DIGITAL ASSET CREATION AND ORCHESTRATION: EMPIRICAL EVIDENCE FROM INDUSTRIAL MANUFACTURING

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This paper addresses the challenge faced by many industrial manufacturers engaged in digital transformation as they rearchitect their physical products into digital assets that can be orchestrated by the firm's business customers as part of their own digital strategic initiatives. In the context of a century old firm that pioneered the professional coffee machine market, we find that architectural innovation occurs at multiple levels – within and outside the individual machines – driven by three design principles: programmatic bitstring encapsulation, hardware abstraction, and physical extensibility and decoupling. Each principle is enacted through a series of cohesive design moves that result in a design hierarchy inversion subverting the historical supremacy of the machine's mechanical architecture over the software, and the resulting digital solutions. This inversion is an example of ontological reversal, pushing our understanding of the phenomenon in industrial settings beyond the current notion of a temporal reversal in design. Our observations suggests that ontological reversal has deeper roots and far-reaching implications than the above view implies, challenging the very foundation of firms' value creation activities.

Keywords:
digital resources, architectural innovation, digital transformation, platformization, potential impact

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1 Introduction

Driven by intensified competition and evolving customer expectations, industrial manufacturers are facing a growing imperative to recombine and reconfigure digital and physical components of their products and services into novel value propositions (Liu et al., 2024; Piccoli et al., 2022; Woodard et al., 2013; Yoo et al., 2010). A key challenge for industrial organizations seeking to embrace the primacy of digital resources (DR) (Piccoli et al., 2024) is that their core products must be abstracted to become components of a digital service layer. From a design standpoint, successfully navigating the transition calls for rearchitecting products that used to provide value as standalone physical assets into digital asset: modular components encapsulated in a bitstring programmatic interface (Piccoli et al., 2022). Note that most industrial products are already sophisticated hybrid digital objects (Faulkner & Runde, 2019) with significant digital components and functionalities. The challenge is therefore one of redesigning them so that they can be orchestrated as part of a value creating generative digital service layer (Piccoli et al., 2022). From a strategic standpoint, abstracting products into modules must be done in a way that prevents their commoditization. This concern is particularly salient for mature industrial product subject to low-end market disruption and design principles[1] must strike the balance between fostering generativity through the openness of the emerging digital service layer and integration of the firms proprietary digital assets. Strategic and design considerations are intertwined because the incumbents' ability to successfully embrace the primacy of DR hinges on their capacity to "extend competitive advantages tied to their legacy physical core" (Liu et al., 2024, p. 6191) during the digital transformation. Digital services must enhance, rather than deplete, the value of the technologies and resources embedded in the firm's physical core (Drechsler et al., 2020). Successfully navigating this transition is critical for industrial incumbents to ensure their long-term viability in the face of relentless digital disruption, a challenge that goes beyond prototype development (Lyytinen et al., 2016). We are aware of no study directly investigating how an incumbent manufacturing firm reconfigures its products into digital assets to enable their value

[1] Design principles are those fundamental rules "derived inductively from extensive experience and/or empirical evidence, which provide design process guidance to increase the chance of reaching a successful solution (Fu et al., 2016, p. 138). They provide guidance for a coherent set of design moves: "discrete strategic actions that enlarge, reduce, or modify a firm's stock of design" (Woodard et al., 2013, p. 539), thus shaping "both short-term opportunities for capturing economic value and the system's long-term path of design evolution" (Woodard et al., 2013, p. 542).

adding orchestration in digital services. Specifically, we ask: *How do organizations rearchitect physical assets into digital assets? What design principles and design moves do firms implement to enable digital asset orchestration?*

Based on a longitudinal case study of a century-old firm that pioneered the professional coffee machine market, we empirically investigate the design and development of digital assets by mapping the evolution of an industrial product as it undergoes multiple architectural transitions (Sandberg et al., 2020). Our results show that the firm simultaneously attempts architectural innovation at multiple levels – within and outside the physical coffee machines. Driving the effort are three design principles: programmatic bitstring encapsulation, hardware abstraction, and physical extensibility and decoupling. Each is enacted through a series of cohesive design moves that result in a design hierarchy inversion that subverts the historical supremacy of the machine's mechanical architecture over the software, and the resulting digital solutions. Such inversion is an instance of ontological reversal, one with deeper roots and farther-reaching implications than the original conceptualization as a "temporal reversal in the way that products are manufactured" (Baskerville et al., 2020, p. 511). Ontological reversal challenges the very foundation of firms' value creation activities, calling into question the design principles that underpin the historical success of incumbents.

The paper proceeds as follows: First, we investigate related work, and define the conceptual framing for our study. We then introduce the methodology and provide a case description, followed by data analysis and a discussion of the findings. Finally, we derive the theoretical implications of our results and offer concluding remarks.

2 Related Literature

Several literature streams inform our research, with digital transformation studies providing the context for our inquiry. This literature largely takes an organizational design perspective and documents how, while some incumbents have effectively navigated the transition (Piccoli et al., 2024), numerous instances of failures underscore the complexities associated with leveraging digital material (Liu et al., 2024; Lyytinen, 2022) as a differentiating component of value propositions traditionally associated with the physical characteristics of products or product components (Grover et al., 2024). This challenge is particularly pronounced for firms in long-established industries, where sector dynamics and economic structures are deeply ingrained in organizing logics (Lyytinen, 2022).

Related research focuses on the internal design of physical products as they are increasingly digitized. Several findings in this stream, focusing mainly on the automotive industry, demonstrate the decoupling of digital control system from the physical product hierarchy (Lee & Berente, 2012) and recognize the "strong tension between the two architectural frames at the point when [digital] patterns were instantiated and deployed to physical parts" (Henfridsson et al., 2014, p. 38). More recently they show the "incongruity between hierarchical and layered configuration of modules" (Hylving & Schultze, 2020, p. 21) that requires technological innovation to become intertwined with traditional and new forms of organizing. Because the focus is on "enhancing physical artifacts by means of digital capabilities" (Hylving & Schultze, 2020, p. 17), it remains unclear how tensions between digital and physical product architecture, change when the product is rearchitected as a module to be orchestrated as a component in "multiple value paths, offered through design recombination" (Henfridsson et al., 2018, p. 89).

Finally, there is an emerging research stream on "platformization" – the "process whereby the structural arrangement of the firm's technology resources transitions from tightly coupled to loosely coupled" (Kaganer et al., 2023, p. 1017). Studies on product platforms (Sandberg et al., 2020) and enterprise infrastructure (Henfridsson & Bygstad, 2013; Kaganer et al., 2023) serve as the foundation for this line of inquiry. They recognize that design principles and mechanisms required for forming successful platforms are "highly interactive," but those interactions have yet to be "examined in detail" (Sandberg et al., 2020, p. 142). In sum, despite valuable insight from the three research streams mentioned above, we lack a theoretical understanding of the architectural changes and design principles guiding the conversion of physical products into digital assets, as they are rethought as modules to be orchestrated by a digital service layer.

2.1 Digital Assets and Digital Strategic Initiatives[2]

Digital resources are "a specific class of digital objects that a) are modular, b) encapsulate objects of value, assets and/or capabilities, c) and are accessible by way of a programmatic interface" (Piccoli et al., 2022, p. 2293). DR have unique structural characteristics that differentiate them from IT resources (Piccoli & Ives, 2005) and IT-enabled resources (Nevo & Wade, 2010) – thus necessitating the use of the term "digital" to connote them. Digital assets are DR that encapsulate either nonmaterial or hybrid digital objects. Value creation with DR occurs through two pathways: a) creation of novel DR and b) orchestration of DR (Piccoli et al., 2022). The former entails the design and implementation of a new digital resource for internal or external use. The latter is the purposeful assembly of DR, IT resources and complementary organizational resources resulting in a value proposition for the firm's customers. No prior work has identified and demonstrated the specific design principles and design moves a firm implements when rearchitecting physical assets as digital assets to make them available for orchestration internally or by its commercial customers.

3 Methodology and Case Description

We analyzed CoffeeCo, a pioneer of the professional coffee machine industry based in Northern Italy. The firm presents an ideal context for our study because the machines are a remarkably complex, yet CoffeeCo's narrow focus on professional coffee machines limits potential confounds. We collected data from multiple sources over multiple waves: technical manuals and product specification, architectural diagrams and use case description; two in-depth visits to the company's industrial museum to review historical product evolution, resulting in detailed analyses of 41 products spanning 1970 to 2021; a first wave of interviews focused on the executive team and subsequent waves on design and production staff, for a total of 16 semi-structured interviews (Table 1).

[2] See Piccoli et al. (2022) for a comprehensive treatment of digital resources and related concepts.

Table 1: Interview schedule, informants, and interviews duration

Month, Year	Length	Participant Details
June 2022	60 min	CEO; Chief Product and Technology Officer; Group Electronic and IoT Solutions Director; CMO; Head of Services
April 2023	90 min	Cloud Solutions, IoT & Digital Officer; Chief Engineer – Fully Automatic Machines
April 2023	60 min	Senior Software Engineer, Digital Touchpoints System Manager; R&D Engineer;
May 2023	60 min	Cloud Solutions, IoT & Digital Officer*; Chief Engineer – Fully Automatic Machines*
May 2023	30 min	Chief Engineer - Traditional Coffee Machines
June 2023	60 min	Cloud Solutions, IoT & Digital Officer **
July 2023	60 min	Group Electronic and IoT Solutions Director *
Nov. 2023	60 min	Group Electronic and IoT Solutions Director **
Dec. 2023	45 min	Group Electronic and IoT Solutions Director ***

* Second interview; ** Third interview; *** Fourth interview

From product and maintenance manuals (1,104 pages of documentation), we cataloged product components, such as the type of Printed Circuit Board (PCB), or the presence of digital functionalities (e.g., telemetry, connectivity). Analysis proceeded from open and selective coding to theoretical coding (Glaser 1978, Urquhart 2013). Then, based on constant comparisons between what was emerging from our data and existing theory, selective coding allowed us to examine the centrality of digital assets in the digital transformation efforts. Informed by theoretical sensitivity (Glaser 1978), the research questions in this paper materialized as we iterated through the data analysis and focused our conceptualization of the findings. In the tradition of architectural innovation research, we highlight "actions that designers take when working on real systems" (Clements & Northrop, 1996, p. 6) to surface key design moves implemented by CoffeeCo, drawing a coherent set of design moves into design principles.

4 Discussion

Our data shows that CoffeeCo, like many industrial incumbents engaging in digital transformation, was challenged to morph from a manufacturer selling machines as finished products in arms-length relationship with its business customers, to a provider of digital solutions fostering ongoing relationship with its clients. Navigating the transition requires the firm to establish design principles and enact design moves that achieve two objectives. First, to rearchitect its products (i.e., professional and superautomatic coffee machines) from hybrid digital objects (i.e., physical assets with digital features) to fully formed digital assets – modular components that are encapsulated in a programmatic bitstring interface (Piccoli et al., 2022). Second, to establish a digital service layer enabling rapid implementation of customer's digital strategic initiatives through the reuse and recombination of those digital assets along multiple and often unexpected value paths (Henfridsson et al., 2018) and design hierarchies (Yoo et al., 2010). The challenge is complicated by the risk of commoditization of the firm's physical core (Liu et al., 2024) in an environment where coffee brewing technology has matured to the point that "everyone can make a good coffee."

Establishing design principles and enacting design moves at this juncture is fraught with ambiguity (Brusoni et al., 2001). Specifically, the firm must leverage the generativity (Zittrain, 2005) and value co-creation potential afforded by the digital service layer while establishing predictable interdependencies between the physical architecture of the machines and the digital architecture of the service layer. Thus, despite its roots as an industrial manufacturing organization, CoffeeCo is challenged to "know more than it makes" by developing system integration knowledge (Brusoni et al., 2001) and reconfigure its physical core accordingly (Liu et al., 2024). Consequently, design principles that historically underpin the success of the company are challenged, requiring a design hierarchy inversion that establishes the primacy of DR while leveraging the established components of professional coffee machines (e.g., boilers, electropumps, touchscreen). The result is a *design hierarchy inversion* whereby the digital service layer comes to dominate the physical architecture of the machines.

As our case analysis shows, before becoming digital assets, the machines had digital functionalities (e.g., configuration, telemetry, customization of the touch screen) that could only be accessed physically or manually via dedicated web applications. Such digital functionalities were developed ad-hoc for each coffee machine model in support of its mechanical functionalities, leading to duplications of efforts and limited standardization. Conceptualized and designed as a finished product, machines accommodated emerging or unforeseen digital services with great difficulty. After rearchitecting machines as digital assets, those digital features could be exposed programmatically and became subordinated in the design hierarchy through the addition of architectural modules.

In the remainder of this section, we discuss a) programmatic bitstring encapsulation; b) hardware abstraction; and c) physical extensibility and decoupling. CoffeeCo introduced these design principles to realize its design hierarchy inversion and facilitate digital asset orchestration by its customers. We describe each design principle, and the associated design moves.

4.1 Programmatic Bitstring Encapsulation

The implementation of this design principle required the encapsulation of the machines within a standardized programmatic bitstring interface by way of several design moves. Aside from the obvious addition of API functionality, each machine needed an abstraction layer that enforced information hiding principles (Parnas, 1972) from the inner design of the machine (i.e., its physical and digital architecture). This design principle was pursued through a series of non-trivial design moves (Table 2).

The architectural innovation implemented by CoffeeCo involved developing a standardized, interface for machine orchestration. The new interfaces were centralized and standardized communication with all machines models and brands, a result achieved by shifting the interfaces to the cloud and exposing them through an API gateway. While many digital functionalities remained available for manual human interaction, such as changing recipes on location using the machine's touch screen or USB interfaces, the cloud-based programmatic interfaces enabled remote management, making the machines visible as "software libraries" to the digital services layer.

Importantly, interface specifications and parameters were the same across all models, in all CoffeeCo owned brands. In other words, CoffeeCo completed an inversion whereby previously hidden information that had to reside in the machine to enable digital services (e.g., payment) became an architectural module in the cloud-based digital service layer, enabling external entities (e.g., payment providers) to interact with the machines without any need for information about the machines' internal specifications. As a result, digital services became loosely coupled with the machine's architecture as shown by the fact that services could evolve at the cloud layer by leveraging full information hiding of the machine internal operations. Most importantly, digital services could develop without requiring physical updates to the software installed on the machines.

Architecturally, the cloud service layer needed no awareness of the machine make or model. Each machine in the customer's fleet would identify itself once connected and register the functionalities and data it could expose based on its electromechanical makeup (e.g., number of brew heads, type of drink dispensers, sensors). The machine was then visible to the customers and ready for orchestration within the specific strategy of the client. This segregation is important because, if the machines are *module complete*,[3] services can evolve in different directions and at different speed from the constraints of the physical design and manufacturing process. Moreover, this architectural shift required that all new machines be equipped with built-in connectivity and telemetry capabilities by default. The rationale was the prerequisite for a standardized machine hardware to effectively deliver digital services. Offering such digital services on a fleet of heterogeneous machine was impractical and inefficient, and often technically impossible. Therefore, this transition was not just a technological upgrade but a fundamental change to align with the company's vision for an integrated and streamlined digital service offering.

4.2 Hardware Abstraction

As described above, a standardized programmatic bitstring interface requires information hiding. Thus, CoffeeCo had to introduce architectural innovations for the machines. While largely reusing the same electromechanical components, the firm introduced an abstraction, in software, of all the physical components of the machine to create a loosely coupled relationship between the digital services layer communicating through the programmatic bitstring interface of each machine, and its mechanical components executing tasks in physical space (e.g., brew a cappuccino with soy milk).

[3] By module complete we mean that they are not lacking a physical component, input device, or sensor needed to support a given service. For example, without a microphone the machine would not support voice ordering, regardless of the software available.

CoffeeCo pursued this design principle through a series of non-trivial design moves (Table 2). Most notably, CoffeeCo transitioned away from developing business and functional logic specific to each coffee machine model. Rather it sought to maintain a universal codebase that incorporated business and functional logic common to all models and brands. This move reduced the need for custom development and streamlined the process of accommodating customer requests for custom features.

The creation of a unified module at CoffeeCo necessitated an architectural shift, making previously hidden information visible to all machines. The hardware abstraction layer guarantees uniform functionality across machines lines. It is also a central element of CoffeeCo's ability to offer digital services by exposing the machines to customer orchestration via standard programmatic interfaces.

As with the design hierarchy inversion described above, the architectural innovation of the machine was possible because, since the first implementations of electromechanical components, CoffeeCo recognized the imperative for deterministic and timely responses in coffee machines under all conditions. Consequently, the company established an architecture predominantly based on real-time and embedded systems, integrating them into the hardware of the coffee machines. Thus, during phases 1 and 2, each machine model required the custom integration of hardware and software. However, while the components were largely ready, architectural innovation was needed to trade-off flexibility for backwards or future compatibility of the codebase of all machines. Without it CoffeeCo faced significant overhead for maintaining previous models and working on new ones – hampering execution of the solution strategy. Due to the monolithic architecture and substantial interdependencies of electromechanical components in previous architectures, any change required considerable effort. Such deterministic and pre-established architectures could not enable rapid response to the changing customer needs that the design hierarchy inversion had created. Thus, innovation also impacted the physical architecture of the machine.

4.3 Physical extensibility and Decoupling

Once it committed to the design hierarchy inversion, with the design principles of standardized programmatic bitstring interfacing supported by hardware abstraction, the firm had to redesign the machine's physical architecture to become mechanical component agnostic. This design principle resulted in a series of design moves that increased the modularity of the physical architecture (Table 2). The change required architectural innovation to move away from bespoke electromechanical architecture to a more flexible and scalable one, anchored around the Controller Area Network (CAN) bus system. While in the previous phase physical components could be reused and recombined across various machine models, they required specific, ad-hoc integrations with their onboard PCB. The use of custom PCBs used up to that point offered enhanced control over electromechanical components, surpassing the capabilities of traditional direct one-to-one connections. Yet, links between components had to be hardwired in the PCB during manufacturing, preventing future flexibility and evolvability of the machine. These limitations were significant, ranging from insufficient space for additional wiring, lack of suitable connector types for extra components on the PCB, constraints in data processing and transmission capacity, overload of the PCB and potential for overheating. When a PCB ran out of available pins to connect external actuators or sensors, an entire PCB had to be redesigned, tested, certified, and manufactured to allow for an extra connection. Data sharing between subsystems was severely limited because components communicated through signals unique to their connection and they did not share common communication protocols. Data generated by one subsystem typically remained within its point-to-point connection with the PCB. It was the microcontroller residing in the PCB that was responsible for receiving, processing, and sending out instructions with the appropriate signal to each component. Thus, the microcontroller acted as a bottleneck in data handling and communication across components. Importantly, the introduction of the CAN bus facilitated the modularization of the architecture by eliminating bespoke connections to a central PCB. This capability enhanced the physical adaptability of the machine, not only during its design and manufacturing phases but even after deployment in the field.

Table 1: Design principles and design moves at CoffeeCo[4]

Principles	Design Moves
Programmatic Bitstring Encapsulation	Create programmatic interfaces to orchestrate machine fleets
	Establish standardized interfaces to digital services
	Deprecate legacy access points to the machine
	Re-architect existing software features and solutions
Hardware Abstraction	Modularize software functionality for each machine
	Standardize hardware specifics, unified computing architecture
	Implement configurable features across different machines
	Standardize around a unified codebase across all machines
	Implement remote activation capabilities for digital services
Physical extensibility	Adopt the CAN bus architecture
	Develop proprietary specs for the CAN bus architecture

Transitioning to a standard common communication bus required adjustments in the machine's components. Physical changes were required as each subassembly must incorporate their own microcontroller to process data, execute commands, and send data to the shared network bus – as opposed to having a central microcontroller that directly controls the behavior of each component. Moreover, each subassembly must comply with the CAN bus interface, which includes compatible wiring for data communication and power. This transition required software changes, to incorporate logic to enable each subassembly to communicate via the CAN bus, share data and receive inputs. Digital services also required the machines to allow for physical extensibility over time and after delivery to customers. To this end, CoffeCo departed from their established approach where most software development was done by component suppliers and external vendors, with CoffeCo's primary role relegated to integrating these physical components and related software.

4 Theoretical Implications and Conclusions

The dynamics described above, where digital service design drives the digital and physical architecture of industrial assets, is arguably the catalyst of the recent frenzy of digital transformation of industrial manufacturing firms (Piccoli et al., 2024). Conceptually, such design hierarchy inversion is a manifestation of reverse ontology (Baskerville et al., 2020) whereby the requirements of the "digital world" that follow

[4] We documented 33 design moves across the three historical architectural transitions. Due to space constraints only the 11 underlying the transition from physical products to digital assets are shown.

the logics of digital design assume primacy in industrial organizations. In the case of CoffeeCo, it is the digital services the firm seeks to offer, such as telemetry, remote maintenance, or re-programmability of drink recipes that ultimately determined the architecture of the machines and the requirements for its electromechanical components.

This finding pushes our theoretical understanding of ontological reversal in industrial organizations beyond its original formulation as "a temporal reversal in the way that products are manufactured. The digital version is created first, the physical representation second" (Baskerville et al., 2020, p. 511). Our case hints to far-reaching implications and deeper roots of ontological reversal than the above view would imply. Ontological reversal appears to call into question the very foundation of the firm's traditional value creation activities. Design principles that historically underpin the success of the company are challenged, requiring a design hierarchy inversion establishing the primacy of DR. More specifically, decisions about *what* functionalities to incorporate and about *how* to implement them, challenge the firm to accrue new architectural knowledge not needed in any of the previous transitions (i.e., phase 1 and phase 2). At CoffeeCo, while the functioning and characteristics of electromechanical components were established over decades of R&D and market research, new physical requirements emerged, guided by digital service imperatives originating from customer needs. The rise to prominence of the digital architecture required a detailed understanding of the "optimal" implementation for each functionality.

How the asset should be architected to optimally respond to market needs is also driven by a digital strategy that is "created first" (Baskerville et al., 2020) and is subject to the digital logics of "software companies" (Lyytinen, 2022). Consequently, the physical and digital architecture of the machine must accommodate such ontological reversal, introducing a new design principle: physical extensibility. For a company like CoffeeCo, this physical extensibility of the machine can only be achieved by modularity in architecture and the reliance on an ecosystem of partners.

Despite the inevitable limitations of a single case analysis, such as generalizability, we believe the CoffeeCo case yields interesting insights. Hybrid digital objects, like industrial machines and components, face unique constraints. Identifying the three design principles of programmatic bitstring encapsulation, hardware abstraction, and physical extensibility and decoupling that underpin a design hierarchy inversion provides empirical support for scholars drawing attention to the need for a nuanced understanding of digital objects in industrial organizations (Grover et al., 2024).

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