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Reconfiguring Modularity: Closing Capability Gaps in Digital Innovation

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Abstract

It is widely acknowledged that modularity, as an approach to both product design and organization design, provides product developing firms with dynamic capabilities that allow them to more effectively respond to changes in the environment. However, the innovation literature is silent on how such dynamic capabilities might require reconfiguration as firms in traditional industries embed digital technology into their products. Drawing on theories of modularity, capability, and software engineering, we therefore conducted a multi-level study of car navigation technology. On the industry level, we investigated how automakers' traditional hierarchical control over the innovation process was challenged as they faced multiple digital options for navigation systems design. On the firm level, we investigated how one large automaker exploited these options by reconfiguring modularity and distributing control over the innovation process. The paper makes two inter-related contributions. First, we extend the innovation literature by identifying and characterizing a capability gap that product developing firms in traditional industries face if they merely accommodate digital technology within the confines of current approaches to modularity. Second, we present a new understanding of modularity that draws on the innovation literature as well as the software engineering literature. Rather than relying mainly on components as interrelated physical parts of a hierarchical system, we argue that digital innovation requires product developers to fully exploit physical as well as logical design perspectives, and to differentiate between components as parts, as patterns, and as platforms. We posit that the capability to combine such approaches to modularity is essential for effectively embedding digital technology into traditional physical products.

Keywords: digital innovation, modularity, capability, innovation networks, parts, patterns, platforms, product innovation

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INTRODUCTION

Digital innovation is becoming commonplace in product development within traditional industries. A modern automobile consists of a set of computer networks interconnecting numerous electronic control units and sensors. The amount of software in cars now exceeds ten million lines of code (Broy et al. 2007) and as much as 80 % of innovations in a car can be traced to Information and Communication Technology (ICT) (Leen and Heffernan 2002). Enabled by gradual appropriation of new ICT capabilities (King and Lyytinen 2004), digital innovation has rendered radically improved functionality of many of the car's components including brakes, climate, engine, and transmission.

Digital innovation presents new options and threats to automakers. Embedding ICT capabilities, the digital car may, for instance, enable new forms of business models (Barabba et al. 2002), design supply chains (Joglekar and Rosenthal 2003), and product differentiation and variety (Andreasson and Henfridsson 2009). At the same time, the effective utilization of ICT as an options generator depends on the acquisition of capabilities that position organizations to seize emergent opportunities (Sambamurthy et al. 2003). It is widely acknowledged that such dynamic capability, i.e., a firm's capability to deploy resources for a desired end result (Amit and Schoemaker 1993), can be acquired through modularity as an approach to both product design and organization design.

However, existing approaches to modularity in product developing firms are tightly coupled with the idea of decomposing products into loosely coupled components, hence relying on an understanding of components as interrelated physical parts of hierarchical systems (Sanchez and Mahoney 1996; Schilling 2000). Because there are intrinsic differences between traditional products and software products (Brooks 1987), approaches to modularity in software engineering emphasize physical as well as logical perspectives in which data and software can be physically co-located without being logically bundled into the same component and vice versa (Parnas 1972; Gamma et al. 1993, 1995). Moreover, design of software systems aggregate components through a variety of architectural configurations, including hierarchies as well as networks (Mathiassen et al. 2002) and they rely on different notions of components: as interrelated parts of a larger system (Parnas 1972); as generalized patterns of solutions to specific classes of problems (Gamma et al. 1993, 1995; Alexander 1964, 1999); and as common platforms for developing a variety of specific software applications (Dikel et al. 1997; Bosch 2001; Pohl et al. 2005).

New forms of competition and collaboration in innovation leadership in the context of the digitized car (Henfridsson et al. 2009) challenge automakers' traditional approaches to modularity and hierarchical control over the innovation process (Yoo et al. 2008). In responding to this challenge, automakers need to develop new practices that integrate approaches to modularity from the software industry and enable the firm to distribute control over the innovation process. It is, however, generally difficult to acquire new capabilities in firms operating in industries where the dominant mode of product development has been shaped over long periods of incremental innovation (Abernathy 1978; Anderson and Tushman 1990). Automakers might, as a result, experience an increasing capability gap between current innovation practices and the capabilities needed in order to leverage from digital innovation. Referring to capability gaps as "the distance between needed capabilities and the firm's existing capability base" (Capron and Mitchell 2009, p. 295), we argue that closing such gaps is essential for automakers involved in digital innovation and the current confines of modularity therefore

need to be reconfigured by developing new digital capabilities. Such capability reconfiguration can take the forms of substitution, evolution, or transformation (Lavie 2006).

On this backdrop, this research adopts a multi-theoretic lens drawing on theories of modularity (Schilling 2000), capability (Capron and Mitchell 2009; Lavie 2006), and software engineering (Brooks 1987; Pohl et al. 2005) to address the following research questions: *Why are automakers traditional approaches to modularity in product design and organization design challenged as they face a variety of new digital options for innovation? How can automakers reconfigure traditional approaches to modularity to leverage new digital options as part of their innovations?* The research was conducted as a multi-level study of digital capability gaps in the area of car navigation. First, we conducted an *industry-level analysis* to trace the development of navigation technology and its impact on digital options and required firm capabilities. Our content analysis (Krippendorff 2004) of publically available information about the navigation market demonstrates that, over the last six-year period, technological options increased dramatically and firm capabilities diverged among competitors. Second, we conducted a *firm-level analysis* of how a global vehicle manufacturer, GlobalCarCorp, reconsidered and reconfigured its modular architecture and hierarchical approach to controlling the innovation process to close the experienced capability gap.

The paper makes two inter-related contributions. First, we extend the innovation literature by identifying and characterizing a capability gap that product developing firms in traditional industries face if they merely accommodate digital technology within the confines of current approaches to modularity. In closing this gap, firms need to disintegrate digital component packages and transcend existing approaches to modularity and innovation control. Second, we present a new understanding of modularity that draws on the innovation literature as well as the software engineering literature. The innovation literature's focus on components as interrelated physical parts of hierarchical systems (Baldwin and Clark 2000; Garud et al. 2003; Sanchez and Mahoney 1996; Schilling 2000) is extended to embrace physical as well as logical design perspectives, and to differentiate between components as parts (Parnas 1972), as patterns (Gamma et al. 1993, 1995; Alexander 1964, 1999), and as platforms (Dikel et al. 1997; Bosch 2001; Pohl et al. 2005). We posit that the capability to combine such approaches to modularity and to distribute control over the innovation process is essential for effectively embedding digital technology into traditional physical products.

MODULARITY IN DIGITAL INNOVATION

It is commonly agreed that modularity facilitates control over complex systems, allow for concurrent design, and accommodate uncertainty (Baldwin and Clark 2000). At the heart of modular design is the principle of loose coupling implemented in the form of interdependence within, and independence across, product components (Baldwin and Clark 1997a; Ulrich 1995). Such loose coupling allows organizations to manage product complexity through division of expertise and isolation of changes to specific modules (Baldwin and Clark 2000; Parnas 1972). This implementation of nearly decomposable systems (Simon 2002) provides firms with strategic flexibility that allows them to incrementally improve and adapt product designs over time (Sanchez and Mahoney 1996).

However, beyond these general principles of modularity, it is equally clear that the modularity literature is divided along disciplinary lines. The innovation literature on modularity (Baldwin and Clark 2000; Garud et al. 2003; Sanchez and Mahoney 1996; Schilling 2000;

Sturgeon 2002; Ulrich 1995) is primarily focused on physical products and how such artifacts can be modularized to gain competitive advantage in dynamic markets. The software engineering literature (Bosch 2001; Dikel et al. 1997; Mathiassen et al. 2000; Gamma et al. 1993, 1995; Parnas 1972; Pohl et al. 2005) is instead geared towards configurations of logical (software) and physical (hardware) products and how such artifacts can be combined and integrated to improve systems design.

Digital innovation in the traditional industries calls for embracing the wisdom of these literatures simultaneously. Firms investing in digital innovation cannot afford adopting the received knowledge of one of them at the expense of the other. Yet, institutionalized practices and dominant designs can make it difficult to develop and host the capabilities needed to achieve that balance (Abernathy 1978; Anderson and Tushman 1990). In what follows, we look more closely at these streams of literature across elements of modularity and their implications for digital innovation. In addition, we present modularity as a dynamic capability that needs reconfiguration over time to bridge capability gaps that emerge from technological change (Capron and Mitchell 2009; Lavie 2006).

Elements of Modularity

The notion of component is the fundamental element in a modular approach to innovation. A comprehensive, yet not exhaustive, understanding of different notions of components encapsulates both their nature as well as relationships between them. In terms of nature, components can be understood as parts, patterns, or platforms (Baldwin and Clark 2000; Alexander 1999; Pohl et al. 2005). These notions reflect different techniques of designing and interpreting the modular structure of a product. Viewing components as physical parts is common in the product innovation literature and directs attention to how components are decomposed or aggregated (see e.g., Baldwin and Clark 2000, Ulrich 1995). Decomposition and aggregation assume a part-whole relationship where parts are associated with the whole through many-to-one relationships in hierarchical architectures.

Rather than only focusing on physical structure and potential for decomposition and aggregation, patterns and platforms are logical constructs that directs attention to generalization and specialization (Mathiassen et al. 2000). This goes especially for the notion of pattern that stems from Alexander's seminal writings on architectural pattern languages (Alexander 1979; Gamma et al. 1993). In its simplest form, a pattern is "a generalized description of a problem and a related solution" (Mathiassen et al. 2000, p.11). Although originating in architecture, the idea of patterns has been adopted widely as a basis for understanding design and reuse of software components and it assumes an instance-type relationship where components on lower and higher levels are related in many-to-many relationships in network architectures.

Lastly, the notion of platform has found a home in both the innovation and software engineering literatures (Pohl et al. 2005; Robertson and Ulrich 1998). The manufacturing industry was pioneering in deploying platforms as "the common basis of all individual products within a product family" as a strategy for achieving product variety in a cost-efficient way (Halman et al. 2003, p. 150). Although not limited to a physical basis, this view is echoed in writings about software platforms where a platform is seen as "a set of software subsystems and interfaces that form a common structure from which a set of derivative products can be efficiently developed and produced" (Pohl et al. 2005, p.15).

While all products are more or less modularized, the structuring of a product into components is an intentional act to develop the capability to recombine and reuse components

into new configurations (Sanchez and Mahoney 1996; Schilling 2000; Gamma et al. 1995). However, the resulting capability does not only rely on the nature of the resulting components, but equally on the relationships between and within components as expressed in the terms of coupling and cohesion. Loose coupling, as opposed to tight coupling, between components means that the inner working of a component is largely irrelevant and can be hidden to other components (Baldwin and Clark 2000; Parnas 1972; Sanchez and Mahoney 1996). Loosely coupled components are therefore easier to modify and more available for new relationships in reconfiguration of a modular system. The degree of coupling between components is dependent on the specificity with which the component's functionality is implemented (Schilling 2000). As Schilling propose, "the degree to which functionality is achieved through component specificity will be negatively related to increasing interfirm product modularity" (p. 322). As low degree of component specificity can be achieved through application of standard interfaces such design approaches can facilitate loose coupling and the adoption of a modular architecture.

The degree to which a component can be easily reused in new product configurations also depends on the cohesiveness of the component itself (Yourdon and Constantine 1979). While coupling concerns the independence between components, cohesion involves interdependences within a component. Cohesion provides a measure of how well a component is tied together and high cohesion ideally renders a component that produces a single and well-defined function (Mathiassen et al. 2000). When components have high cohesion they are easier to modify, it is more likely they will be resilient to changes in their environment, and last but not least, it is easier to determine the fit of their functionality in other product configurations.

Control of Modular Architectures

As outlined in the organization and innovation literature (Baldwin and Clark 2000; Sanchez and Mahoney 1996; Schilling 2000), modularity implies a particular type of hierarchical control. Rather than relying on coordination through the exercise of managerial authority, control is inscribed into the interfaces between modules through design rules (Baldwin and Clark 2000). As Sanchez and Mahoney (1996, p. 63-64) argue, "much work in product development may be coordinated by specifying standardized component interfaces that govern the outputs of component development processes". Reflecting a shift from hierarchy through organization design towards hierarchy through product design (Sanchez and Mahoney 1996), modular architectures are often seen as an important element in the ongoing trend towards vertical disintegration (Christensen 2006). Codifiable transfer of specifications from the product lead firm, or the brand name firm, to a wide range of contract manufacturers plays an important role in modular firm networks (Sturgeon 2002).

However, the portrayal of components as elements organized through a hierarchical structure where a product-lead firm determines requirements only provides a partial understanding of control of modular architectures. When viewed as patterns or platforms, component control is better described as networked. This can be traced to the instance-type relationship of such components. A specific instance of a pattern is typically not exclusive to its type but can belong to other patterns in a many-to-many relationship between components on lower and higher levels. For instance, map data can be used beyond car navigation. Using a common design pattern for cross-vehicle distribution of information about road curvature, slope information, speed limits, and accident black spots, map data can enrich and improve a wide range of active safety services (Loewenau et al. 2007; Ress et al. 2008). Thus, this pattern,

typically referred to as “electronic horizon”, is used by engineers with heterogeneous objectives located across organizational units. Similar reasoning can be applied to components as platforms.

Reconfiguring Modularity for Digital Innovation

Modularity provides dynamic capabilities by allowing product developing firms to develop architectures that allow them to deploy organizational and technical resources in a flexible way to effectively respond to changes in the environment (cf. Amit and Schoemaker 1993; Baldwin and Clark 2000). Given loosely coupled components that display high cohesion, modular architectures help product developing firms reconfigure their products and reuse its components to improve its competitiveness to develop attractive offers on the market. However, as Schilling (2000) notes optimizing for maximum independence may negatively affect the performance of a product because of loss of synergistic specificity, i.e., “the degree to which a system achieves greater functionality by its components being specific to one another” (p.316). Thus, the decomposition of a product into a modular architecture always involves “a balance between the pressure to become modular and the functionality gained through synergistic specificity” (p. 317). For instance, in-car navigation systems typically come with tightly integrated components such as display and hard drive, although these resources are general and could be used to support other functions as well. Essentially, the integrated design secures quality of service, latency, and the necessary bandwidth and access for the navigation function.

Pressures to change this balance by increasing the degree of modularization of a product derives from the diversity of technological options available and the differentiation in firm capabilities in a market (Schilling 2000). Diversity in technological options increases the number of available product configurations for the customer and results in a higher pressure on the product developing firm to increase its flexibility. Similarly, differentiation in firm capabilities increases the potential gains reaped from specialization in particular components of the product and therefore results in higher pressure on product developing firms to further modularize its product.

Responding to pressures of options diversity and capability differentiation, firms need to consider assumptions about the nature and relationships of the components underlying its modular architectures. In digital innovation, involving the embedding of ICT options in physical products, such assumptions would necessarily incorporate both physical and logical components, involve both coupling and cohesion relationships, and imply hierarchical as well as networked forms of control. This escalation of complexity for product developing firms challenges them to reconfigure modularity as their core capability for product innovation (Capron and Mitchell 2009; Lavie 2006; Schilling 2000). As noted by Lavie (2006), capability reconfiguration basically takes three forms: substitution, evolution, and transformation. Substitution refers to the replacement of a core capability as a result of existing competencies being superfluous through introduction of superior technology (Tushman and Anderson 1986). While appropriation of ICT capabilities in physical products certainly necessitates new capability, substitution appears as a less likely form of capability reconfiguration as logical perspectives on modularity rather interlace than replace physical perspectives. As for evolution, it pays heed to reconfiguration in the presence of path dependencies that form institutional pressures to further develop capabilities along current directions (Nelson and Winter 1982). Capability reconfiguration is then a form of path creation that evolves as mindful deviation by designers and entrepreneurs from the existing path (Garud et al. 2003; Henfridsson et al. 2009). Lastly, transformation denotes an objective-driven process of changing capabilities (Lavie 2006). Rather than replacing the capability as in the case of substitution, or modifying existing capability in a path-dependent manner as in the

case of evolution, transformation seeks to develop new capability by modifying some routines, discarding others, and acquiring new ones.

The next section outlines the methods used in our multi-level study of digital capability gaps in the area of car navigation. Thereafter, we demonstrate why automakers' traditional approaches to modularity are challenged as a result of increased diversity of technological options and increased differentiation of firm capabilities on the navigation market. We then present a case study of an automaker that transformed their approach to modularity by incorporating software perspectives on modularity to close the capability gap perceived relative to new types of competitors. Lastly, we discuss implications of our research for the innovation literature and outline a perspective on how to understand digital innovation in a product developing setting.

RESEARCH METHODOLOGY

We report a multi-level study (Klein et al. 1999; Hitt et al. 2007) of car navigation technology to understand (1) why automakers' traditional approaches to modularity in product design and organization design are challenged by new digital options and (2) how automakers reconfigure these approaches to leverage new digital options as part of their innovations. This reporting is based on case study research conducted at a car manufacturer, CarCorp, and its owner, GlobalCarCorp.

CarCorp is a manufacturing firm that produces, markets, and sells around 125,000 cars per year primarily in Europe and the U.S. CarCorp is a fully owned subsidiary of a major global vehicle manufacturer, GlobalCarCorp. The number of employees at the main production plant of CarCorp was 4,500 in 2007. Concurrent with GlobalCarCorp's attempts to streamline their global business, which includes many other brands, CarCorp's business functions are tightly integrated with GlobalCarCorp's global organization. While many areas of R&D have been relocated within the global firm to avoid redundancy, navigation technology as part of its larger R&D domain, infotainment, is one R&D area for which CarCorp has been attributed significant global responsibility.

Contextualized within a longitudinal study that was initiated in 2002, the research on modularity and capability-building in digital innovation was concentrated to a three-year period between 2006 and 2008. In addition to our intensive involvement as researchers into CarCorp's design practices (Walsham 2006), we complemented the resulting in-depth understanding of navigation technology at the firm level with a content analysis study on the industry-level (Krippendorff 2004). Hence, the presented case study is based on multiple data collection methods including interviewing, participant observation, project document analysis, as well as analysis of industry-related secondary data such as press releases, trade press articles, and reports of navigation technology analysts. In what follows, we describe the methods used for the firm-level and industry-level analyses.

Firm-Level Analysis

The firm-level analysis focused on CarCorp and GlobalCarCorp's R&D activities in the car infotainment area with a special focus on navigation technology. It addressed how CarCorp reconfigured its approach to modularity to better leverage from new digital technology. Given the institutionalized innovation patterns following long-established product architectures in the automotive industry (Abernathy 1978; Nevins and Whitney 1989), such reconfiguration represents an unusual event that breaks with the industry's received understanding of product

innovation. In addition to the suggestion that a single case study is useful when the purposes of the study are revelatory (Yin 2009), we reasoned that intensive research would be suitable for detailed tracing of such breaking with the past.

When producing knowledge about a complex phenomenon an insider perspective is preferable (Van de Ven 2007). This entails an open-ended and inductive mode of inquiry where knowledge is derived in an emergent manner over time without a priori guidance of a particular theoretical framework (Mason 2002). Over time, inductive reasoning yields patterns of action that stabilize as opportunities for theorizing that can be related to existing research streams. While the data should tell the story in qualitative studies (cf. Wolcott 2001), multiple and equally valid stories can co-exist in a rich data material collected through inductive reasoning. Hence, our story of modularity and capability gaps during digital innovation at CarCorp complements a previous one focusing on automotive designers as path creators (Henfridsson et al. 2009).

The main data collection methods used throughout the firm-level study included interviewing, participant observation, and project document analysis. This data was collected through three consecutive R&D projects at CarCorp. First, we conducted 65 interviews during 2006 and 2008. Our respondents came primarily from CarCorp and GlobalCarCorp but also from automotive suppliers, competitors, consultancy organizations, mobile device manufacturers, and mobile network operators that were engaged in infotainment projects at CarCorp. Using a snowball approach (Knoke et al. 2008), we interviewed individuals from different ranks of the automaker, including automotive engineers, product managers, departmental managers, and electrical engineering directors. Interviewees came from a variety of functions, including advanced engineering, marketing, software and control, infotainment, telematics, and R&D. Since GlobalCarCorp is one of the Big Three automakers with operations around the world, respondents had different nationalities and were primarily interviewed on-site in both Europe and North America.

Another important source of data is the significant volume of archival data including system specifications, reports, strategies, and sales forecasts related to the R&D projects covered. For the purposes of this study, the complete set of system specifications and analyses produced and documented throughout the study period have been an invaluable source for tracing changes in product architecture and approach to modularity. Apart of being boundary objects for informal discussion with CarCorp practitioners in situ, they have provided solid documentation for reconstructing the details of modular change that took place. All in all, this documentation consists of more than 30 reports recorded in different versions. Lastly, participant observation was a valuable data source. We participated in more than 30 meetings related to developments of the product architecture for in-car navigation. In addition to these project meetings, we conducted frequent visits at various sites of CarCorp and their partners.

Following the suggestions of Charmaz (2006), we repeatedly read and coded the data to identify key themes from major events, activities, and technology choices. We soon identified the tension between physical and logical design perspectives as a major theme of interest. As suggested above, this tension congealed as an opportunity for iterating between the modularity literature and our empirical observations at CarCorp to develop a new theoretical perspective on modularity. During this process, we discovered that practitioner perceptions and project documentation could not fully account for the external pressures of digital innovation with regard to navigation technology. We therefore decided to design an industry-level analysis to fill that void in our analysis.

Industry-Level Analysis

To increase our understanding of why digital options challenged the understanding of modularity at CarCorp in the area of car navigation technology, a content analysis (Krippendorff 2004) was conducted at the industry-level. Our in-depth study gave us an understanding of the pressures perceived by CarCorp employees and their associated business partners. The content analysis was intended to complement that understanding with a theory-informed analysis focused on options diversity and capability differentiation (Schilling 2000) as indicators of pressure to increase the modularization of navigation technology.

The content analysis was conducted as a process study (Langley 1999). The analysis was geared towards activities, events, and decisions of relevance to the development of navigation technology and related innovations. The analysis hence manifests an understanding of “process as developmental event sequence” (Van de Ven 1992). Based on the firm-level analysis, we already had a well-grounded suspicion that new digital options related to car navigation had emerged over the last years. However, we did not have a detailed account of the diverging technology options for realizing basic navigation functionality such as positioning, route calculation, and user interface. In addition, we wanted to understand the increases in possible navigation system functionality. We considered the adoption of new technologies within the industry as a key indicator of increased capability differentiation. Moreover, we identified new business relationships with industry partners that normally would not cooperate in the development of embedded navigation technology.

We first gathered data from trade press publications such as Telematics Update and Automotive News to develop an initial understanding of the topic area. This data collection confirmed the existence of three fundamental navigation technology options: embedded solution, portable device, and online service. We then identified main players for each of the options and focused on TomTom and Appello as leading actors of the two navigation technology options competing with the automakers’ embedded solution. All publicly available press releases and company information of these firms were then collected and recorded in our research database. All in all, this summoned up to a total of 282 data items, comprising 464 pages of text, that were used to generate a close examination of why digital options challenge the received understanding of modularity in the area of car navigation technology.

Content analysis is about developing results from texts. Among different ways of defining the units to be recorded and analyzed (Krippendorff 2004), we adopted categorical distinctions as the basis for conducting our data analysis. Categorical distinctions “define units by their membership in a class or category” (2004, p. 105). Categories distinguished in our analysis included functionality, complementary assets, business partnerships, and product releases. These categories emerged in the iteration between the theoretical conceptions “options diversity” and “capability differentiation” and the data collected.

OPTIONS DIVERSITY AND CAPABILITY DIFFERENTIATION IN CAR NAVIGATION TECHNOLOGY

Seeking to address why new digital options challenged modularity practices at GlobalCarCorp, this section presents our industry-level analysis of the evolution of navigation technology over a five-year period (2004-2009). The resulting story documents increasing options diversity and capability differentiation (Schilling 2000) among key players on the car navigation market through a detailed account of activities, events, and decisions related to three

fundamental navigation technology options (embedded solution, portable device, and online navigation). Summarized in Table 1, we describe the diverse characteristics of each of these options. We conclude the section by discussing the capability gap automakers face in relation to navigation technology and the resulting pressure to reconfigure their current approach to modularity and innovation control.

Option	Description	Industry	Design	Strengths	Limitations
Embedded Solution	Integrated into car dashboard, interconnected with other in-car systems	Automotive	Car-centric	<ul style="list-style-type: none"> - Integrated interface - Look-and-feel - Ease-of-use - High-precision positioning - High computing specificity 	<ul style="list-style-type: none"> - High price - Map update - Functionality update - Weak support - Car dependency
Portable Device (Exemplar TomTom)	Single-purpose device, portable across different contexts	Consumer electronics	Device-centric	<ul style="list-style-type: none"> - Low price - Portability - Dedicated interface - Ease-of-use - High computing specificity 	<ul style="list-style-type: none"> - Map update - Functionality update - Interface integration - Positioning precision - Single-purpose - Device dependency
On-line Service (Exemplar Appello)	Server-based application, available across a portfolio of devices	Telecom, Internet	Service-centric	<ul style="list-style-type: none"> - Low price - Map update - Functionality update - Device independence 	<ul style="list-style-type: none"> - Connectivity dependency - Limited interface - Network provider coverage - Positioning precision - Low computing specificity - Device compatibility

Table 1: Fundamental options for car navigation.

Embedded Solution Option

Until 2004, car navigation was dominated by embedded solutions offered by automakers in top-end car models. Such solutions are location-based applications for route guidance. They are integrated into the car dashboard and interconnected with other in-car systems such as steering wheel controls, loudspeakers, and displays (see Figure 1).



Figure 1: Three navigation technology options.

There is some controversy over when car navigation was first offered for commercial use, but Akerman (2006) suggests Honda Legend in 1990 as the first car equipped with navigation technology. By the time the US government provided a more accurate GPS-signal for commercial use in 2000, most automakers offered embedded navigation solutions, typically building on the systems provided by tier-1 suppliers such as Denso, Harman Becker, and Siemens VDO. While the penetration rate has been relatively low over the years, the profit margin on embedded navigation solutions has been high.

The primary strength of the embedded solution from a customer's point-of-view is its integrated interface based on in-car resources such as steering wheel controls, loudspeaker system, and screens. As suggested by JD Power's biannual "navigation usage and satisfaction management reports", the embedded solution option also rates high on look-and-feel and ease-of-use. Moreover, the interconnection with other in-car systems allows for the use of dead reckoning for increasing positioning precision beyond GPS.

However, the synergetic specificity of the embedded solution comes with a high customer price and significant inertia. Tied to the car, functionality and map updates of the system are not only expensive and slow. They can be unattainable because of the dependency on other car systems. In addition, automakers' support organizations have generally insufficient expertise in navigation systems compared to traditional subsystems of the car such as engine and transmission.

These downsides of the embedded navigation option paved the way for alternative technology options that are personal rather than integrated into the car. In fact, sales figures in Europe (see Figure 2) demonstrate that automakers were losing this market to personal navigation systems during 2004-2006 (cf. Hart and McClure 2006). Today, there are two different personal navigation options: portable device and online service.

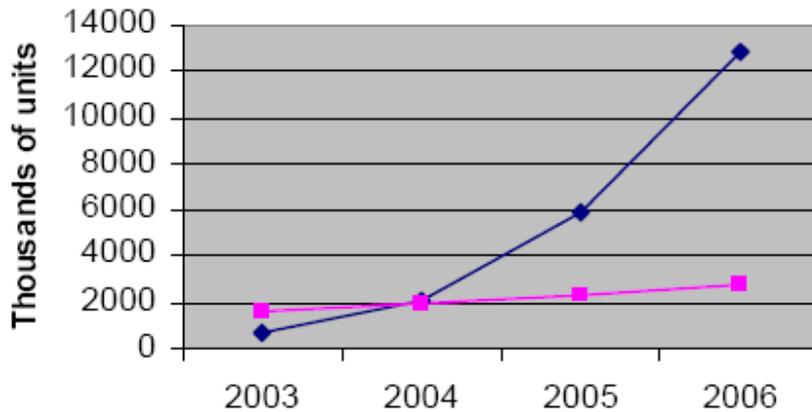


Figure 2: Sales of navigation systems. (source: Canalis)
 Blue line: personal navigation; purple line: embedded navigation

Portable Device Option

The first low-cost alternative to challenge embedded solutions was portable device navigation (see Figure 1). The primary strength of the portable device option is its low price compared to the embedded solution. In addition, its ease-of-use, portability, and dedicated interface are typically suggested to be qualities contributing to the recent market success. Similar to the embedded solution, however, functionality and map updates stand out as limitations of the portable device. The interface integration with other car functions is poor and positioning relies on GPS-technology only. Lastly, the implementation of this option as a single-purpose, stand-alone, device increases the number of devices in users' everyday life.

As a key example, TomTom Navigator was first launched in 2002 as a software solution running on selected Portable Digital Assistants (PDA) equipped with external GPS receivers. With the subsequent launch of TomTom Go in March 2004, the firm paved the way for dedicated and portable navigation devices. Virtually abandoning the PDA-based option, the "all-in-one navigation device" equipped with touch-screen technology and built-in GPS receiver attracted new consumers that valued the low price for an easy-to-use navigator. As a result, TomTom's sales sky-rocketed in 2005 (720 € millions) with a 375% increase over the previous year (192 € millions). This success attracted many other players into the market for portable navigation devices. In fact, between 2004 and 2005, the number of portable navigation suppliers doubled, from 15 to 30 (Hart and McClure 2006). Already at this time, portable navigation devices had dramatically surpassed the embedded solution market in terms of sold units (see Figure 2).

In response to this competitive pressure, a set of automakers developed partnerships with portable navigation providers to offer joint solutions. As early as in March 2005, TomTom announced that Opel Corsa would be equipped with "play and go-navigation", where the TomTom Go-device was fitted into the dashboard of the car and supplied with power from the car. Agreements with automakers such as Fiat, Lancia, Nissan, and Volkswagen followed, manifesting new forms of industry spanning alliances on the navigation market.

Online Service Option

Stimulated by the success of the portable device, another navigation technology option emerged: the online service (see Figure 1). Online navigation services run on cell phones and are either offered by mobile network operators through subscription plans or sold directly by the navigation service provider. The primary strengths of the online service option are its low price and device independence. In addition, functionality and map updates are conveniently handled by the service provider. Depending on mobile network coverage, however, online service use is limited to the coverage provided by the operator providing the service. In addition, the cell phone interface is obviously limited in the car setting because of its small size and limited user input techniques.

As a key example, Appello launched Wisepilot as “the first complete navigation system for cell phones” in 2004. Wisepilot provided clients (i.e. cell phones) an online navigation service with critical functions, such as routing and map database, hosted on a server, and accessible on-line through network technology. With this client-server architecture, clients can be relatively thin (i.e. with little local software) and make use of object oriented software such as Java to access software service located on the server. An immediate and important benefit of this architecture is easy maintenance. Appello can update maps, routing, and other complementary services on the server and thereby making them immediately available on all clients. As a result, the navigation service will always be based on the most recent version of maps and navigation functionality.

In 2005, Appello signed a license contract with TeliaSonera about making Wisepilot the basis of an online navigation service called Telia Navigator. Similar deals were signed with a multitude of mobile network providers over the following two years. In late 2006, Appello was approached by CarCorp for participating in a R&D project with the intention to develop a platform for in-car online navigation. Over the next 12 months, Appello participated in the project, which resulted in three “strategies for wireless integration of Appello's mobile online navigation service WISEPILOT® into a vehicle environment” (Appello press release, January 18, 2008).

Summary of Industry Level Analysis

Our analysis revealed three fundamental technology options for car navigation. The commercial and technical advances of the portable device and online navigation options document why the embedded navigation technology option at CarCorp and other automakers was challenged. As proposed by Schilling (2000), such increased options diversity will likely lead to increased inter-firm modularity to facilitate partnerships. It is therefore not surprising that several car manufacturers engaged in joint ventures with TomTom as early as 2005 and CarCorp later in 2006 engaged with Appello in a joint R&D project. These responses resulted from the increased capability differentiation among the players on the navigation market. As firms such as TomTom and Appello took increased leadership over navigation technology in the years 2004-2006, it was clear that GlobalCarCorp and other automakers needed to adopt new approaches to car navigation, but in doing so they faced a serious capability gap. Next section deals with CarCorp's attempts to close this gap by reconfiguring their approach to modularity.

MODULARITY RECONFIGURED AT CARCORP

Embedded navigation solutions are developed, implemented, sourced, and maintained by automakers based on a traditional approach to modularity and hierarchical control over the innovation process. In this way, automakers can secure the final design as an integrated, yet separable, part of the car as a product and they can align the design of navigation systems to the product development processes of specific car models.

One significant motive for designing a navigation system as an integrated, yet distinct, part of a car concerns product differentiation. In CarCorp's case, navigation systems are sold as options. Rather than selling navigation as standard equipment, these systems serve as a differentiator included in more exclusive editions of the car model¹. Such differentiation enables customization of the car and it increases the profit margin². Another motive is that modularized parts can be shared by other functions of the car. For instance, the screen used for embedded navigation in a modern car such as those of CarCorp is increasingly used as interface to the audio system.

Moreover, this traditional approach to modularization is also manifested in the organization design with important implications for how the overall product development process can be managed and coordinated. The process at GlobalCarCorp (and therefore also CarCorp) is based on a stage-gated process where modularization is essential to determine progress in development projects and secure that parallel development of the multitude of parts eventually will aggregate into a well-functioning car. First, stage-gates are implemented as review meetings where results and timelines are evaluated. Deviations may result in project termination or that resources are adjusted to speed up the process, kept intact, or reallocated to projects in need. Modularization facilitates such meetings by clearly separating concerns between different parts of the car, the infotainment system, or the navigation system under development. Second, the stage-gated process also facilitates project coordination. For instance, a navigation project must early on determine which information it needs from other parts of the car (e.g., the braking system) so that development activities can be coordinated (e.g., engineers working on braking systems make gyro and wheel pulse information available in the correct format). Such early binding of interface requirements between different parts of the car also allows sourcing processes to be initiated. Since most components in a car are sourced to tier-1 suppliers, the management of supplier relationships is essential to automakers and effective modularization enable the definition of scope in sourcing.

Figures 3 and 4 describe the typical modularization of an embedded navigation solution³. Figure 3 depicts the logical view of a navigation system including core functionality such as map rendering, routing, and guidance. Each sub-function inherits (downward arrow) features from one or more functions on the higher level and the resulting logical architecture is therefore a network rather than a hierarchy. The lowest layer of the diagram depicts various physical sensors used for feeding the system with dynamic data and each of the lowest level functions therefore aggregate (upward arrow) data from one or more sensors. For instance, guidance is a core

¹ However, navigation is often bundled with other luxurious infotainment functionality. For instance, the navigation system sold as an option in CarCorp's mid-sized car on the US market in 2009 is bundled with a more advanced audio and stereo system.

² It is well-known that features sold as options can be priced higher than features sold as standard equipment.

³ To date, the exact architecture varied within GlobalCarCorp. The chief infotainment software architect estimated that the global automaker had around 15 different navigation suppliers in 2007. The process described in this paper was part of harmonizing architectures across brands and regions to gain economics of scale and reduce complexity.

functionality of a navigation system that draws on map matching, a map database, information about the active route, and traffic information. In turn, map matching is an algorithm that matches the vehicle position with the map data. Vehicle position is a function that draws on a satellite sub-function and brake sub-function. These latter sub-functions interpret data collected from sensors.

While the logical view provides a functional view of different modules of a navigation system, these functions are typically implemented as distinct software modules allocated to different physical parts of the system. This allocation varies between car models. However, a common feature of the physical view of virtually any existing system is its hierarchical design. As illustrated in Figure 4, the infotainment master controls the navigation (hardware) node, the traffic information mode, the satellite navigation node, and the brake node. In addition, it manages the display, speakers, and user controls.

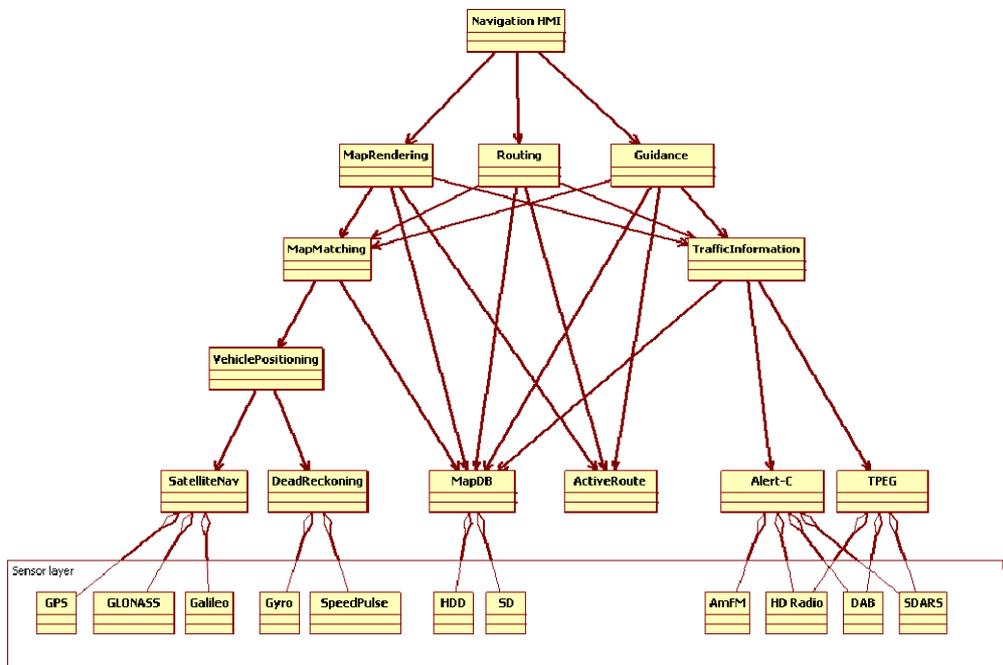


Figure 3: Logical view of a modularized embedded navigation solution.

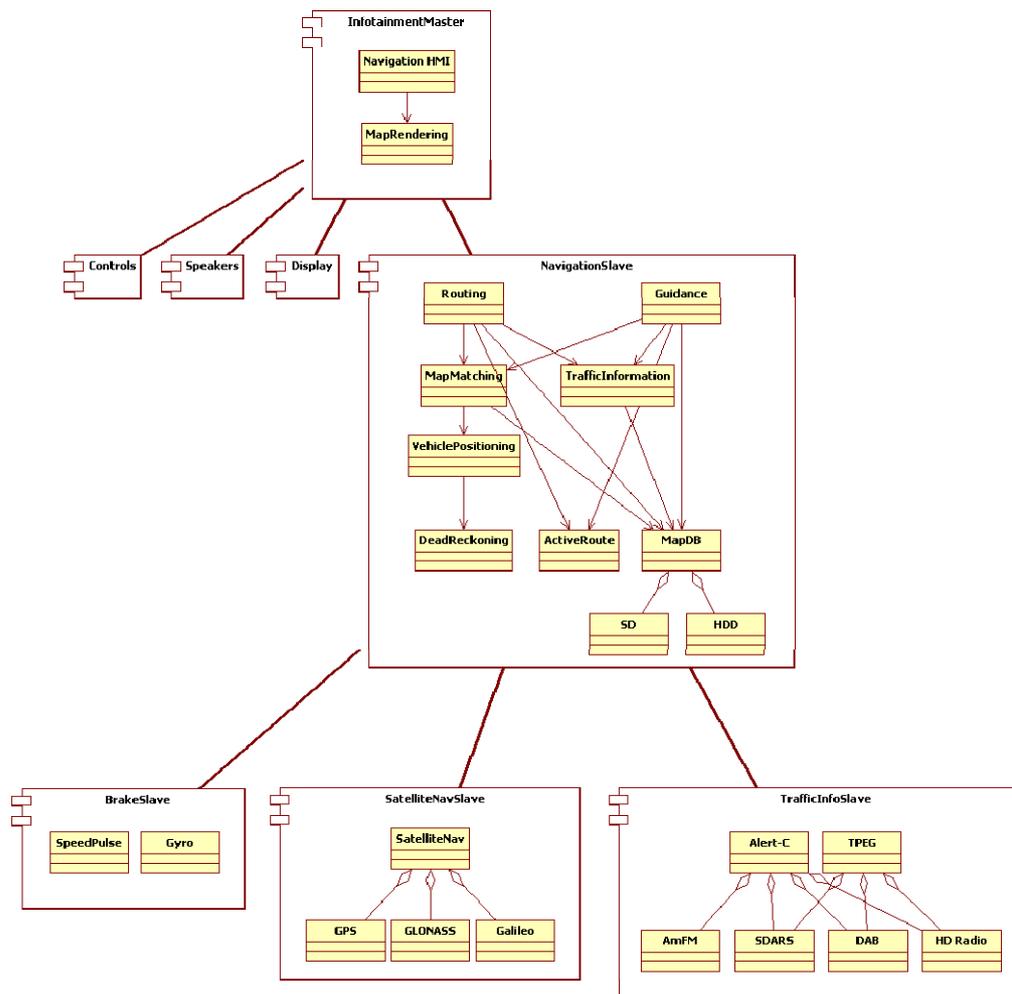


Figure 4: Physical view of a modularized embedded navigation solution.

Whether approached from a logical or a physical perspective, modularity, as practiced at CarCorp and GlobalCarCorp, built on a hierarchical product architecture where the automaker designs the main node and its interfaces. For instance, control of the infotainment node and the HMI software enables CarCorp to manage the system’s appearance to customers. CarCorp defines the detailed functional and non-functional (e.g., temperature range) requirements and the specific ways in which users can interact with the navigation system. Based on such detailed specifications, the navigation node is sourced to tier-1 suppliers, which bundles routing and guidance features into one dedicated solution that can be effectively integrated into the car.

Responding to New Options

As late as in 2004, CarCorp’s approach to the new emerging technology options, portable device and online navigation, was dominated by attempts to fine-tune the embedded solution. CarCorp still considered embedded navigation superior of other options both in terms of functionality and look-and-feel (cf. Table 1). It was therefore not surprising that one of the early R&D projects on car integration of portable devices such as cell phones and PDAs focused on enhancing the embedded solution option rather than on exploring possible collaboration projects.

For instance, it was investigated how phone address book data could be used to facilitate user input of guidance information. One use scenario described how calendar entries in the cell phone were used as input to the route guidance function. This feature would facilitate entering of address information into the navigation system for, e.g., a sales man driving to a customer meeting. When she connected her cell phone to the car system, the embedded system would automatically pick up the address as destination.

In view of the tremendous success of portable devices, however, the year 2006 marked a significant change in CarCorp's thinking about navigation and technology options. One early sign was serious consideration about what it takes to compete on a market characterized by options diversity. A chief software architect commented:

You need to provide the customer with added value for making him purchase a more advanced system in the car. On top of being at least as good as what exists on the market, you need to keep up with all new that is coming along. [...] Already today you can buy a cell phone with navigation [online service]. There are a lot of options out there that we don't offer and you can update after a year and download cool features. We are currently in a situation where indentifying a nice way of integrating with the car is necessary to match what can be found elsewhere. Typically, it costs significantly more when we do it because our low economy-of-scale compared to TomTom's navigation devices pushed out in millions of units.

Gradually realizing the market success of alternatives to embedded navigation and noticing other automakers' collaboration initiatives with TomTom (e.g., Fiat, Lancia, Opel, Nissan, and Volkswagen), increasing attention was paid to the problems of keeping up with the functionality expansion and diversity offered by the two personal navigation technology options. Typically, the differences between automotive industry practices on one hand, and consumer electronics and telecom industry practices on the other hand, dominated when designers and managers at CarCorp and GlobalCarCorp discussed the increasing capability gap. An infotainment manager provided an illustrative comment:

The most obvious reason why we have not responded to the market shift is related to the product life cycle differences between the industries. Traditionally we have operated separately but now when we are forced to coexist, it is clear that the automotive industry is pretty slow compared to those working with consumer devices. This is a huge problem. The product development cycle of car products is around 3 to 4 years, while on the device side it is around 6 months. Before we have even completed half our product development time, they have completed the entire product life cycle. And this causes significant problems, problems that emerged already when we tried to integrate cell phone functionality a few years back.

With an increased understanding of the problems facing automakers, infotainment managers and designers were gradually making sense of the nature and profile of the capability gap and forming a vision for how to overcome it. In doing so, the capability gap was typically traced to the existing modular architecture. In particular, the difficulty to flexibly responding to new emerging user requirements was associated with current ways of tightly integrating hardware and software and navigation systems features with other car parts. An infotainment R&D manager, who later became the project manager of an upcoming platform project explained:

Our systems are not designed for this today. They are very inflexible. If you want to put something into production, it takes three years, almost regardless of what it is. So, if we could get away from a hardware solution, we might address the problem of long lead times for introducing new functionality in the car. [...] The hardware used should remain the same over time, while the software modules should enable the adaptation needed.

As noted by this R&D manager, the existing infotainment architecture, including the navigation system, could not accommodate flexible adoption of new features over time because embedded solutions are inherently inflexible when it comes to functionality and map updates (cf. Figure 1). As a result, CarCorp embarked on a new infotainment platform project in 2006 in which navigation was at the center of attention. At this point, earlier disappointing attempts to predict future requirements and push promising functionality into the traditional stage-gated product development process triggered a totally new approach to navigation technology development. The chief software architect reasoned about what this turn around would require in terms of design and modularity:

We need to develop a software platform in the car that provides opportunities for SonyEricsson, Nokia, or other players to develop third-party applications. We have got many generic in-car resources that can be attractive [for such application developers]. I am convinced that you don't win this game by doing all things yourself. We don't know what's best in three years. We should rather look at the actors who are successful and encourage them to develop on our platform and earn jointly from such a process.

Accordingly, CarCorp invited a number of different firms including Appello and SonyEricsson to participate in the new R&D project with the purpose of developing generic solutions that would allow more flexible adoption of infotainment technology beyond the traditional hierarchy of modularity and control. Given their online navigation service expertise, Appello was invited. A key account manager at Appello commented:

I think that the automakers are desperate to accomplish a paradigm change for navigation. They increasingly recognize that they are losing the game. I don't know their sales figures exactly but they see that other players occupy more and more of the market space and that they must do something. The embedded systems are too expensive and they [CarCorp] view this project as an opportunity to get some guidance, to know what they need to change and what opportunities to exploit.

As CarCorp had no previous collaboration experience with online service providers, the project was difficult to benchmark and it was primarily seen as an exploratory effort to develop new patterns of generic solutions that would be evaluated in terms of feasibility for both parties. The CEO of Appello noted:

We own very up-to-date technology for telecom-based navigation and telecom-based services. [...] However, no one knows what the best solution is [when integrating online navigation with cars] and we want to explore which technology configuration is best. [...] We want to test the potential by exploring different options, to acquire the flexibility we are looking for. We think we know what's best, but it needs to be assessed before instantiating a solution.

Exploring Patterns and Platforms

As a result of inviting Appello as a project partner, the boundary condition for CarCorp's platform project was to apply an online navigation pattern as a basis for exploring new patterns of integrating (rather than embedding) navigation software into the car. The online pattern is a generic solution for providing navigation based on a client-service architecture. Appello's Wisepilot application is an instantiation of the online pattern (recall that Table 1 provided an overview of its strengths and limitations).

Concurring with the observation of Appello's CEO, project participants therefore spent considerable time exploring integration patterns that would augment the inherited properties of the generic online navigation pattern in different ways. Three patterns – streaming, host, and

hybrid – were developed on the basis of the online pattern and analyses of available technological options. Figure 5 depicts how these patterns relate to each other in a modular architecture. For instance, the hybrid pattern inherits properties of the host pattern, which in turn inherits properties of the online pattern.

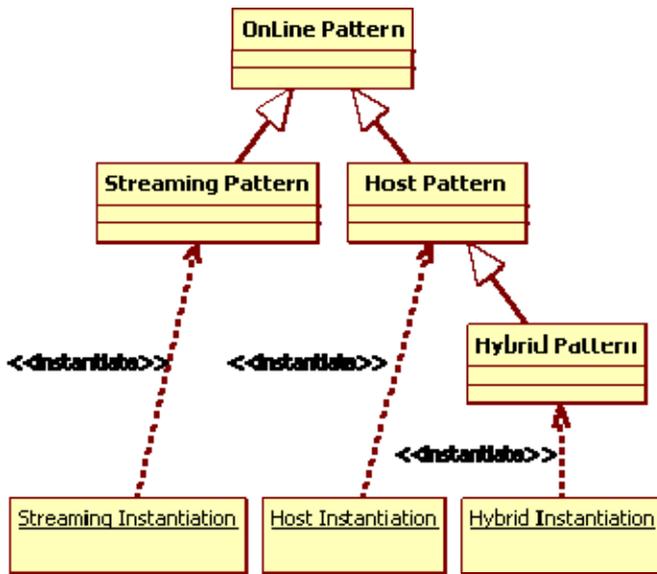


Figure 5: Modularity of navigation solutions based on patterns

Table 2 summarizes these patterns based on a simplified template for specification of software patterns (cf. Gamma et al. 1993) that highlights key characteristics and main differences.

	Streaming Pattern	Host Pattern	Hybrid Pattern
Intent	Augments the online pattern by enabling external control of the navigation solution through streaming.	Augments the online pattern by porting the navigation solution to the in-car software platform.	Augments the host pattern by reallocating computing and storage resources between the server and the in-car software platform.
Motivation	The user can control the online service through in-car resources, such as screens, speaker system, and steering wheel buttons.	The service is truly integrated with the car. In addition, the user can make service hand-over to the cell phone, and vice versa.	The service is truly integrated in the car but augmented with capabilities that reduce the dependency on connectivity.
Applicability	This low-level integration of navigation software into the car offers low-cost, car-integrated navigation that inherits	This high-level integration of navigation software into the car exhibits the advantages of embedded navigation and adds the	This hybrid integration of navigation software into the car exhibits the advantages of embedded navigation and adds the advantages of map and

	some of the advantages and disadvantages of the online service pattern.	advantages of map and functionality updates of the online service pattern. However, it also exhibits the disadvantages related to connectivity and network provider coverage.	functionality updates of the online service pattern with significant reduction of the connectivity issues. However, the disadvantage related to network provider coverage remains.
Implementation	Open standards such as the AMI-C, Bluetooth, and SVG protocols enable in-car interface control of the online service.	The client-side application is ported to the car platform. The Bluetooth protocol is used to connect and deploy the cell phone as communication link to the server.	The client-side application is ported to the car platform and extended with computing and storage capacity to enable local routing and limited map caching. The Bluetooth protocol is used to connect and deploy the cell phone as communication link to the server.
Examples	CarCorp's platform project implemented the pattern in a test vehicle demonstrated for GlobalCarCorp executives.	CarCorp's platform project implemented the pattern in a test vehicle demonstrated for GlobalCarCorp executives.	After assessments on a test platform, CarCorp designers decided not to implement the pattern in a test vehicle.

Table 2: Patterns of integrating online navigation software into the car at CarCorp

First, the streaming pattern is a generic solution for augmenting the online pattern with a remote control function. The remote control function enables user manipulation of the online service via in-car resources such as screens, steering wheel buttons, and the speaker system. This low-level integration of navigation software into the car offers low-cost, car-integrated navigation that inherits some of the advantages of the online service pattern. In particular, it inherits the advantage of always using the latest versions of functionality and maps. In addition, it offers low-cost car integration that outperforms the online service pattern when it comes to the limited interface of the cell phone. However, the other disadvantages of the online service pattern including connectivity dependence and network provider coverage are also inherited since the core functionality runs on the cell phone.

Second, the host pattern is a generic solution for augmenting the embedded navigation option with a consumer device-based communication link. The communication link enables a navigation solution based on the most recent version of navigation functionality and maps. Moreover, it enables seamless transitions between in-car and device navigation for sustained service across contexts (cf. Henfridsson and Lindgren 2005). While it exhibits the advantages of the embedded navigation option, it also inherits the connectivity dependence and network provider coverage disadvantages of the online service option.

Finally, the hybrid pattern is a generic solution for augmenting the embedded navigation option without inheriting the connectivity dependence disadvantage of the online service option. This hybrid integration of navigation software into the car has the advantages of embedded navigation and adds the advantage of up-to-date maps and functionality of the online service option without inheriting the disadvantages related to connectivity. However, the network

provider coverage disadvantage is still inherited since the online service depends on the coverage provided by the mobile network subscription selected by the user.

Towards a New Understanding of Modularity

Understanding components as patterns rather than as parts represented a new way of developing navigation systems at CarCorp. As outlined above, the development of these patterns for integrating online navigation software into the car clarified options for CarCorp and GlobalCarCorp infotainment managers and designers. The joint project with Appello gave important and detailed insights into the online service option and pattern. It suggested that blending the embedded solution and the online service could be a feasible way forward. As the key account manager at Appello noted:

Talking about hybrid solutions [referring to all three patterns], this is a step towards more open thinking, a step towards the unknown world of mixing embedded and online navigation.

To further assess each pattern, CarCorp decided to implement them on a test platform before deploying them in an actual car. This evaluation showed that the streaming and host patterns were the most promising options. The connectivity dependency was considered a temporary disadvantage, and the hybrid pattern was therefore not considered useful because of significant additional development costs.

However, even with the promising results, CarCorp realized that implementing the streaming and host patterns would not overcome the capability gap caused by the existing modular architecture. As stated earlier by the project manager and the chief software architect, CarCorp needed to accommodate changing requirements through flexible software configurations. This required a shift away from emphasizing complete specification of requirements towards development of an infotainment platform that could support a portfolio of different navigation solutions. As the project manager explained:

The biggest difference is that we [in the project] are turning around the entire issue. We have realized that we cannot define all future services that people will desire. This is probably not our job at all.

With this recognition as a basis, the platform project was geared towards the creation of subsystems and interfaces that facilitate the participation of actors who would be able to define and develop such future services over time in GlobalCarCorp's R&D. Because the navigation patterns generated clearly suggested that such participation would go beyond the traditional supplier relationship, the platform needed to be harmonized with technologies used by the consumer device and telecom industries. In fact, the online pattern that formed the basis for the project was outside CarCorp's control. Personal navigation actors such as Appello control requirements determination and therefore also the set of technologies used.

The implications for automakers were underlined by one of CarCorp's key consultants in the project, who had considerable working experience at one of CarCorp's competitors. He noted that:

Clearly, the most important issue is to avoid selecting technology that is automotive-specific and get stuck in the world of automobiles. We must select technology that exists in the world of nomadic devices because then the time difference problem is virtually eliminated. [...] You cannot have a typical auto operating system such as QNX. Then it is difficult, because you have to develop drivers and all sorts of software that you would get without effort

otherwise. I believe that flexibility ... functionality should be developed somewhere else. This problem requires other types of suppliers, which participate and promotes flexibility.

The adoption of consumer electronics and telecom technologies was considered important to facilitate porting of applications and services developed. This would enable more agile and flexible development and not least pave the way for implementing appropriate incentive structures for outside developers. The vehicle architecture, platform interface, and technology strategy work packages of the project therefore suggested a software platform based on Linux and a Java Virtual Machine. The platform dramatically lowered the barrier for adopting new technology options and patterns.

Over a series of demonstrations of the instantiated streaming and host patterns to GlobalCarCorp executives, as well as a successful gate stage meeting at towards the end of the project, the support for the infotainment platform idea increased significantly at the automaker. Accordingly, a new follow-up project was sanctioned and initiated. The project would develop the new product development process that would leverage from the new software platform. To realize new forms of modularity that support external firms to develop new requirements and applications for navigation, the organization design needed to reflect the new product architecture. The consultant responsible for the software platform highlighted this need but also noted its complexity:

This [redesign the organization to reflect the platform] is the major problem. People at electrical engineering departments are used to think about how to embed and control more functionality. This is in their own interest. The electrical engineering department, with say 20 people working on infotainment and 20 people working in telematics, is geared towards specifying in-car functionality so that their own organization becomes more important. [...] This is a matter of short-term survival.

DISCUSSION

In this paper, we investigate how digital innovation presents new options and threats to automakers. In particular, we focus on modularity as a dynamic capability and its changing role when digital technologies are becoming increasingly embedded in traditionally non-digital products. To this end, we trace why the traditional approaches to modularity in product design and organization design are challenged when automakers face new digital options, and we describe how these traditional approaches can be reconfigured to leverage from new digital options. Seemingly stuck in the industrial society, new knowledge about these issues is vital for automakers that attempt to close existing capability gaps and redefine their current innovation path.

On the basis of our case study research across multiple levels (Klein et al. 1999; Hitt et al. 2007), we extend the innovation literature by identifying and characterizing a capability gap that product developing firms in traditional industries face if they merely accommodate digital technology within the confines of current approaches to modularity. The content analysis (Krippendorff 2004) of navigation technology demonstrated an increasing degree of technology options diversity and firm capability differentiation, both of which are proposed to be positively related to increased inter-firm modularity in the literature (Schilling 2000). Sales figures and perceptions of CarCorp and GlobalCarCorp employees indicate that the changes in options diversity and capability differentiation contributed to a rapidly growing capability gap between needed capabilities and the firm's existing capability base for competing on the car navigation market (cf. Capron and Mitchell 2009). We trace this capability gap to the traditional approach to

modularity among automakers, which cannot accommodate digital technologies in a sufficiently responsive and distributed way (Yoo et al. 2008).

In addition, we present a new understanding of modularity that draws on the innovation literature (Baldwin and Clark 2000; Garud et al. 2003; Sanchez and Mahoney 1996; Schilling 2000) as well as the software engineering literature (Alexander 1999; Brooks 1987; Dikel et al. 1997; Gamma et al. 1995). Rather than relying mainly on components as interrelated physical parts of a hierarchical system, we argue that digital innovation requires product developers to fully exploit physical as well as logical design perspectives, and to differentiate between components as parts, as patterns, and as platforms. We posit that the capability to combine such approaches to modularity is essential for effectively embedding digital technology into traditional physical products. For instance, in view of the perceived capability gap at CarCorp, designers of navigation technology abandoned some of the established modular principles for the embedded navigation option. Rather than defining requirements for the navigation solution and decomposing it into parts for sourcing to suppliers, the use of patterns provided the capability to envision a number of different configurations in collaboration with Appello. The streaming, host, and hybrid patterns all represented generic solutions based on the online pattern. Since an online service never can be a physical part of CarCorp's solution, the traditional approach to modularity was at odds with the attempts to integrate navigation software into cars.

The adoption of patterns and platforms as bases for digital innovation at CarCorp represented a break with the received view of modularity. It was an attempt to reconfigure capabilities for making the automaker more attuned to the challenges of digital innovation. Distinguishing between substitution, evolution, and transformation as different forms of capability configuration (Lavie 2006), it can be noted that CarCorp's new approach to modularity cannot be considered as substitution. It goes without saying that an automaker still manufactures physical products, which suggests that decomposition into physical parts will remain important for effectively addressing the hardware side of digital innovation.

However, it is too early to determine if the reconfiguration of modularity at CarCorp is best described as evolution or transformation. Clearly, the platform project initiated in 2006 marked the beginning of a more substantial transformation of modularity practices. Yet, previous research on path creation in digital innovation shows that the creation of new innovation paths is demanding in institutionalized settings and embroiled in tensions and contradictions (Henfridsson et al. 2009). Thus, it would be unfortunate not to accommodate the last words of the CarCorp consultant expressing doubts about the firm's capacity to accomplish a swift transformation of both the organizational design and product design in a concerted manner.

At the same time, some of the big unknowns relate to what type of industrial players and technology options will continue to emerge in the car navigation space given the dynamic nature of the basic digital technology. New players, such as Google, are already establishing strong positions in location-based services and it would probably be a mistake not to assume increased technological diversity on the navigation market.

Implications

The automobile industry was one of the early adopters of modularity (Nevins and Whitney 1989). Product decomposition supports product change, product variety, component standardization, product performance, and product development management (Ulrich 1995), all of which are important aspects for competing successfully on the automobile market. It is therefore not surprising that our findings confirm earlier research about the central role of

modularity as an approach to product and organization design during innovation (Baldwin and Clark 2000; Garud et al. 2003; Langlois 2002; Sanchez and Mahoney 1996). The findings also confirm a number of propositions of Schilling's (2000) general modular systems theory and its application to interfirm product modularity. In particular, our study demonstrates how greater diversity in technology options in the market, as well as how the degree to which firms in the market have different capabilities, are positively related to increasing interfirm modularity. It also provides evidence for Schilling's (2000) proposition that increasing customer heterogeneity in desired function or scale of product is positively related to increasing interfirm product modularity. Indeed, it was the emergence of new customer demands of personal and inexpensive navigation that stimulated CarCorp to initiate collaborative innovation with Appello and SonyEricsson.

It is equally clear, however, that the increasing role of digital technology in automobiles challenge some of the established innovation principles of the industry. Our multi-level case study tracks some of the challenges and our analysis offers a number of significant implications for the innovation literature on modularity (Baldwin and Clark 2000; Garud et al. 2003; Sanchez and Mahoney 1996; Schilling 2000) and the emerging innovation network literature on how digitization triggers new forms of control and coordination (Andersson et al. 2008; Zammuto et al. 2007; Yoo et al. 2008). First, our analysis shows how automakers' attempt to close capability gaps involves **an increasing distribution of control and coordination** of the innovation process. CarCorp's first response to the emergence of the portable device and online service options was to draw on their established modular architecture. This exploitation of existing dynamic capability resulted in attempts to enhance the existing embedded option by incorporating features and content from cell phones. In view of the market success of the portable device and online service options, however, CarCorp radically transformed their approach to car navigation by releasing control of the requirements definition. As a result, the platform project, which started in 2006, adopted a view of modularity that placed patterns and platform center stage. Grounding the design in an online pattern for integrating navigation software into the car, the control of the core navigation functionality was attributed to firms with technological capability in the consumer electronics and telecom domains. CarCorp adopted a platform strategy to stimulate external innovation by developing a set of software systems and tools from which derivative services could be generated. This observation confirms Yoo et al.'s (2008) thesis that innovation in the digital era increasingly involves distribution of control across innovation networks through cognitive and social translations.

Moreover, we argue that the changing landscape of car navigation technology between 2004 and 2008 in general and within CarCorp in particular cannot be described and explained based on a traditional simplified notion of modularity and its expressions in relation to product architectures and related organization designs. The extant product innovation literature on modularity typically assumes a one-dimensional view of components as parts. This view needs to be extended to incorporate components as patterns and platforms too. This provides an avenue for **understanding modularity as hierarchy and network at the same time**. Looking at how CarCorp managed to bridge its capability gap, it was new and differentiated notions of modularity that allowed them to engage in new forms of collaboration with existing and emerging partners. This is a central observation to recognize when studying and explaining distributed control and interfirm modularity in digital innovation.

Third, **the modularity of digitized artifacts exhibits multiple ontologies**. Cars are physical products that can be conceived as consisting of aggregated parts. As outlined by Brooks

(1987), software is different than cars because of its complexity, conformity, changeability, and invisibility. It cannot be understood as aggregated parts alone. Yet, physical parts and software co-exist in the digital car. This coexistence can take different shapes. Embedded navigation represents an example where software is tightly coupled to the system as physical part. Decoupling of the software from the navigation system can only be achieved by orchestrating a co-existence where patterns and platforms also are used as modular principles in parallel with the parts' view. As evidenced in the CarCorp case, this allows for networked forms of interfirm modularity, where the automaker can inherit properties of the online service option. Yet, the automaker will still source parts such as electronic control units, screens, speaker systems, and their software drivers to traditional tier-1 suppliers. The three identified forms of components as parts, as patterns, and as platforms are distinct. They cannot substitute each other, and they capture essential properties of digital artifacts.

Finally, as an exemplar of the modularity literature, Schilling (2000) portrays the essence of modularity as its implementation of adaptability, or dynamic capability, to environmental pressures, diversity, and heterogeneity. Essentially, Schilling views modularity as the “solution” to the need of responding to shifting conditions in a firm’s environment. While such adaptability works within the realm of one form of modularity, we suggest that the Schilling’s notion of modularity may create limitations to a firm’s capability to adapt in response to increased digitization of its products. In digital innovation, firms may experience their approach to modularity as the barrier to effective response to environmental pressure as long as they are not capable of adopting **different forms of modularity** including logical perspectives as complements to the prevailing physical perspectives.

Limitations and Issues for Future Research

Our multi-level case study research involved a number of limitations. First, one limitation is that we have conducted our study in the automotive industry. The industry is currently experiencing the culmination of a severe crisis and might be more attentive to potential capability gaps related to various technologies. Second, we concentrated our analysis on car navigation technology for understanding modularity and digital innovation. This is an area which can be considered to be a more likely target for competition from actors of previously unrelated industries. However, we suggest that this need of reconfiguring modularity as a response to digital innovation applies to, or will soon apply to, other subsystems of the car as a digital artifact. As a very senior infotainment engineer at CarCorp noted:

You know, we have software bugs without the customer knowing, and the customer just have to live with that bug throughout the car’s lifecycle. As long as the engine doesn’t stop, we don’t change it. Only in new product development [...] And this fact has to do with our way to organize. Something that should be seamless, requires a workshop visit. [...] Within five years I expect that software updates be done regularly. With wireless communication, such updates can be done when passing the workshop on the way home from work.

In terms of future research, one suggestion is to replicate our study in other industries centered on traditionally non-digital artifacts. Taking Jonsson et al.’s (2008) study of the value proposition of shipboard cranes as an example, it is more than likely that the new remote diagnostics technology enabling McGregor Cranes to become service providers offers excellent opportunity to investigate digital innovation and its implications for modularity.

Moreover, other research methodologies can be applied to investigate the options and threats presented to manufacturing firms. Conducting in-depth research into digital innovation in

the automotive industry, our investigation has generated a detailed understanding that tracks how general trends play out in the practice of innovation design and the application of digital technologies. Future research can conduct, for instance, a cross-sectional survey that uses econometric methods for generating additional theoretical insights.

CONCLUSION

In the June 2009 issue of the Wired magazine, the Editor-in-Chief, Chris Anderson, recalls Tom Malone's 10-year old prediction of the birth of industry ecosystems as an introduction to Charles Mann's (2009) article entitled "Beyond Detroit". Mann proclaims that "The auto industry must learn to incorporate ideas from outsiders – as the PC industry did 30 years ago", suggesting that increased inter-firm modularity is essential to "reimagine" the troubled industry. The same article suggests Baldwin and Clark's (1997a) work on modularity as a source of inspiration for promoting the much needed open-ended innovation.

It remains to be seen if this transformation will play out as dramatically in the automotive industry as it did in the computer industry (Baldwin and Clark 1997b). However, our conviction is that the capability to build clean, convenient, safe, and inexpensive cars is to a large extent associated with modularity as an approach to product design and organization design. Our conviction is also that building that capability for the digital age requires a reconfiguration of modularity to fit those pockets of innovation where manufacturing meets software.

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