be conducted in the future.

Having presented some predictions and analyses, let us move on to an exploratory investigation of the architectural diversity of future green vehicles.

3.2 A modified framework of architectural analysis for futuristic product types

Critical functions

Now that we have made some predictions about the possible diversity of technologies, architectures and providers of future green vehicles, the next step in this exploratory analysis is to conceive an appropriate framework for examining potentially competitive vehicle types in the future market.

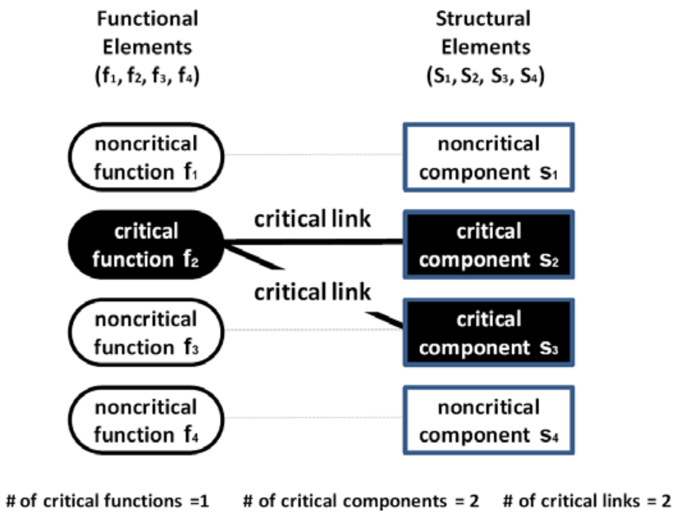
Again, it should be noted here that this paper does not focus on the architectures of today's vehicle types but rather on what might be the architectures of future vehicles. This is because, as mentioned earlier, all of the above green vehicles are unlikely to play a significant role in the world automobile market of the future unless they overcome certain critical weaknesses which are specific to each vehicle type. Thus, the present analysis attempts to compare the architecture of the various types of green vehicles which can capture a significant portion of the automobile market in the future.

For this research purpose, we focus exclusively on each vehicle's *critical functions*, or the specific functional parameters in relation to which its performance falls considerably short of current market or societal expectations. In other words, without filling in these critical performance gaps, the product type in question will not be accepted by the markets and/or the societies with enough sales volumes to make its commercial production sustainable. Such uncompetitive vehicles may find only very small niches, or survive only thanks to heavy government subsidies, or come into production only after considerable penalties are paid for missing government standards (e.g., on fuel efficiency). In any case, none of these candidates is likely to become a successful future green vehicle if it fails to fill its critical performance gaps.

Critical components and links

After determining the critical functions of each vehicle type, our next step is to identify key components, modules, or structural elements which are likely to contribute to the functional gap-filling efforts of the firms. We may call them *critical components*. For each critical function, there may be only one or several critical components. Likewise, one critical component may serve only one or several critical functions.

Figure 5 Critical functions and components (example) (see online version for colours)



We may then identify the *critical links* (or critical 'edges' in the terminology of graph theory) between critical functions and critical components and regard the number of such links as a measure of the complexity of the gap-filling efforts needed for each product type, assuming that all non-critical problems have already been solved for all vehicle types. In other words, when comparing the architectures of a set of potential product types for the future, we focus only on the relations between their critical functional and structural elements, while assuming, for the sake of simplicity, that other non-critical design problems can easily be overcome. Figure 5 shows an example with 1 critical function, 2 critical components, and 2 critical links between them.

3.3 An architectural analysis of the green vehicles of the future

Functional requirements for the green vehicles' power trains

Having described our predictions and framework concerning the green vehicles' potential architectures and performance, let us now move on to a concrete functional and architectural analysis. Since the concept of product architecture refers to formal patterns of correspondence between a product's functional and structural elements, it is best to start by making a list of the main functional requirements for green vehicles in general, focusing particularly on their power trains.

For the sake of simplicity, we assume that the performance of the green vehicles' chassis and bodies does not vary greatly across different types. We also assume their performance in terms of electronic controls, automatic driving, and smart-city compatibility to be essentially the same. Thus, we focus only on differences in performance among different power train types.

Firstly, the types of green vehicles analysed in this paper are listed below. Without going into detail about their technological features, we also provide some indications regarding possible *critical functions* for each vehicle type, based upon interviews with experts and reviews of secondary material on state-of-the-art green vehicle technologies.

- advanced gasoline internal combustion engine vehicles (G-ICEVs) – *fuel efficiency*
- advanced diesel engine vehicles (D-ICEVs) – *fuel efficiency, NOX emissions*
- parallel-series or parallel hybrid vehicles (HEVs) – *fuel efficiency, high-performance range*
- PHEVs – *high-performance range*
- series hybrid or range extenders with ICE (ICE-REVs) – *high-performance range*
- series hybrid or range extenders with fuel cell (FC-REVs) – *density of stations, vehicle cost*
- BEVs – *high-performance range, recharge time, density of stations, vehicle cost*
- fuel cell electric vehicles (FCVs) – *density of hydrogen stations, vehicle cost*.

Specifying vehicle-function matrix

The functional requirements of the above-mentioned types of green vehicles, focusing mainly on the functions of their power trains, may include the aspects listed below. Brief comments on which types of vehicles may display weaknesses in relation to each function are also provided.

- *Energy consumption:* advanced ICEVs have performance limits in the long run.
- *Acceleration (torque):* electric motors and diesel engines have advantages vs. gasoline ICEVs.
- *Maximum speed:* low specification vehicles (e.g., low performance REVs) may have limits.
- *Driving range:* BEVs have disadvantages due to low energy density of advanced batteries.
- *High-performance driving range:* REVs may have disadvantages after batteries are depleted.
- *Energy refuelling/recharge time:* recharge time disadvantages for BEVs and PHEVs.

- *Location of refuelling/recharge facilities:* FCVs (hydrogen stations) have disadvantages.
- *Quietness:* BEVs and FCVs may have advantages. Key for product differentiation.
- *Emission gassespp.:* diesel ICVs have NOx problems. EVs/FCVs depend on power generation.
- *Safety:* relative safety of batteries, FC, and fuel tanks is key.
- *Ease of driving/fun:* key for product differentiation. Not so different across types.

Based on discussions with technology experts from automotive companies and others, the author has formulated a preliminary *vehicle-function matrix*, which includes *critical functions* for each type of future green vehicle (Table 1).

Table 1 Vehicle-function matrix

	G-ICEV	*D-ICEV*	*HEV*	*PHEV*	*ICE-REV*	*FC-REV*	*BEV*	*FCV*
Energy efficiency	X	X	X					
Acceleration								
Max. speed								
High perf. range			X	X	X		X	
Recharge time							X	
Station density						X	X	X
Quietness								
NOx/PM emissions		X						
Safety								
Fun to drive								
Vehicle cost						X	X	X
Operating costs								

Notes: X = estimated critical function (the gap between required functional levels and current performances is large).

Note again that this is a rough estimation of the strengths and weaknesses of green vehicles. Note also that the main purpose of this paper is not to provide detailed forecasts concerning the competitiveness of future vehicle types but to propose a potentially useful method for estimating it.

3.4 Analysis of critical functions and structures for each vehicle type

Identifying critical components and links

In the above analysis, we specified a list of functional requirements for the power trains of all types of green vehicles. We then estimated critical functions for each vehicle type and elaborated a *vehicle-function matrix* for the green vehicle types investigated here: G-ICVs, D-ICVs, HEVs, PHEVs, ICE-REVs, FC-REVs, BEVs, and FCVs.

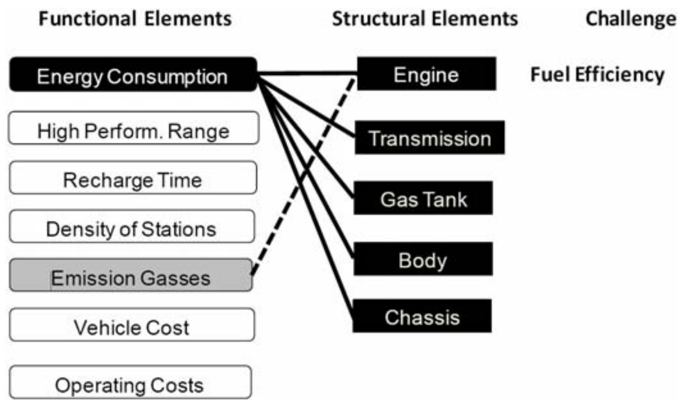
Let us assume for now that the above identification of critical functions for each vehicle type is reasonably accurate. Our next step is to single out *critical components* and *find critical* links or causal relations (or conversely means-ends relations) between critical functions and components for each vehicle type.

Since the aim of this paper is not so much to accurately evaluate each type of green vehicle but rather to provide an alternative method for such evaluation, we include only a brief function-structure analysis of the eight vehicle types taken as examples for the proposed approach. We also assume that this analysis compares only high-performance versions of each vehicle type with, for example, high cruising speed (e.g., at least 100 km/h), long driving range with high performance (e.g., at least 300 km), and sufficient production volumes to make average unit cost acceptable for the market (e.g., 200 K units per year).

G-ICEVs

Gasoline-type internal combustion engine vehicles (G-ICEVs) have occupied the vast majority of the world automobile market since the beginning of the 20th century. Although the overall competitiveness of state-of-the-art G-ICEVs, including costs and utilities, continues to be superior to that of other types of green vehicles, it is obvious that, in the future, the critical function for this conventional vehicle type will be fuel efficiency. Emission gasses are another problem but, compared with diesel engines, G-ICEVs have solved this problem more effectively so far (Figure 6).

Figure 6 Critical functions and components (G-ICEVs)

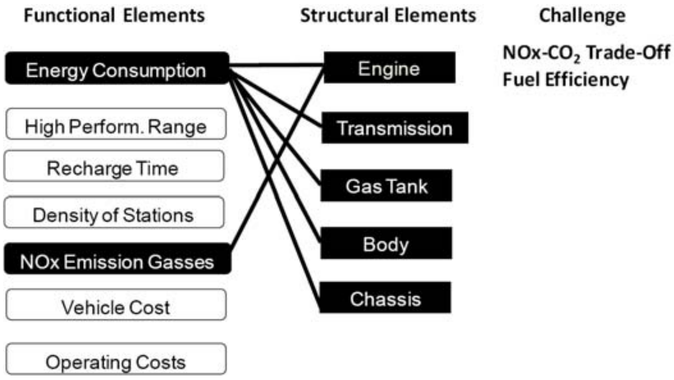


It should be noted that, since improving fuel efficiency requires not only advancements in engine technologies but also significant reductions in total weight, this is a global performance issue which affects the design of most vehicle parts. This is shown in Figure 6 – virtually all the components become critical components in this regard.

Diesel internal combustion engine vehicles (D-ICEVs)

The functional profile of D-ICEVs is similar to that of gasoline engine vehicles (G-ICEVs). D-ICEVs tend to have higher torque and better fuel efficiency than comparable G-ICEVs, and they have been popular especially in the European market. However, besides fuel efficiency, their additional critical function is NOx emissions, which makes the links between critical functions and components even more complicated than in the case of G-ICEVs (Figure 7).

Figure 7 Critical functions and components (D-ICEVs)

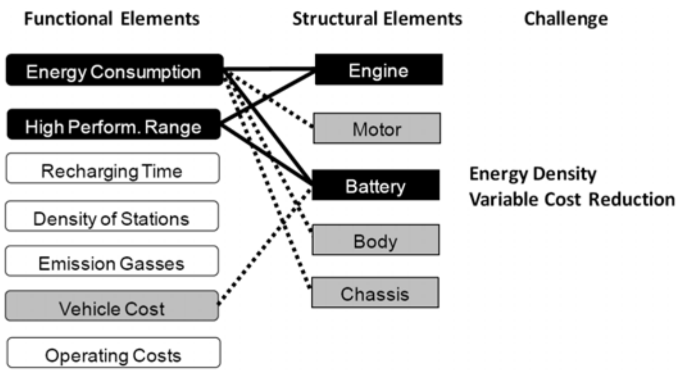


Parallel/HEVs

This vehicle type combines an ICE and an electric motor for its power train and improves its fuel efficiency by continuously optimising its torque allocation. Unlike PHEVs, HEVs do not need external electricity recharge, as all the electric power is provided by the engine and the regeneration brake. Since this vehicle type requires a highly sophisticated control system and still relies extensively on the ICE, its profile in relation to critical functions and components is somewhat similar to that of ICEVs. Fuel efficiency remains a critical function, just like for ICEVs, although to a lesser extent, and high-performance range may be an additional critical function. Battery cost may represent a further problem, although to a lesser extent than in the case of BEVs, PHEVs and REVs, discussed later (Figure 8).

Note that in this and the following figures, the functions and components which are deemed to be semi-critical (middle range) are shown in grey boxes. Also, the links that include either *critical functions* or critical components are shown as dotted lines (semi-critical links).

Figure 8 Critical functions and components (HEVs)



PHEVs

This vehicle type is also powered via the combination of an engine and an electric motor, but it normally has larger size batteries and electricity may be recharged from an external source. Compared with HEVs, PHEVs rely more heavily on batteries and electric motors during normal driving, but the main question is whether they can retain satisfactory power train performance when the batteries are depleted. Fuel efficiency is less problematic, but battery cost is more of an issue, compared with HEVs. Overall, the profile of *critical functions* and components for PHEVs falls somewhere between those of HEVs and BEVs (Figure 9).

Figure 9 Critical functions and components (PHEVs)

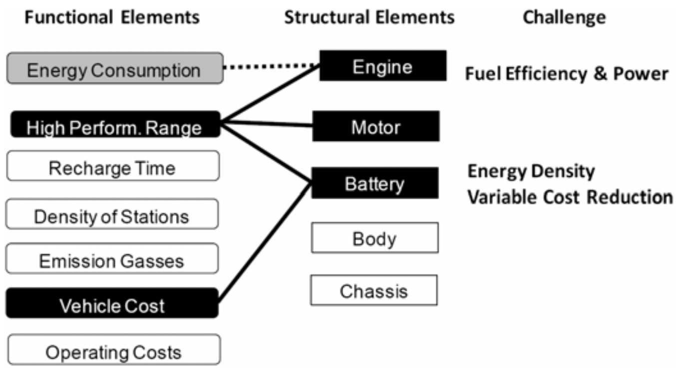
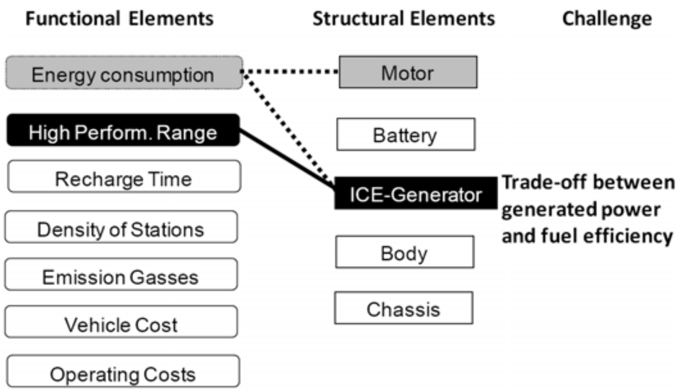


Figure 10 Critical functions and components (ICE-REVs)



Series hybrid vehicles or range extenders with ICE (ICE-REVs)

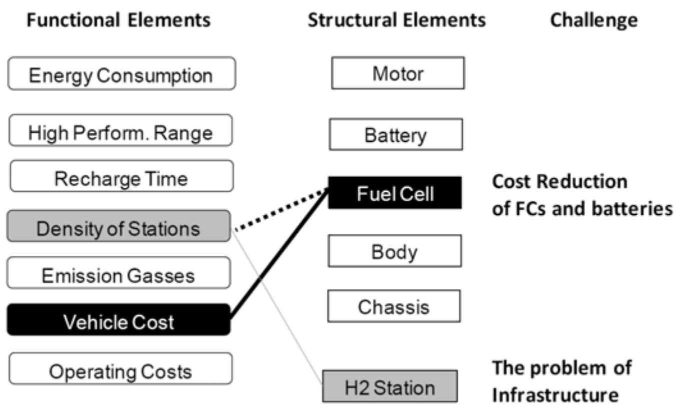
Another hybrid vehicle type is called series hybrid vehicle or range extender (REV). In this case, the power train is an electric motor, just like in the case of BEVs, but the battery is recharged by a power generator propelled by an ICE. Hence, the power and fuel efficiency of the electric power generating unit are crucial for its overall performance. If it cannot generate enough electricity, its high-performance range will become shorter and its power train performance will decrease significantly after the batteries are depleted. If the fuel efficiency of the power generation unit is low, the fuel efficiency of the vehicle as a whole will also deteriorate accordingly. So the *critical functions* and critical components are concentrated around one or two factors, which makes the vehicle's architecture relatively simple and modular (Figure 10).

Series hybrid vehicles or range extenders with fuel cell (FC-REVs)

This type is also a series hybrid vehicle or range extender (REV), but in this case the batteries are recharged by FC. Thus, the fuel efficiency of the power generating unit (FC) is no longer an issue, but the high vehicle cost represents a new criticality because FC-REVs carry both secondary batteries and FC. The geographical density of hydrogen and electricity stations, particularly the former, is another obstacle to their diffusion for the time being, but this is a problem of the transportation infrastructure rather than of the vehicle itself. We will therefore exclude such infrastructural concerns from the following analysis of the vehicle architecture.

Like in the case of ICE-REVs, critical functions and components are concentrated around one or two factors, so the vehicle's architecture is relatively modular (Figure 11).

Figure 11 Critical functions and components (FC-REVs)



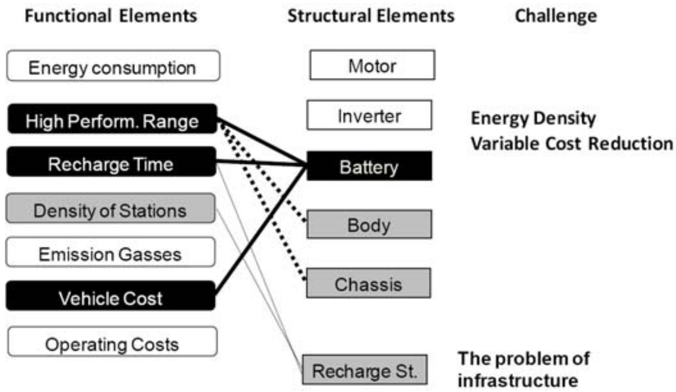
BEVs

This is what we usually call electric vehicles. There is a stereotypical image of BEVs as highly modular products, and it is partially true that the mechanical structure of BEVs may be simplified, but an architectural analysis also involves a functional analysis. In fact, high-performance BEVs may have more *critical functions* to deal with than conventional ICEVs, mainly because their only source of energy is their on-board batteries, whose energy density is so far too low to guarantee long-range driving for one day without electricity recharge. If a BEV needs to be recharged on the way, it will take 20 to 30 minutes to do so, even at a fast charging station. Users can carry a large amount of batteries to avoid this, but then the cost of the batteries will increase considerably.

In other words, state-of-the-art BEVs with lithium-ion batteries have a fundamental problem of low energy density, so there are functional trade-offs linked to driving range per charge, recharge time, and battery cost. This will not be an obstacle in the case of small vehicles used for short trips around cities, but otherwise the triple problem will persist. Radically innovative batteries whose energy density is several times higher will solve most of the issues, but we do not know if and when such breakthrough technologies will become available.

Due to the multiple critical functions mentioned above and since the driving range problem calls for a reduction in weight, which is a global performance matter, the links between BEVs' critical functions and components seem to be more complex and integral than expected (Figure 12).

Figure 12 Critical functions and components (BEVs)



FCVs

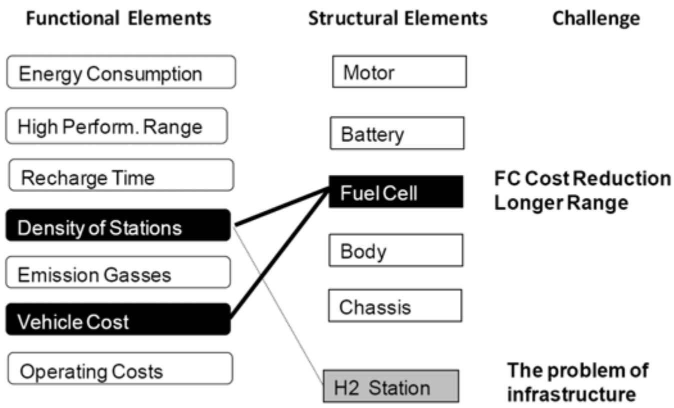
Finally, let us briefly analyse FCVs. While FCVs, just like BEVs, use only electric motors for their power train, in most cases electricity is generated using hydrogen. Hydrogen's energy density is several times higher than that of state-of-the art batteries (even higher than that of gasoline) and the time currently needed for hydrogen refuelling is about three minutes, which makes a major difference in the patterns of critical functions and components of FCVs and BEVs. The common problems of BEVs, short driving range and long recharge time, do not exist in the case of FCVs,

Instead, handling hydrogen safely and efficiently is still a challenging issue. FC stacks are still very expensive without heavy government subsidies. In Japan, construction of hydrogen stations is slow due to safety concerns, high construction costs, and lack of space. Thus, the critical functio*ns* of FCVs are chiefly related to unit product cost and insufficient number of hydrogen stations.

To a certain extent, the latter is a problem of transportation infrastructures rather than of the vehicles themselves, but passenger cars tackling relatively long-haul trips and occasionally unexpected routes will need even longer driving ranges between refuelling, assuming that, for the time being, a long trip is necessary to reach the nearest hydrogen station (Figure 12).

Toyota Motor Company started commercial production and sale of FCV passenger cars in 2014, but its production volumes are quite limited and prices are still very high, even with heavy government subsidies. The experts say that a more feasible application of FCVs would be long-haul trucks and busses travelling along relatively stable routes because a smaller number of hydrogen stations on the main intercity speedways would cater for a considerable amount of FCV operations in this case.

Figure 13 Critical functions and components (FCVs)



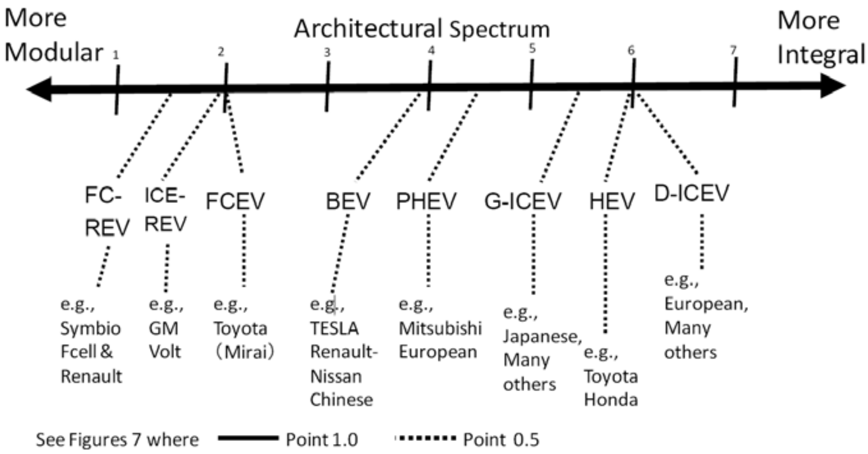
3.5 Positioning green vehicles along the integral-modular spectrum

Diversity of green vehicle types in terms of architectural position

Having made a preliminary investigation of *critical functions*, components, and links for the eight types of green vehicles of the future, let us now summarise this architectural analysis by plotting the vehicle types along the integrality/modularity axis of the *architectural spectrum* (Figure 14).

As explained earlier, this paper applies the concept of architectures to the product types which have the potential to capture a significant portion of the future market, on condition that firms fill the performance gaps in their critical functions. Thus, the position of each vehicle type along the spectrum in Figure 14 reflects the problem-solving complexities which its designers have to address in order to develop a reasonably competitive product, given current technological constraints.

Figure 14 Architectural diversity of green vehicles



For the sake of simplicity, here we assume that all non-critical problems can be effectively solved for all of the vehicle types, so that the architectural differences among them can be captured by looking only at their critical functions and components. We also ignore the problems caused by constraints in the transportation infrastructure and thereby focus only on the development challenges at the individual vehicle level for now.

With the above assumptions in mind, let us look at the results of our analysis of architectural patterns, discussed in Figures 6 to 13. As suggested in Figure 3, a simple method to measure the integrality/modularity of similar products is to count the number of links between a given set of their functional and structural elements. For the sake of simplicity, we assume that the problem-solving efforts for the function-component links in Figures 6–13 are all equally important, so we assign 1.0 to each critical link and add up the number of critical links for each product type. As for the links that are deemed to be semi-critical, they are assigned a value of 0.5 instead of 1.0

Figure 14 summarises the results of the calculations: G-ICEVs = 5.5; D-ICEVs = 6.0; HEVs = 6.0; PHEVs = 4.5; ICE-REVs = 2.0; FC-REVs = 1.5; BEV = 4.0; FCVs = 2.0.

A great deal of diversity among the product architectures of the different technological types of green vehicles clearly emerges. ICEVs and parallel hybrid vehicles (G-ICEs, D-ICEs, HEVs) tend toward the integral end of the spectrum, whereas range extenders and FCVs (FC-REVs, ICE-REVs, FCVs) tend toward the modular end, and electric and PHEVs (BEVs, P-HEVs) are in the middle. Thus, the above results appear to be consistent with our hypothesis that the technological diversity of green vehicles results in their architectural diversity.

Continuing complexity of future automobiles

Note here that what matters in relation to products' design-based comparative advantages (or comparative advantage in general) is the relative value of the explanatory variables, as opposed to the absolute one. This means, for instance, that a firm or a country endowed with *relatively* higher coordination capabilities is more likely to gain comparative advantages in terms of design costs for products with relatively higher coordination intensity or integrality.

We should also keep in mind that an automobile is, after all, a complex artefact, a heavy and fast-moving object used in public spaces, whether it is an ICEV or a BEV. Due to the sheer weight of this complex product, the ever more stringent societal constraints on vehicle safety, environmental protection, and energy conservation introduced in this century will keep on pushing its architectural position toward the integral end of the spectrum.

Thus, if we plot all the products from all the industries along the 'total architectural spectrum', the automobiles segment, whether in the past, present or future, tends toward the relatively integral end, certainly more integral than most weightless digital and software products which are driven only by electrons and logic. In other words, the 'modularisation' of automobiles (mostly closed-modular) and the modularisation of most digital/ICT products and software (often open-modular) are very different in nature, and they should not be confused with each other. The modularisation of automobiles, though relatively coordination-saving, will still need a significant amount of coordination efforts, particularly in the early phases of individual product development, because of the inevitable complexity of this weighty artefact (Persson and Åhlström, 2013; Sanchez, 2013; Fujimoto, 2014; Rivero, 2014).

3.6 Discussion about possible competitive manufacturers for each vehicle type

Different firms for different architectures?

Assuming that our tentative conclusions about the architectural variety of green vehicles hold true, the theory of design-based comparative advantages predicts a certain degree of diversity among the firms, regions, or countries which may take a leading role in different architectural types of green vehicles. For now, too few examples of leading firms or regions/countries are available to carry out a systematic empirical study, but it is possible to determine whether some of the early examples are consistent with what the theory predicts (Fujimoto, 2007, 2012, 2014).

The first-cut investigation seems to point to a number of facts which are at least partially consistent with our predictions.

First, as our hypothesis on the capability-architecture fit suggests, certain established automobile manufacturers (e.g., Toyota, Honda, VW) with higher coordination capabilities in coordinator-rich countries (e.g., Japan and Europe; Clark and Fujimoto, 1991; Fujimoto, 1999) tend to enjoy design-based comparative advantages in green vehicle types with relatively integral architectures, such as HEVs and advanced ICEVs.

Second, the results in Figure 14 also suggest that BEVs are not as modular as many people believe. This seems to be consistent with our observation that Tesla, one of the leading manufacturers of BEVs located in California, is seen by experts as a considerably coordination-oriented firm, as opposed to typical Silicon-Valley-type start-ups which tend to rely on market imagination and combinatorial business-model constructions rather than on design optimisation and coordination. As of the mid 2010s, other market leaders in BEVs and PHEVs, such as Renault-Nissan, Mitsubishi and some European firms, are generally seen as having relatively high coordination capabilities, though not as high as leading coordination-rich firms such as Toyota and Honda, which might also reflect the architectural position of BEVs and PHEVs in Figure 14.

Third, one of the leading firms in range extenders (ICE-REVs), apparently the most modular types of green vehicles according to Figure 14, is General Motors (Volt, etc.), and this company is known as less coordination-oriented and more specialisation-oriented (Womack et al., 1990) than its Japanese and European rivals. This fact also seems to be consistent with our hypothesis that specialisation-oriented firms tend to be good at coordination-saving products.

Another example which proves to be consistent with our hypothesis is that of SymbioFCell in France, a start-up firm coming from the telecommunication industry, which forged an effective alliance with Renault Trucks in the field of innovative range extenders (FC-REVs) combining batteries and FC for specific applications, such as taxis and mail delivery vehicles. Note that range extenders (REVs) are seen as one of the most modular green vehicles, and that city use of commercial vehicles does not need extremely high performance.

To the extent that REVs are likely to be more modular than high-performance EVs, as Figure 14 suggests, the case of SymbioFCell seems to be consistent with our hypothesis about the fit between the capabilities of new entrants relying on market imagination and combinatorial business model constructions and apparently one of the most modular green vehicle types at this point, namely FC-REVs.

Note here, however, that the above statement does not always mean one-to-one fit between a certain vehicle type and a certain firm. Since today's automobile firms can be multinational and/or multidivisional, a firm may be able to effectively compete in multiple vehicle types with different architectures by establishing multiple organisational units, each focusing on a certain product category, through either internal business development or M&As.

For future research

Again, our discussion on which types of firms and regions tend to be more competitive in which architectural types of green vehicles is highly exploratory at this point, and further investigation seems to be indispensable in future research. To explore the matter thoroughly, it will be necessary to consider not only the technological or design aspects of future green vehicles, but also the firms' strategies regarding business models and profit, as well as government policies and social conditions in the countries and regions concerned (Freyssenet, 2011; Proff and Fojcik, 2015).

Yet, the framework for the architectural analysis of futuristic products proposed in this paper may provide additional insights to better understand and predict industrial performance and intra-industrial trade of future green vehicles. It may further be argued that the technological diversity of these vehicles may result in diversity of their product architectures and of successful firms, regions, or countries which will develop and produce them in the future.

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