EVOLVING THE MODULAR LAYERED ARCHITECTURE IN DIGITAL INNOVATION: THE CASE OF THE CAR'S INSTRUMENT CLUSTER

Completed Research Paper

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Abstract

Digital innovation entails the combining of digital and physical components to produce novel products. The materiality of digital artifacts, particularly the separation between their material (e.g., hardware) and immaterial features (e.g., software and data), which is expressed through a layered architecture, lays the foundation for the generative potential of digital innovation. Gaining an understanding of the work involved in creating such a layered architecture and tracing the shifts in the material sub-stratum as physical products are digitalized provides insight into the organizational implications of digital innovation. To this end, we study the digitalization of the automobile by focusing on the evolution of a car manufacturer's instrument cluster or Driver Information Module (DIM) from 2005 onwards. Based on laddering interviews with 20 people involved in the development of three increasingly digitized DIMs, this paper traces the progressive dissociation between the material and non-material aspects of digitalized artifacts and the organizational implications of evolving a modular layered architecture.

Keywords: Digital innovation, digital control system, layered modular architecture, laddering interviews

Introduction

The last decade has seen the increasing embedding of digital capabilities into physical products such as cars, household appliances, books and cameras. Through digitalization, these devices' functionality is enhanced. To visualize this trend, just compare the single-utility rotary-style telephone to today's smart-phones, which serve as email client, camera, alarm clock, mirror, flash light, … and a phone.

Combining digital and physical components to produce novel products lies at the heart of a practice labeled digital innovation (Yoo et al. 2010). Digital innovation relies not only on the *digitization* of physical components such that products become programmable, addressable, traceable and communicable (Yoo 2010), but also on their *digitalization*. Digitalization implies that not only the material aspects of the product change (i.e., the technical process of digitization), but that the social aspects of the product's production, use and consumption are also adapted (Hylving et al. 2012; Tilson et al. 2010). This is evident when we consider how entire industries, e.g., the camera industry (Tripsas 2009) and the newspaper industry (Ihlström and Henfridsson 2005), have changed due to shifts in the material conditions of representation from analog to digital.

Some attribute the speed, product diversity and transformative capacity of digital innovation to the materiality of digital technology, highlighting its potential to create a new relationship between function, form, and matter thanks to the dissociation between the material (e.g., hardware) and non-material (e.g., software, content) layers in the computing architecture (Kallinikos 2012). Yoo (2012) ascribes the generativity of digital artifacts to four characteristics of their material make-up: the homogenization of data, the re-programmability of digital devices, the immateriality of software and data, and the self-referential nature of digital artifacts. These material conditions of digitalization have shifted the balance of power from matter towards immaterial ideas, thus loosening the constraints that physical material has traditionally had over human agency (e.g., a designer's ability to instantiate his/her imagination). The immaterial (e.g., a technology's function or purpose as expressed through software that can be combined with different hardware) thus dominates and domesticates the physical materiality of a digital artifact (Kallinikos 2012; Yoo 2012).

Even though the digitization of physical products, such as books and music is proving a transformative – and at times disruptive – force that has generated profound shifts in the structure and competitive landscape of various industries (Tilson et al. 2010), the IS literature has paid little attention to the implications of digitalization. Even though there have been recent theoretical developments related to digital innovation (e.g., Yoo et al. 2010) and the digital infrastructures needed to support this practice (e.g., Tilson et al. 2010), there is relatively little research that demonstrates empirically how organizations evolve their material and organizational infrastructures in an effort to infuse their physical products with more and more digital capabilities. Nevertheless, a recent special issue in *Organization Science* (Yoo et al. 2012) suggests that digital innovation is a nascent area of research.

Furthermore, drawing on the literature about the material conditions of digital artifacts that support the generative potential of digital innovation (e.g., Yoo 2012), we note Kallinikos' (2012, p. 83) claim that "the progressive dissociation of function, form and matter from one another is the most remarkable attribute of technological evolution whose implications are poorly understood and … seldom investigated to a sufficient degree." In other words, the material and social implications of uncoupling the material from the immaterial aspects of technology's architecture need to be studied in order to gain insights into the practice of digital innovation.

The objective of this research is to contribute to our understanding of an organization's migration from product innovation to digital innovation (Svahn and Henfridsson 2012; Yoo et al. 2010). In particular, we seek to generate insight into the progressive dissociation of the material from the immaterial aspects of the digital technology's architecture during the course of digital innovation and the implications of these shifts on social structures (including organizational roles, routines and logics). To this end, we rely on a case study of a car manufacturer, AutoInc[1], which digitalized its Driver Information Module (DIM) – the instrument cluster on the driver's side of the dashboard – over a 9-year period.

Using laddering interviews (Reynolds and Gutman 1988) with HMI (Human Machine Interface) designers, system engineers and others who were involved in the three DIM projects AutoInc worked on between 2005 to today, this study generates the following key insights:

(1) To take advantage of the generative potential of digital artifacts, a layered digital architecture needs to be developed (Kallinikos 2012). Defining boundaries between the various material and non-material components of the digital artifact proved challenging for a traditional product manufacturer like AutoInc, which had limited experience with software development. Each iteration of its instrument cluster entailed the construction of boundaries (e.g., standards, protocols) that progressively dissociated the functions offered by the DIM from its material sub-stratum. In this way, HMI designers gained increasing control over the DIM's material conditions, which was accompanied by a shift in the HMI group's organizational status (from a shared services organization to a fully-fledged division with its own budget).

(2) A critical success factor of digital innovation is the development of modular layered architecture (Yoo et al. 2010). This implies combining the modular architecture of the physical components that make up the car with the layered architecture of the digital control system that monitors and integrates these physical components. These two architectures are orthogonal to each other (Lee and Berente 2012), necessitating to the development of social structures, such as cross-functional teams, to facilitate the interleaving of the modular/physical and layered/digital architectures.

This paper will proceed as follows: we begin by outlining the prior literature on digital innovation, especially as it pertains to the material conditions needed to support the combining of digital and physical components to produce novel products. Then, AutoInc, the site of this empirical research, is described, together with the three DIM projects we studied. This is followed by a discussion of the data collection and analysis strategies we used. After presenting our empirical data, we will discuss the findings, focusing particularly on the intertwining of the material (both digital and physical) and the social (i.e., organizational roles, routines and logics) as organizations engage in digital innovation.

Digital Innovation

Digital innovation is defined as "the carrying out of new combinations of digital and physical components to produce novel products" (Yoo et al. 2010, p. 2). This implies that digital innovation necessitates the hybridization of physical and digital products and the modes of production and organizing logics associated with each. This hybridization often involves the creation of digital representations of physical phenomena (Bailey et al. 2012), which can complicate how we organize to take advantage of the different materialities. That is, we still organize according to the physical phenomena that the digital representation depict even though more other, more hybrid, organizational logics are called for (Svahn and Henfridsson 2012).

Yoo et al. (2012) visualize an organization's journey into digital innovation as a migration along a continuum bounded by *product innovation* on the one end and *digital innovation* on the other. Traditional product innovation emphasizes modular product architecture with segmented product hierarchies separated by standardized interfaces (Sanchez and Mahoney 1997; Ulrich 1995). Individual components are located at the bottom of the product hierarchy and the sub-assemblies that aggregate these components are located in the middle. Larger assemblies form the top of the product hierarchy. Based on "mirroring" theory, a fundamental isomorphism tends to exist between this modular product architecture and the organization (Baldwin and Clark

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[1] All data presented in this paper is anonymized.

2000). For example, an automotive manufacturer has an organizational unit called Engine and one called Steering that reflect the car's material architecture. Each organizational unit has deep knowledge about the components it owns and it typically makes all decisions related to the artifacts it controls with little interference from other parts of the organization.

When these physical components are enhanced through digital capabilities, the architecture of digital products however does not line up with the modular hierarchy (Lee and Berente 2012). For one, the architecture of digital products achieves its modularity through layers (Yoo et al. 2010) that separate the material aspects of digital artifacts (e.g., hardware) from the non-material aspects (e.g., software and data). This dissociation affords generativity (Zittrain 2006) as the layering of digital artifacts' architecture supports the addressability, sensibility and associability and other characteristics (Yoo 2010).

Additionally, non-rivalry in use, infinite expansibility and recombinability (Faulkner and Runde 2010) are properties that make digital artifacts somewhat different from purely physical components. For example, the non-rivalry in use of Microsoft Word implies that several people can work on the software simultaneously without losing any functionality. In contrast, a physical letter-sized sheet of paper can only be used by one person at a given point in time at in a specific place. However, physical objects can be used in a non-rivalry way too. Take for example the lighthouse; there are usually many boats independent of each other that use the lighthouse for navigational help. However, the physical space hinders too many boats to see and use the lighthouse. This will not happen no matter how many people are using Microsoft Word due to its "non-physical mode of being" (Faulkner and Runde 2010, p. 8).

Key to enabling these characteristics of digital artifacts is their layered architecture (Figure 1), which decouples the material from the non-material components of digital products. The layer metaphor implies that, despite the ability to separate between the different tiers in the product stack, there is a hierarchical dependence between the different strata, such that higher-level layers rely on lower-level ones for their functionality.

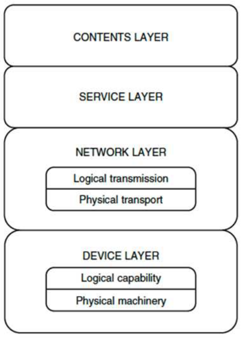

Figure 1: The Layered Architecture of Digital Technology

A simplified view of the digital product stack reveals four layers (Yoo et al. 2010): the bottom-most or *device layer* encompasses the physical components. In the case of a car's DIM, this could be the fuel tank sensors that generate data. The *network layer* consists of physical network buses and communication protocols that aggregate and transport this data to the *service layer*, which consists of applications that manipulate and combine data into information that can be displayed on the driver dashboard. The top-most stratum of the stack is the *content layer*, which includes not only the data that is displayed in the DIM, but also the graphical elements (e.g., fonts and colors) used in the displays. In other words, the content layer also encompasses the user interface or HMI.

Even though Yoo et al. (2010) highlight that one of the critical success factors of digital innovation is the development of a modular layered architecture that integrates the physical and digital product hierarchies, their focus is on the layered architecture of digital technology (see Figure 1), which highlights the hierarchical dependence between the hardware, software and data elements in a digital artifact. Inspired by Lee and Berente's (2012) notion of an orthogonal relationship between a digital control system and a product hierarchy, we propose Figure 2 as a visualization of the modular layered architecture.

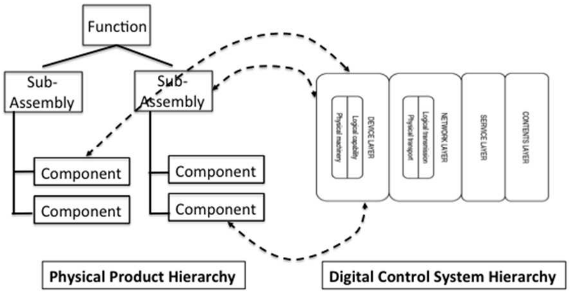

Figure 2: The Modular Layered Architecture

Figure 2 highlights how digital products connect to different parts of the physical product hierarchy thus integrating functionality and data from components that were traditionally separate (Yoo 2012). To the extent that the digital aspect of a product's innovation monitors, integrates and controls the physical components in a complex system, they can be classified as control systems (Lee and Berente 2012). As their name suggests, these control systems, which are more digital and immaterial relative to the product hierarchy, gain dominance over the physical material, enabling its creative (re)combination in pursuit of a designer's ideas for a given function. This lends support for Kallinikos' (2012) argument that the immaterial aspects of digital artifacts domesticate the artifact's material sub-stratum.

The orthogonal relationship between the physical product and digital control system hierarchies is also reflected in the organization's social structures. Since the product architectures, organizing logics and market dynamics for product and digital innovation are at odds with one another (Svahn and Henfridsson 2012), a firm's desire to enhance its products by digital means is likely to be fraught with contradictions. Indeed, prior research has highlighted how organizations struggle to break with their existing roles, structures and practices when products become digitalized (Andreasson and Henfridsson 2009; Hylving et al. 2012). Organizations with established product innovation practices frequently have difficulties understanding and adjusting to necessary digital options and the need for organizational agility (Henfridsson et al. 2009; Sambamurthy et al. 2003).

Our analysis of the empirical data is informed by our visualization of the modular layered architecture as two orthogonally-placed material architectures. Since the DIM monitors and integrates information from the various physical components and subassemblies that make up the car, we consider it a control system that, in the case of AutoInc, became increasingly digital over time. In our data analysis, we trace the progression of digitalization in the AutoInc's DIM, paying particular attention to the increasing dissociation between the material and non-material aspects of the instrument cluster's architecture and the organizational (i.e., social) implications of these changes. In this way, we demonstrate that the increased digitalization not only served as an occasion for affecting organizational change, but actually constitutes the change (Barrett et al. 2012).

Method

Case Organization: AutoInc

AutoInc is a global car company producing a range of passenger vehicles, including sedans, SUV's and hatchbacks. To learn about the material and social implications of digital innovation, we chose to focus on the development of AutoInc's DIM. This decision was motivated not only by AutoInc's increasing appreciation for the car's human-machine interface as a source of competitive differentiation, but also by the fact that the car's instrument cluster communicates the vehicle's increasing digitalization to the customer. In other words, alerts pertaining to tire pressure and high-emission driving that are displayed in the DIM demonstrate to the driver the car's digitally enhanced capabilities.

Three HMI Projects: Increased Digitization of the DIM

Each of the three DIM projects included in this study reflects an increase in digitization. Table 1 provides a summary of the material differences between the projects.

Table 1: DIM Project Comparison

	Partition	**Personalization**	**Platform** [2]
Project start date	2005	2010	2012
CONTENT LAYER			
Units of Information displayed	39 symbols, service messages, and variables (e.g., speed, time,)	49 symbols, service messages, animated information, personalizable by means of different "skins"	Expected to be the same as previous and possibly additional information made available by driver-selected 3rd party apps
Display mode	Black and white	Color and graphics	Color, graphics, video
SERVICE LAYER			
Applications	Driver alerts	Turn-by-turn navigation, animated parking assistance, personalization of the DIM	Expected to be the same as previous and possibly full navigation and apps available from AutoInc and 3rd party vendors
NETWORK LAYER			
Communi-cation capacity	125 Kb/s	125 Kb/s 500 Kb/s	> 8 Mb/s, > 2 Gb/s
DEVICE LAYER			
Size of display	2.5"	8"	>>8"
Pixelation of display	42 DPI (Dots Per Inch)	117 DPI	>117 DPI
Number of physical components in DIM	- 2 black/white LCDs (Liquid Crystal Displays) - 1 PCB (Printed Circuit Board) with 1 CPU (Central Processing Unit)	- 1 full color LCD - 1 PCB with 1 CPU, 1 GPU (Graphic Processing Unit), Flashmemory, RAM (Random Access Memory)	Expected to be the same as previous

With each project, the degree of digital content in the DIM increased. Not only did the number of digital devices increase (e.g., graphical processing units, RAM, Flashmemory added in the Personalization project), but they also became more sophisticated (e.g., color LCDs with higher pixel rates, as well as higher speed and larger bandwidth communication buses). This increased digitization at the hardware layers, which made the generation and communication of more data possible, in turn enabled the development of more elaborate applications at the service layer. In the first DIM project, only a messaging service was available beyond the standard display of driver information such as speed and engine revolutions. However, in the Platform project, which

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[2] The features listed in this column are anticipated since this DIM project is still ongoing.

connects the car to the Internet, the DIM is expected to be able to host third-party apps. This represents the ultimate in DIM personalization.

Data Collection: Sample

Data were collected by means of 20 interviews with people who worked in AutoInc's R&D organization. Many of the respondents had long tenure with AutoInc: two had been with the company since 1994 and the most recent employee among the interviewees started in 2009. The interviewees were chosen based on their involvement in the three projects; they had worked on all three projects albeit in varying capacities. For example, one interviewee tested the production HMI on target hardware in the first project, conducted prototype testing on the second project and early testing of HMI in the last project.

The interviewees represented a wide variety of roles including Technical Specialist, Interaction Designer, Team Leader, System Engineer, Designer, Navigation Function Owner, Advanced Engineering Leader, Product Division Manager, Software Lead. This diversity of perspectives helped us gain insight into the evolution of AutoInc's material and social structures as they moved from product to digital innovation.

Data Collection: Laddering Interviews

All but three interviews applied a laddering approach. A laddering interview, which is frequently considered part of the Repertory Grid (or RepGrid) method in IS (Tan and Hunter 2002), is a powerful meaning elicitation technique (Schultze and Avital 2011). It was used in this study to gain insight not only into the similarities and differences among the three DIM projects, but also into the significance of these distinguishing characteristics.

The laddering interview consisted of two main phases (Reynolds and Gutman 1988): (1) eliciting distinctions among the three DIM projects so as to identify the key characteristics or attributes that were meaningful to the interviewee as the DIM became increasingly digital, and (2) selecting the distinctions that were particularly salient to the increasing digitalization of the car in order to ladder them for further insights.

Kelly's (1955) triadic sorting technique, which relies on comparison and contrast to identify as many meaningful distinctions as possible between the DIM projects, as well as the bi-polar opposites that define them (e.g., collaborative vs. adversarial supplier relations), was used to elicit interviewees' personal perspective on each project. Following Reynolds and Gutman (1988), a typical question the researcher asked at this elicitation stage was: "How are the Partitioning and the Personalization project similar to each other, yet different from the Platform project?" By repeatedly asking this question with different project combinations, key project attributes were identified.

After isolating on average five project attributes in each ~1.5hr interview, the next step was to gain more insight into the interviewee's underlying assumptions about these attributes' significance in digital innovation. The laddering technique, which encourages the interviewee to elaborate on the meaning of project attributes by narratively forging links between them, repeatedly asks 'how' and 'why' questions. For instance, if a participant identified "supplier relationships" as an attribute that differed among the DIM projects and they described these relationships in terms of being "cooperative" and "adversarial" the researcher might ask the following laddering question: "Why is a cooperative supplier important to you?" If the interviewee responded, "because we need to find a win-win way of working," the researcher would then continue with "why is it important to have a win-win way of working?" By repeatedly probing the significance of project attributes, the researcher was able to gain deeper insight into the organizing logic operating in these DIM projects.

Three additional interviews with a System Design Engineer, a Software Engineer and a Hardware Engineer were conducted after the laddering activity was concluded. These semi-structured follow-up interviews lasted about an hour and focused on the material details of each DIM.

Data Analysis

A mind map, inspired by Miles and Huberman’s (1994) data displays, was developed based on the laddering interview sessions. This map showed attributes and distinctions that came up in the interviews. It highlighted themes that were common among interviewees, for example, system specifications (for example paper specifications vs. simulations) and software development (for example internal vs. external development).

All interviews were transcribed and then coded in an initial attempt to identify themes and patterns (Charmaz 2006). The transcriptions were imported into Atlas.ti and were used throughout the data analysis process. The coding procedure started with reading the interview transcripts and listening to the audio recordings, to get an overall understanding of the data corpus. On the second pass through the interviews, codes were added to the transcribed interviews. The different codes, in conjunction with memory notes taken during the coding process, were regarded as tentative analytic categories (Charmaz 2006). The analytic categories and the relations between them and the three projects studied provided a conceptual understanding of the increased digitalization at AutoInc. A total of 21 codes were developed; these included Internal Development”, “HW vs. SW”, “Supplier relation” and “Product Architecture”. These codes were then associated with each project to identify thematic similarities and differences among the projects.

Additionally, rich descriptions (Rousseau and Fried 2001) of AutoInc’s digital innovation effort and the three DIM projects were written. Some of these descriptions were sent to AutoInc for verification and additional insights to add further nuance to our data analysis.

Evolution of the Modular Layered Architecture

Historically, DIMs most commonly consist of two displays, a speedometer and a tachometer (which shows the rotation speed of motor shaft). Frequently, these displays took the form of a dial (see Figure 3) dedicated to presenting one type of information only, as the units of measure (e.g., miles per hour) were permanently printed on the physical display. This tight coupling between the information and the device was further reflected in the transmission of signals from the vehicle components (e.g., engine) to the display. This connection was direct and hard-wired, suggesting that each display was treated as a distinct component dedicated to a single function, thus reflecting the modular product architecture where no distinction is made between the different layers of a display dial’s architecture (see Figure 4).

Figure 3. Traditional DIM with physical display dial

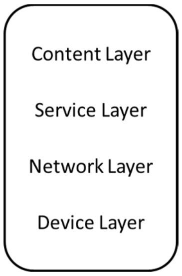

Figure 4. DIM component treated as single unit without recognition of layers

This modular product architecture was mirrored in the organizational structure. AutoInc was arranged into Product Divisions that reflected its product hierarchy of assemblies, subassemblies and components. The organizational unit that owned a given component, e.g., the engine, was responsible for all of its functions. Thus, “function owners” (as AutoInc called them) would specify the type of component-related information, e.g., revolutions of the motor shaft, to display in the DIM. The design group, which was responsible for creating the overall look of the car, determined the fonts and colors to be used in the DIM. Lastly, the HMI group, which was a shared services organization housed within the Infotainment Product Division, was tasked with arranging these design elements into a DIM that met AutoInc's strict safety standards.

In our analysis of AutoInc's three DIM projects, each of which represents a step along the continuum of product to digital innovation (Yoo et al. 2010), we highlight both the product and organizational changes that occurred in order to gain insight into the co-evolution of the material and social infrastructures that are implicated in digitalization. In particular, we focus on the organizational implications of developing a modular layered architecture that integrates the physical product and the digital control system hierarchies (Lee and Berente 2012).

The Partition Project (2005)

This project was AutoInc's first foray into digitizing the DIM, which, together with the center stack (i.e., the console between the driver and the front passenger's seat), formed the vehicle's infotainment system. Wanting to take advantage of the increased flexibility of digital information displays, AutoInc decided to incorporate two 2.5" LCD screens into the DIM. These displays were located behind the still physical dials of the speedometer and tachometer (see Figure 5). The intention was to leverage these two LCDs to display information in a more dynamic, just-in-time fashion, by showing alert messages such as "Vehicle needs service" or "Fuel tank is almost empty". Also, information such as time, outside temperature and fuel consumption, which previously would have required dedicated DIM components, could now be dynamically displayed on the LCDs.

This uncoupling of the information presented from the physical component that displayed it prompted an appreciation of a layered architecture. The DIM was no longer seen as an assembly of individual components limited to representing information for a single function (Figure 4), but of multi-purpose devices that were capable of providing a variety of services. However, at the beginning of the Partition project, the interfaces that were needed to clearly delimit each layer in the architectural stack were not yet in place (shown by the dotted lines in Figure 6).

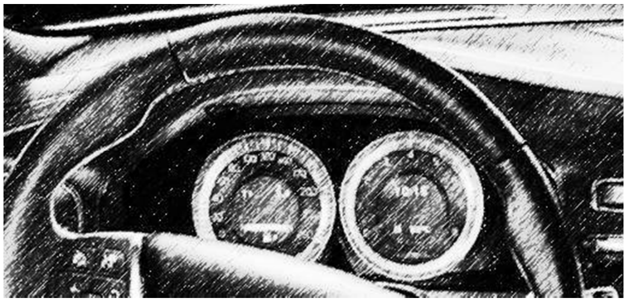

Figure 5. The Partition project DIM with two digital displays

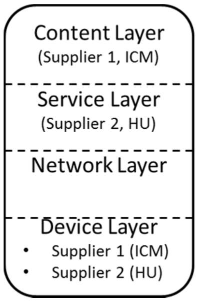

Figure 6. Recognition of Layers in the DIM Architecture but not Interfaces

At the time of the Partition project the decision was made to separate the entire Infotainment system architecture in order to enable a more flexible approach for developing the system. This was achieved by separating the entire infotainment system architecture along the following lines, namely, the Head Unit (HU) and the Infotainment Control Module (ICM). The HU represented the *service layer* in the system. In the navigation system, for instance, it provided the programming logic to provide such functionality as route calculation, location searching and map drawing. In contrast, the ICM supplied the HU with content and managed the display of this content. It thus fulfilled the functionality of the *content layer*. For instance, the ICM handled all text and graphics presented on the display, and provided to the HU information such as the vehicle's current location, the compass, and map data.

The owner of the navigation function explained the logic and implications of this architectural decision:

> "We will get one component [HU] that many customers will buy [embedded in their car] for a good price. But we knew that the different car projects within AutoInc wanted different HMI solutions. […] So the other component [ICM] had to enable different kinds of logics for HMI. But it became clear that this kind of interface [between HU and ICM] would be difficult to do."

Given the size of the HU and ICM contract, AutoInc decided to award the work of developing these components (which consisted of both hardware and software) to two different suppliers. In this way, AutoInc sought to check each supplier's power. Additionally, this partitioning of the control system architecture gave AutoInc the opportunity to insert itself between the two suppliers in order to exercise control over the suppliers as well as the infotainment system. Given their contextual knowledge of the car and all the components that the DIM had to interact with, AutoInc believed it was well-poised to take on the responsibility for integrating the HU and ICM.

As the development of the HU and ICM commenced, AutoInc had no clear delineation of the content and service layer. There was only one specification for the entire DIM, which meant that the requirements for the HMI, the various functions in the DIM, the system design and the graphics were all mixed together in one document. This made it difficult for the suppliers and AutoInc to have an unequivocal sense of their respective responsibilities. One system engineer described the situation as follows:

> "When I tried to read the specification, I didn't understand anything. I don't know how the suppliers were supposed to interpret it. It was total chaos and I don't think the supplier knew what to implement. They did different things in different parts of the software; they did a lot of HMI stuff in the head unit software that wasn't supposed to deal with HMI … there were lots of errors."

Integrating the HU and the ICM was a formidable and complex task because of the extensive amount of data that needed to be exchanged between these two components. In the absence of a common interface that outlined what data variables the two components respectively produced and required in order to deliver a service, AutoInc's had to specify the interaction between these two DIM components for every vehicle component that supplied data to the DIM. The owner of the navigation function described what this integration work looked like:

> "We went to one of the supplier's office and had integration exercises together with the other supplier. […] 'Ok, so now this view [i.e., information display] is supposed to be presented. Nope, it doesn't work. Hmm, why?' Then we had to check in [supplier 1's] internal logs and check why it didn't work. 'Ok, so we don't get that status [data] from [supplier 2].' So then we had to ask [supplier 2], 'why don't you send that status?' And they say, 'Oh we have to call the main office…' And that is how we worked for like two days with only one view to understand where the error originated."

With the boundaries between the different layers not clearly defined, it was uncertain which supplier needed to adapt their product to resolve a problem or to deliver the needed DIM functionality. What exacerbated these integration challenges, was that organizationally, AutoInc had not adapted to the digitalization of its DIM. As a result, function owners were still responsible for ensuring that information pertaining to their vehicle component was adequately presented in the DIM. As a result, the integration between the HU and ICM required the involvement of individual function owners to ensure that the connections between each vehicle components and the new DIM technology were generating the correct views. The complexity of the integration task ultimately caused not only delays in the project's completion, but also a reduction in the DIM's functionality.

The Personalization Project (2010)

The Personalization project had its start in the R&D department, where some HMI engineers were experimenting with altering the look and feel of the DIM to create different emotional responses from the driver and to enhance his/her driving experience. With drivers increasingly used to advanced consumer electronics with sophisticated user interfaces, AutoInc decided to follow the trend and develop a more contemporary look and feel for their cars. Using an 8” full color display (Figure 7) that afforded animations, like parking assistance, and visual effects such as water drops running down the display, enabled AutoInc to significantly upgrade the look of their DIM.

This project represented AutoInc’s first incursion into the realm of personalization. This was accomplished by implemented different “skins” as part of the HMI. A skin was an optional setting where the user chose the DIM´s look (e.g., color and display format) as well as what information to display. For example, in the skin designed to convey a sporty, high-speed driving feel, the central dial on the LCD displayed the engine revolutions to give the driver a sense of how much more power was available to him/her. Another skin intended to convey a feel of environmental responsibility, presented the driver with information on current fuel consumption and emissions.

The Personalization project included two changes in the product architecture: (1) the separation of the visual (content) and the logics (service) of the HMI by means of Persona, a HMI design tool (Figure 8.A), and (2) a protocol enabling standardized communication between the network and the service layer (Figure 8.B).

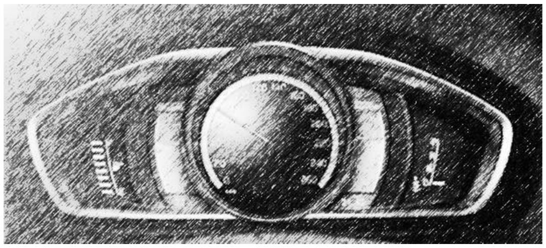

Figure 7: The larger full color display used in Personalization project with animation capabilities

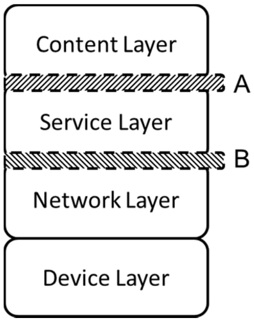

Figure 8. A: Persona that divides the interaction logic and the visual elements of the HMI

B. System engineers aggregating signals from the Network layer creating a protocol to be used in the service layer by the HMI

The HMI design tool, Persona, separated the interaction logic from the visually graphical layer of the HMI. Persona comprised of one module that handled the flow and modality of the human-computer interaction (service layer) and one that rendered the graphical elements and data to achieve different visualizations (content layer). The former took the form of a user interface editor where the logic of moving through content by means of menus or scroll bars, for example, was defined. The latter was a graphical design view that allowed the designer to change the look and feel of the display.

By using Persona, a HMI design tool not specific to the car industry, the layered logic that was embedded in it became inscribed in AutoInc’s DIM architecture and replaced its earlier internal integration efforts. In other words, AutoInc DIM inherited an externally-developed definition of the layered architecture.

The second change was the development of a protocol that aggregated and manipulated data generated by various components’ sensors for use in the DIM. A system engineer explained the need for this HMI-specific data collection:

> "For example outside temperature. You have to moderate it a little; you have to have certain rules on how it should be presented. [The outside temperature] cannot change as rapidly as the raw data generated by the sensors. We have to have some smoothening, some rounding of the numbers. [...] What we do is that we get an outside temperature from some sensor and then we put some damping on it depending on how fast you drive and then we have internal variables which include if it is Celsius or Fahrenheit. [...] We also get a quality flag saying if the data is good or bad. If a circuit in the sensor is broken, the flag shows it's bad and we don't want to display it."

Given the increasing amount of data that was being made available thanks to more and more sensors in the car as well as higher bandwidth and higher speed communication bus, some mechanism for simplifying the data flow to the DIM was needed. This protocol aggregated the data that was needed in the HMI and standardized the interface between the network and the service layer. The development of this protocol by the systems engineers, who had been moved from individual product divisions to the HMI group, also prompted the separation of the single DIM specification into two: the first specification handled HMI issues at the service and content layer, such as the variables to be presented in the DIM and the logic for animations needed for parking assistance, whereas the second dealt with the CAN bus signals, i.e., which component they came from and how they had to be manipulated to be usable in the HMI.

Developing this protocol at the interface at the network layer placed the HMI system engineers between the function owners -- whose components generated the CAN-signals the new protocol was aggregating and refining -- and the HMI group. This seemed a good fit for a group that had recently been moved out of the functional areas. Furthermore, the system engineers found themselves intermediating between different function owners. One of the HMI system engineers describes the intermediary work as follows:

> "We work as an intermediary between groups [for example those responsible for back cameras and park assistance]. There are different groups working with similar things, but they don't communicate. But both [the back camera group and the park assistance group] have interfaces towards HMI so we are in contact with both of them."

The growth of the HMI group did not stop with the absorption of the system engineers. During the Personalization project, the HMI group tripled in size, from 14 to 45. In part this was due to the increased visibility it had garnered through the use of Persona. The simulations of the HMI this tool facilitated were shared with upper management during the course of the project. This generated attention and support for the role HMI played in digital innovation. It helped shed the perception that HMI was merely "putting the last coat of cosmetics" on the vehicle's functional component.

The layering of the DIM's architecture was mirrored in the organization of the HMI group. Whereas previously one HMI engineer completed tasks that cut across the layers of the product stack (e.g., communicating with function owners, specifying the HMI logic and graphics and testing the implementation against the specifications), HMI tasks became increasingly segregated among the different specializations. For example, simulation designer focused on simulating the graphical user interfaces that represented the content layer, interaction designers developed the logics and flow of interaction that reflected the service layer, and system engineers worked on the protocol that demarcated the network layer.

The Platform Project (2012)

During the Personalization project, AutoInc felt more and more pressured to respond to the rapidly changing expectations of consumers, who increasingly sought ways to integrate their consumer electronics into their driving experience. Thus, AutoInc embarked on another DIM project, one that would bring Internet connectivity as well as open innovation in the form of third party apps to the car. The project's name captured the notion of the car as a software platform, akin to Facebook and Google, whose digital services could continuously be extended through an ecosystem of innovative application developers. As one of the managers within the HMI group put it, the car as technology platform promised endless opportunities for digital innovation:

> “The biggest difference [for the Platform DIM] will be the connected services or apps. With them a whole new world is opening up with more data to manage. The sky is the limit so to say.”

Given the increasing availability of data and services that this new DIM would have to cope with, the Platform project entailed a complete overhaul of the car’s entire infotainment system, starting from the device and network layers. The manager responsible for all the software in the Platform project further explained why a new technology infrastructure was needed:

> “[…] we have created a patchwork of technical solutions and it is starting to get very difficult to get an overview of it and understand the consequences of a change. If we pull one thread we don’t know where all the ends are. Because of that, we think we have to start from scratch and create a new structure, a new scaffold to grow into.”

The lack of architectural integrity made it difficult for AutoInc to achieve the flexibility that a technology platform promised. The Platform project adopted a larger LCD for the DIM (Figure 9), one that was capable of displaying video and animations. Internet connectivity would allow drivers to download and rely on third party apps for use in the DIM. A driver might download a navigation service when s/he needed it thereby personalizing the driving experience in a more dynamic manner than heretofore possible.

Additionally, the DIM was intended to be extended through a heads-up display (HUD) capable of projecting information onto the vehicle's windscreen. This indicates yet another degree of uncoupling between the layers in the product stack, such that drivers can choose where they prefer certain information to be displayed, namely in the DIM, in the center stack, or in the HUD.

With the increased focus on applications (service layer) delivered from internal as well as external resources, i.e., third party suppliers, AutoInc established the Connectivity group. The group was tasked with developing car-specific APIs to be used by third party application developers. These APIs would serve as the interface to the car as a technological platform (Figure 10).

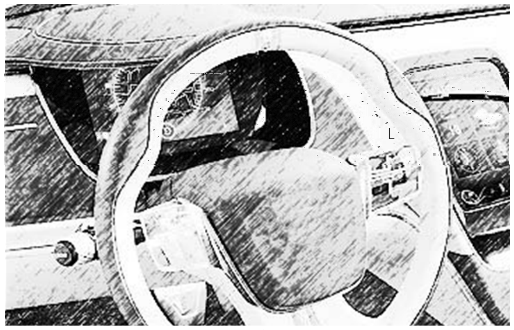

Figure 9: The DIM is a full color >>8” LCD with video capability and Internet connectivity

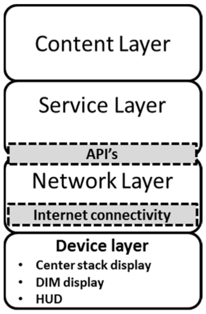

Figure 10: The Platform project includes connectivity to internet, and API’s for 3rd party apps as well as communication to all displays simultaneously

Organizationally, the changes in the architecture for the Platform project were accompanied by significant structural changes. Firstly, in March 2012 the HMI group became its own Product Division putting it on a par with the functional areas that it had previously served as a shared services organization. It now had its own budget, took responsibility for the hardware and software required for realizing the car’s HMI, and had defined deliverables on the car’s development schedule.

The HMI Division was organized into three overarching groups: HMI Advanced Research, HMI Implementation and HMI Systems. This represented a much more deliberate structure that had evolved during the Personalization project. The Advanced Research group tended to rely on various simulation tools to prototype new innovative user interfaces, thus focusing on the content and service layers of the DIM architecture. They also tried out new hardware to enable innovative interaction design, such as interactions through gestures and voice. As such, the group also dealt with the device layer of the DIM architecture. The Implementation group also focused on the service and content layers; they received graphics for the content layer from the graphical design group and relied on the protocol that aggregated the HMI-relevant CAN signals in order to develop new applications (service layer). The System group mainly worked with the protocol that demarcated the network layer for the DIM architecture. However, they also evaluated hardware and software for DIM projects.

With the HMI group being a fully-fledged division, the process of developing the HMI became more top-down. Instead of relying on function owners (device layer) to define what information to include in the DIM, HMI engineers now decided, based on consumer research, what information should be presented and how. This top-down approach thus replaced the function-centric design with a customer-centric one. An example that illustrates the implications of this top-down, customer-centric approach was the integration of what were previously five distinct safety functions (all owned by different function owners) into one safety setting whose level the driver could select my means of a single slider that set each of the five safety functions according to an overarching high, medium or low indicator. This collection of functions, referred to as "features," underlined the uncoupling of the immaterial services in the DIM from their underlying material components.

A consequence of switching from functions to features was the creation of cross-units design teams, referred to as "feature teams." Led by a person from the HMI group, each feature team focused on a specific set of DIM services, such as vehicle settings or navigation. The teams consisted of people from different units within the R&D organization who were knowledgeable in the development of a given feature. In most feature teams, interaction designers, HMI system engineers and function owners were represented.

Discussion

Digital innovation, that is, enhancing physical products by means of digital capabilities (Yoo et al. 2010), is becoming a strategic imperative in many firms not least because the digitalization of physical goods has changed the competitive landscape in many industries (e.g., Tripsas 2009). However, despite these dramatic changes in industrial ecosystems caused by digitalization, IS research is only just beginning to pay attention to the organizational implications of infrastructures (Tilson et al. 2010) and products (Yoo et al. 2010) becoming increasingly digital (e.g., Bailey et al. 2012; Barrett et al. 2012; Lee and Berente 2012). Embracing the sociomaterial orientation that is inherent in the notion of digitalization (Tilson et al. 2010), the objective of this paper is to gain insight into the material and social shifts that occur in an organization's infrastructure as traditional manufacturing firms embark on a journey of digital innovation, that is, moves along the continuum from product to digital innovation (Yoo et al. 2010).

Our analysis of AutoInc's progressive digitalization of its DIM generates a number of insights and contributions. First, it highlights that the migration from product to digital innovation revolves around the development of a layered architecture that progressively dissociates the immaterial from the material aspects of the digital artifact. As the case of AutoInc's evolution of the DIM shows, drawing boundaries between the layers of the digital product stack is challenging, not least because it is influenced by social constraints, such as AutoInc's supplier management strategy and its organizational structures (i.e., divisions owning the vehicle components including their representation in the DIM). Inheriting the definitions of the various layers in the digital artifact's product stack from the software industry, which is what AutoInc did when it adopted Persona as an HMI design tool, might prove a useful strategy for leapfrogging the arduous work of developing home-grown interfaces and protocols.

Second, the case provides empirical support for Kallinikos' (2012) contention that increasing digitalization shifts the power balance between the immaterial and the material aspects of digital artifacts. As software becomes increasingly decoupled from its material substratum, designer's ideas for product functionality domesticates physical matter. In other words, the upper layers of the architectural stack do not only become increasingly independent of the lower, more physical layers, but they also start to dominate them. This shift in the materiality of the DIM was further reflected in the organizational status of the HMI group, which not only gained independent divisional status (from its previous position as a shared services organization), but also started exerting control over the vehicle component groups when it came to the DIM design. Increasingly the HMI group identified features that they sought to materialize in the DIM and they led the feature teams (with representative of the implicated vehicle component organizations) to realize this functionality.

Third, this paper presents the DIM as a control system that monitors and integrates the physical components that make up the car (e.g., engine, steering). As the DIM becomes digital, it adopts not only a layered architecture (Yoo et al. 2010) but one that is distinct from and orthogonal to the organization's modular product hierarchy (Lee and Berente 2012). Figure 2 provides a visualization of the modular layered architecture that is advanced, but not clearly articulated, by Yoo et al. (2010). We consider this diagrammatic representation of the modular layered architecture a contribution in that it helps visualize the material and social tensions that organizations are likely to encounter as they migrate from product to digital innovation (Svahn and Henfridsson 2012). Figure 2 also highlights the importance of cross-functional teams as a mechanism for integrating these misaligned material and social architectures. Indeed AutoInc's feature teams illustrate how digital innovation benefits when the discontinuities in the orthogonal material architectures are smoothed over by dynamic coordination across functions at the organizational level. While this organizational arrangement might be the most appropriate mechanism for integrating the modular hierarchy of the physical product with the layers of the digital control system, this orthogonal relationship needs further study.

Fourth, this paper has taken the material aspects of AutoInc's digital innovation efforts seriously, thus heeding the many calls in IS for theorizing materiality (Faulkner and Runde 2010; Leonardi 2011; Orlikowski and Scott 2008). To this end, we have traced the changes in the architectural arrangements of the DIM technology and the extent to which these changes are reflected in the social arrangements of the organization. We note that the layering of the digital architecture is indeed mirrored in the HMI organization, which became its own Product Division over the course of the three projects. Work responsibilities were assigned to different groups whose expertise more or less corresponded to one or two of the layers in the digital product stack. This suggests that Baldwin and Clarks' (2000) theory of isomorphism appears to hold even in digital products. Nevertheless, additional research is needed to assess how the characteristics of digital artifacts such as addressability, sensibility and associability (Yoo 2010) and non-rivalry in use, infinite expansibility and recombinability (Faulkner and Runde 2010) manifest themselves in the social dimensions of organizing.

Conclusion

This paper provides insights into how digital innovation is accomplished in a traditional automotive manufacturer by tracing how the case company, AutoInc, moved along the continuum from product to digital innovation. Adopting a perspective that takes the material changes associated with the digitalization of products seriously, this study followed the evolution of AutoInc's DIM across three projects. Our analysis highlights the need to develop a layered digital architecture in order to reap the benefits of flexibility associated with digital innovation. It also demonstrates how the progressive dissociation between the material and immaterial components of digital artifacts that is effected through such a layered architecture, shifts the balance of power from the physical layers at the bottom of the hierarchy to the logical layers at the top of the hierarchy, as well as from the modular physical product hierarchy to the digital control system.

This shift in the material aspects of the organization is also mirrored in the social structures, with the HMI group, which is responsible for the digital control system that is the DIM, not only becoming larger in size, but also more powerful relative to the divisions responsible for the vehicle components.

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