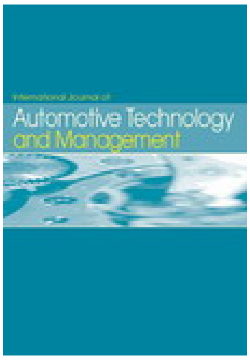

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The great unbundling: from integrated architecture to orchestrated fluidity in the software defined vehicle era

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Abstract: This paper theorises a fundamental paradigm shift in architecture theory, driven by the software defined vehicle. It posits the *inverted mirroring path*, a conceptual framework that overturns the traditional causal logic of the *mirroring hypothesis*. In this new paradigm, product architecture ceases to be a mirror of internal organisational structure and instead becomes a dynamic *strategic interface* that actively mediates exogenous forces – institutional mandates, market dynamics, and user experience. The Chinese SDV ecosystem exemplifies this architectural unbundling: flexible industrial policy, a user base demanding perpetual evolution, and a proactive *swarm strategy* pursuing *emergent heterogeneity* have institutionalised a fluid design paradigm. Within this paradigm, the *boundary configuration* on what to integrate, decouple, or outsource becomes the primary locus of competition and value creation. Consequently, competitive advantage is redefined: it derives not from optimising a fixed architecture, but from a firm's capacity to orchestrate architectural fluidity within an open, evolving socio-technical system.

Keywords: software defined vehicles; SDV; architecture orchestration; swarm strategy; architectural flexibilisation; decoupling; socio-technical systems; product architecture evolution; Chinese automotive industry; BYD; NIO.

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1 Introduction

1.1 Institutional, market, and user-experience dynamics in the shift towards software defined vehicles

The global automotive industry is experiencing a significant structural transition driven by the adoption of electric vehicles (EVs) and the emergence of the SDVs. While this shift is visible worldwide, the pace and direction of change differ considerably across regions (Figure 1). In North America, plug-in hybrid electric vehicles (PHEVs) accounted for approximately 68% of global PHEV stock in 2012, whereas in Europe the share remained between 31 and 46% during 2016–2021. By contrast, China's transition has been dominated by battery electric vehicles (BEVs). Although China represented only 15.7% of the global BEV fleet in 2011, it became the world's largest BEV market by 2015 and has maintained around 60% of global stock since 2018 (IEA, 2024).

These interregional divergences reflect more than contrasting technological preferences. They stem from broader institutional and socio-economic conditions. In China, BEV diffusion has been enabled by flexible policy interventions and an economic environment that favoured rapid experimentation. Since the late 1990s, the Chinese government has treated automotive electrification as part of its industrial self-reliance agenda, deploying policy instruments designed to shape market formation through direct and indirect signals (Liu and Kokko, 2013). Such institutional embeddedness illustrates how policy frameworks can influence the developmental path of emerging technologies (Granovetter, 1985; Pardi, 2021). At the same time, inclusive consumption practices in China have exerted dynamic convergence pressures on firms, reinforcing the legitimacy of SDV-related strategies.

Conventional analyses of automotive competition have long relied on the mirroring hypothesis, which posits a structural correspondence between product architectures and organisational arrangements (Colfer and Baldwin, 2016). This hypothesis, historically influential in explaining the competitive advantages of Japanese automakers (Clark and Fujimoto, 1991), rested on the notion that product architecture reflects the division of labour embedded within established supply networks (Fujimoto, 1999).

However, the ascent of SDV technologies reveals the temporal limits of this endogenous model. As cloud computing, over-the-air (OTA) updates, and artificial intelligence (AI)-enabled functions reshape vehicle development, design authority increasingly emerges through interactions with external stakeholders such as regulators, users, and infrastructure operators. In the SDV context, product architecture thus ceases to function as a mirror of organisational capability and instead becomes an interface that reflects the cognitive demands, experiential expectations and institutional codes of the broader socio-technical environment.

Nowhere is this shift more visible than in China. NIO's in-vehicle agent, NOMI, for instance, functions not merely as a voice interface but as a learning agent that captures emotional cues, behavioural patterns and user preferences, dynamically connecting them to the ongoing evolution of the vehicle's architecture (Qu and Yang, 2024). Such developments challenge the linear causality embedded in the conventional sequence organisation → architecture → competitive advantage. With the rise of pre-trained large AI models and the implementation of embodied intelligence, architectural principles themselves are increasingly defined by institutionally anchored, market-generated and experience-oriented forms of demand (Jacobides et al., 2018).

Consequently, SDV design information now forms a distributed, temporally fluid circulation system, mediated through cloud platforms, regulatory bodies, user communities and infrastructure operators. The vehicle becomes a dynamic translation device that continuously reconciles heterogeneous expectations – user desires, social norms and policy imperatives – in real-time. Firms, in turn, are no longer the initial input-givers of architectural specification. Instead, they act as adaptive configurators, iteratively reorganising SDV structures in response to feedback from institutional environments and user experience. Competitive advantage emerges not from predefined intra-firm capabilities but from the relational process through which firms align with shifting external architectures.

This transformation reveals SDV's essence not merely as technological change but as a fundamental reordering of industrial theory itself. It represents a socio-technical paradigm shift wherein design authority and architectural control are redistributed to the boundary configuration – the primary arena where heterogeneous institutional codes (policy, industry, user psychology) not only intersect but dynamically clash and recompose, thereby redefining the very logic of value creation.

To theorise this shift, the present study introduces the concept of the Inverted Mirroring Path. This denotes the reversal of the traditional sequence firm → product → market towards a new progression: market/institutions/user experience → product → industry grouping → firm. Under this inverted structure, SDV product architecture cannot be characterised by the static dichotomy of modularity versus integrality. Instead, it must be understood as a process of user-experience-oriented architectural flexibilisation, dynamically reshaped by institutional demands, user experience and data governance (Holweg and Oliver, 2015).

Accordingly, the research begins with a theoretical critique of the endogenous design determinism that has dominated product architecture theory – namely, the causal chain in which organisational capabilities within firms determine product structure, which then translates into performance (Clark and Fujimoto, 1991; Ulrich, 1995; Baldwin and Clark, 2000). It treats SDV not simply as a redesign of automobiles, but as a turning point in industrial theory in which external structures form product structures. The aim is to expand product architecture theory from an endogenous determinist model to an exogenously led, strategically evolutionary perspective. Section 2 critically examines the mirroring hypothesis, the core of existing product architecture frameworks, and outlines how SDV challenge its assumptions. Section 3 presents a tripolar model of evolution – Tesla's software-led trajectory, Volkswagen's hardware-legacy-constrained trajectory, and China's user-experience-oriented architectural flexibilisation trajectory – and discusses their evolutionary trajectories and theoretical implications. Section 4 analyses the interactions between user psychology, policy, and corporate behaviour in China's SDV industry, clarifying the fluidity of power structures at the junctions between software and hardware. Section 5 presents the new theoretical frameworks of the inverted mirroring path and the experience-oriented architecture strategy (EOAS), repositions the product evolution discourse on SDV, and summarises the significance of the theoretical shift proposed here, along with prospects for future research on product architecture strategy.

2 Theoretical background and analytical framework: the non-deterministic theoretical reorientation of SDV architecture innovation

2.1 Existing product architecture theory and the basic structure of the mirroring hypothesis

Product architecture theory, systematised by Ulrich (1995) and Baldwin and Clark (2000), is a structured framework that classifies products into modular or integral types based on the correspondence between functional logic and physical structure (Sanchez and Mahoney, 1996). At its theoretical core lies the mirroring hypothesis, which assumes that a firm's organisational structure and the flow of information are reflected in its product architecture (Colfer and Baldwin, 2016; Fixson, 2005; MacCormack et al., 2012). The central proposition of this hypothesis is that the dependency structure between physical components of a product is isomorphic with the organisational structure responsible for its development (Sosa et al., 2004; Chen et al., 2019). In other words, in modular products, tasks can be divided, leading to organisations with a distributed structure; in integral products, tasks with high interdependence are developed by tightly integrated organisations (Colfer and Baldwin, 2016; Sosa et al., 2004).

This theoretical framework seeks to explain how structural complexity, information-processing load, and the need for design coordination in product architecture are reflected in organisational boundaries and governance structures (Brusoni and Prencipe, 2001). It has had a strong influence, particularly in manufacturing, by linking organisational design in product development to architectural strategy. It was especially important for theorising the efficiency of keiretsu structures and hierarchical supplier networks in the Japanese automotive industry of the 1980s–1990s (Fujimoto, 1999; Clark and Fujimoto, 1991).

2.2 The emergence of SDV and the challenge to the mapping relationship

However, the emergence of SDV has exposed the limitations of this endogenous causal model (Baldwin and Woodard, 2009; Szalavetz, 2024). SDV are characterised by logic – physical decoupled systems such as OTA updates, cloud connectivity, and AI-based functional evolution (Gawer and Cusumano, 2014). These systems are expected to evolve into embodied intelligent agents capable of understanding spatial and temporal contexts and making autonomous decisions and actions through dynamic interaction with the physical world (Xie et al., 2025).

In the SDV era, the flow of design information extends beyond firm boundaries (Jacobides et al., 2018). In conventional in-vehicle electronic control units (ECUs), each function was fixed to specific hardware, and updating or reconfiguring a function required replacing or redesigning the ECU itself (Ebert and Jones, 2009). By contrast, SDV adopt a structure in which functional logic is segmented, modularised, transferred to the cloud, and abstracted through middleware (Broy et al., 2007). Consequently, functions are no longer embedded within hardware but are called via networks, enabling flexible layer separation (decoupling) between hardware and software (Broy, 2006). This reverses the view of Ulrich (1995) that product structure serves merely as a container for functions.

However, as this decoupling of layers' progresses, delivering rapid and accurate physical responses to user input requires high levels of coordinated design across the full stack – from the chip level to middleware and the application layer (Pan et al., 2024). This has given rise to a phenomenon that could be termed integral regression.

In other words, SDV are not simply the result of advancing modularisation. Rather, software-led design logic is increasingly interlinking multiple functions with multiple hardware elements, reinforcing many-to-many mapping (Baldwin and Clark, 2000) and reconstructing a new type of integrality through cycles of decoupling and recoupling (Zellmer et al., 2024). Crucially, this new integrality is not the manifestation of an endogenous design capability, but a contingent and reactive integrality shaped through perpetual adaptation to external imperatives (Holweg and Oliver, 2015). This phenomenon exposes the limits of the endogenous causal model and signifies an inversion of architectural determinism, where product structure becomes a consequence of, rather than a blueprint for, organisational and industrial form. This, in turn, requires development teams to possess a deep understanding of the physical world and mastery of automotive engineering details, making multi-layered development systems a decisive source of competitive advantage (Pan et al., 2024).

2.3 Analytical framework of this study

To understand the transformation of product architecture in the SDV era, this study introduces a new concept: the inverted mirroring path. This replaces the traditional causal chain of firm → product → market assumed by earlier architecture theory with a new path of market/institutions/user experience → product →industry grouping → firm. In this model, product architecture is no longer the mirror image of a firm's internal structure but the projection surface of the external world (institutions, markets, user experience).

Here, the starting point of product design is not technical efficiency or internal organisational convenience but external factors such as expected user experience values, policy requirements, infrastructure compatibility, and data governance standards. Corporate organisations respond to these external factors and are subsequently reorganised within their positioning strategies.

At the heart of this inverted mirroring path is user-experience-oriented architectural flexibilisation. In the SDV era, decoupling and coupling are not fixed binary opposites; rather, the questions of which elements to decouple, which to keep coupled, which parts to develop in-house, and which to outsource are defined by the dynamics of external factors and inter-firm alliances – namely, swarm strategy. This is dynamically reconfigured across the entire industry value chain.

As a result, product architecture functions not as a static structure but as a dynamic strategic device for realising user experience value. Based on these considerations, this study redefines product architecture as a strategic adaptive process embedded in external structures (institutions, markets, user experience). This theoretical framework connects directly to the comparative analysis in the following sections and forms the basis for evolving architecture theory in the SDV era from a static structural theory to a strategic structural theory.

3 A new competitive axis in SDV Evolution: the advent of user-experience-oriented architectural flexibilisation

3.1 Tesla-type software-led SDV model

Global discussions on SDV are often framed within a linear narrative in which software drives hardware. The most representative example of this is Tesla. Since its founding, Tesla has adopted a design philosophy premised on a centralised electrical/electronic (E/E) architecture and OTA updates, conceptualising hardware as a container for software evolution. This trajectory allows software-driven functional evolution to propel hardware renewal, enabling the vehicle's overall structure to be reorganised under software leadership.

Tesla vertically integrates the design authority of both hardware and software, completing the selection of systems on a chip (SoCs), operating system (OS) development, and control algorithm design in-house to optimise software-led evolution (Inverse, 2019). For example, autonomous driving algorithms and infotainment upgrades are regularly delivered via OTA updates, positioning Tesla vehicles in the market as products that continue to evolve even after purchase (UMATechnology, 2024).

3.2 Volkswagen-type hardware-legacy-constrained SDV model

In contrast, Volkswagen exemplifies an evolutionary trajectory that stands in opposition to Tesla's – what may be termed the hardware-legacy-constrained SDV model. Through its modularisation strategy, typified by the Modularer Querbaukasten (MQB), Volkswagen achieved standardisation of physical components and improved supply chain efficiency (Jürgens and Krzywdzinski, 2016). However, this success also meant retaining a distributed ECU architecture, which became a legacy burden in the context of software integration.

The development of VW.OS by CARIAD – Volkswagen's software division – has suffered repeated delays, partly because the ECU structures underpinning existing platforms such as the Modularer E-Antriebs-Baukasten (MEB) and the forthcoming scalable systems platform (SSP) have constrained the freedom of the software layer (Goswami, 2024). Unlike Tesla, Volkswagen cannot design a centralised E/E architecture from scratch, and must instead integrate software while reusing existing hardware assets. As a result, development resources have been devoted to retrofitting adjustments (Becker, et al., 2017).

This case raises new questions for mirroring hypothesis (Clark and Fujimoto, 1991; Ulrich, 1995), which traditionally assumed that product structure is endogenously determined by a firm's organisational design capabilities. Volkswagen's experience illustrates a reverse causal pathway: legacy hardware constraining current software integration capability (Baldwin and Clark, 2000). Recent developments in China further reinforce this pattern. The 2025 Audi E5 Sportback – developed by SAIC-Audi – offers a striking example of how Volkswagen attempts to evade, rather than resolve, this constraint. Instead of relying on the MEB or the premium platform electric (PPE), the E5 adopts a hardware base derived from SAIC's IM Motor platform, while Audi restructures NVH, crash performance and vehicle dynamics, and implements its newly developed advanced digitised platform (ADP) as the software and E/E layer. This hybrid configuration demonstrates how legacy-induced architectural rigidity forces Volkswagen to search for non-traditional evolutionary trajectory. Paradoxically, the E5 becomes evidence not of legacy being overcome but of legacy avoidance: an attempt to escape accumulated constraints by outsourcing hardware while rebuilding the software stack on a new digital foundation.

3.3 China-type user-experience-oriented architectural flexibilisation model

While Western firms promote SDV transitions within the bounds of their own rationalities and constraints – and as their domestic markets approach saturation, making the emergence of new value models less likely – China's SDV evolution has formed a third pole distinct from both the Tesla and Volkswagen types. At the industry level, this model contains a paradox: it advances the decoupling of software and hardware while also inducing recoupling in response to the dynamics of market competition. This results in an evolutionary mode that embeds fluid design into its architecture.

3.3.1 The paradox of decoupling and recoupling: reproducing technological complexity

The ideal of SDV design is often encapsulated in the concept of decoupling – the dismantling of traditional integral architectures (Broy et al., 2007). This refers not only to the physical separation of components, but also to the functional and structural unbundling that elevates control authority to the software layer. It involves breaking down functional blocks into independent service units that can be flexibly recombined (Baldwin and Clark, 2000; Ulrich, 1995). This deconstructive logic shifts architecture from stable structures to dynamic adjustment and integration.

However, as such separation progresses to an extreme, recoupling becomes inevitable (Colfer and Baldwin, 2016). Decoupled functions are logically reintegrated via abstracted interfaces, middleware, or data orchestration platforms (Alvarez-Coello et al., 2021). Unlike traditional physical or structural integration, this recoupling is achieved through networked governance involving standard protocols, software platforms, and cloud interconnectivity.

For example, while decoupling between software and hardware proceeds, middleware bridging the OS, board support package (BSP), and applications tends to expand, creating new dependencies (Holweg and Oliver, 2015). Similarly, decoupling within the software layer can foster recoupling in specific domains. In autonomous driving sensor fusion, the requirement to integrate multiple sensor streams at extremely low latency necessitates deliberately tight coupling between certain algorithms (Lefèvre et al., 2011). In hardware, although modularisation of chips and sensors advances, BSP and driver adaptation tasks inevitably reintroduce coupling (Holweg and Oliver, 2015).

This chain of events reproduces complexity rather than simplifying SDV structures (Baldwin and Clark, 2000; Brusoni and Prencipe, 2001). In practice, firms must clearly define the domains in which their core value resides as strategic core layers, deliberately establish control points in architecture design, and dynamically manage the decoupling → recoupling → recomplexification cycle in response to technological change and market demands.

An illustrative example is BYD's voltage-boost charging technology, integrated into its e-Platform 3.0, announced in 2021. In 2015, 500V charging stations accounted for 92.44% of the market. Although higher-voltage EV batteries were expected to meet demands for fast charging, weight reduction, and higher efficiency, infrastructure adaptation would take time. Voltage-boost technology emerged as a transitional bridge but faced technical challenges, such as incompatibility when battery pack voltage exceeded charging station output. Traditional solutions required a standalone boost converter physically separated from the traction motor control unit, creating issues of thermal management, installation space, and reduced reliability.

BYD overcame this by ingeniously repurposing existing motor components as inductors for the boost converter, recognising that the motor control circuit could double as a boost circuit. Through a clever separation of control layers – using communication protocols to manage compatibility (decoupling interface) while integrating power control logic (recoupling logic) – BYD developed an adaptable drive-system-reuse voltage-boost technology. This innovative integration of the motor control system with the charging circuit created a unique power-path design, enabling automatic switching between different charging station standards. This positioned energy efficiency optimisation as a strategic core layer, giving BYD a decisive control point in its SDV architecture and contributing to its subsequent market success.

3.3.2 The distinctiveness of China's SDV transition strategy: swarm behaviour as a driver of fluid design mode in the industrial chain

The defining feature of China's SDV evolution is the persistent non-convergence of the decoupling → recoupling → recomplexification cycle. This cycle is continually reset by external factors such as policy, regulation, infrastructure, and data sovereignty, as well as by swarm behaviour among firms (Banerjee, 1992; Zeng and Williamson, 2007). Here, swarm strategy (Banerjee, 1992) transcends mere collective action, constituting a proactive, strategic exploration process aimed at emergent heterogeneity. It is a cycle of mimesis, convergence, and ultimately, strategic divergence, through which firms collectively explore the architectural possibility space to identify and capture latent demand.

Product architecture design thus evolves beyond the mechanical decision of what to decouple and what to couple and into a fluid strategic choice about which layers to develop internally and which to allocate to inter-firm division of labour. This fluidity varies by layer:

- Chips/hardware: parallel adoption of foreign (NVIDIA, Qualcomm) and domestic (Horizon, BYD, Huawei Ascend) SoCs, with rapid shifts towards localisation under sanctions, or towards decoupled designs under rising computational demands.
- BSP layer: suppliers such as ThunderSoft and Joyson Electronics enabling multi-chip compatibility, with OEMs often adopt a hybrid approach, outsourcing certain domains while keeping others in-house.
- Middleware layer: Huawei and Bosch offering common platforms, while safety-critical advanced driver-assistance systems (ADAS) domains are integrated and cockpit domains decoupled.
- OS layer: coexistence of Huawei HarmonyOS, AliOS, Baidu Apollo, etc., with OEMs mixing and switching systems by domain and over multi-year cycles.

- App/user experience layer: the primary arena for differentiation atop a homogenised base, exemplified by NIO's proprietary NOMI while leveraging Huawei or Alibaba app stores.

Triggers for reconfiguration originate in external forces – data localisation rules, sanctions, vehicle to everything (V2X) infrastructure development – then propagate through swarm strategy such as China automotive basic software ecosystem standards committee (AUTOSEMO) or Huawei-led standards alliances, leading to negotiated industry positions. OEMs adjust OS sourcing and middleware development accordingly, suppliers shift their coupling strategies, and internal staffing is reallocated in response (Zhao and Luethje, 2025).

As a result, China's SDV sector has moved away from a fixed OEM–Tier1–Tier2 pyramid towards a dynamic, real-time reallocation model, determining what to develop, decouple, and integrate based on external drivers and swarm interactions. This fluid design mode is thus the core of the Chinese SDV model, functioning as an all-encompassing reconfiguration system engaging technology, policy, regulation, industry power, and user psychology.

4 The battle for the stack: policy, user psychology, and swarm strategy at the software-hardware junctions

4.1 Policy: flexibility and disruption in institutional and policy design

Although China's electrification policy was launched as a national strategy in the late 1990s, with the formal new energy vehicle (NEV) program initiated in 2009, its tangible impact remained limited until the mid-2010s. In 2013, annual NEV sales stood at only 101,500 units (0.46% of total). By 2020, sales had jumped to 1.36 million units (5.36%), and by 2024, they had surged to 12.29 million units (39.09%).

Behind this rapid shift was a new policy approach that combined flexibility and guidance in institutional design. Policy began to function as a dialogue with the market, shifting away from direct command-and-control to a more sophisticated style of nudging behaviour. This is reflected in the Total Marketisation Index developed by the National Economic Research Institute (NERI). In the 2000s, the sub-index for government–market relations rose, indicating reduced administrative intervention. However, in the 2010s, this trend reversed, with increased policy intervention, even as the overall index continued to climb, reflecting ongoing improvements in market efficiency. The apparent contradiction was encapsulated in the 2013 Third Plenary Session of the 18th Central Committee, which elevated the decisive role of the market while signalling a shift towards indirect, framework-based control of strategic sectors.

Under this policy philosophy, the government deployed guidelines, subsidies, and tax incentives that simulated market self-adjustment while effectively maintaining industrial control. A landmark tool was the Government Guidance Fund (GGF) system introduced after 2015. GGFs channelled private capital into strategic industries through two key features:

1. Risk-sharing structure: the government participates as a subordinated investor, absorbing losses first to reduce private investors' risk, while fund manager remuneration is tied to both financial returns and policy KPIs (e.g., patents).

2 Separation of investment decisions: acting as a limited partner (LP), the government entrusts fund operation to private general partners (GPs), granting them wide discretion in investment selection (except in national security areas).

In the automotive sector, designated as strategic, this framework accelerated the SDV transition from the mid-2010s. Its impact extended beyond technology adoption to function as a structural disruption device reshaping design thinking and industrial behaviour.

First, while maintaining consistent strategic direction, the government avoided technological lock-in, frequently revising subsidy conditions and certification standards. Dual-credit policies guided the industry towards BEVs while mandating OTA updates, creating architectural pressure for software–hardware decoupling and institutionalising annual design and organisational adjustments.

Second, the parallel progression of regulation and standardisation is crucial. Regulations such as cybersecurity laws, personal information protection acts, and ISO 26262 (functional safety) prevent excessive openness by mandating that certain portions of in-vehicle software and data processing remain as black boxes. These opposing forces – simultaneously driving toward full decoupling and restraining it to preserve integration – have compelled OEMs to adopt a hybrid design strategy of semi-decoupling/semi-coupling. Consequently, a flexible architecture has emerged, one that switches between decoupling and coupling on a domain-by-domain basis.

Third, policy shifts acted as direct market signals. Initiatives such as opening autonomous driving test zones or tightening data export rules immediately reshaped R&D priorities, investment, and supply chains. Over time, this cultivated a culture of instant adaptation to policy signals.

Overall, Chinese policy has operated less as a fixed path than as a dynamic force for industrial reconfiguration. Its blend of deliberate disruption, regulatory–standardisation cycles, and signalling has entrenched a co-evolutionary relationship between external forces and industrial behaviour, making dynamic reconfiguration routine in SDV development.

4.2 Users: the catalyst for user-experience-oriented architectural flexibilisation

Traditionally, vehicles were perceived as static commodities, evaluated mainly by performance, price, and design. In China's SDV era, this has shifted: users now view vehicles as products that evolve after purchase. OTA updates for new functions, bug fixes, and user experience improvements are regarded as an entitlement rather than goodwill. Consequently, user expectations favour decoupling in domains requiring frequent updates – such as the human machine interface (HMI) and infotainment – while accepting integration in areas that prioritise functional safety and immediacy, like ADAS and vehicle control. Thus, the trajectory of SDV architectures is increasingly determined by the speed and psychology of user experience rather than by internal technical or organisational logics. Chinese consumers adapt quickly, form collective preferences rapidly, and treat products as instruments for self-redefinition, directly shaping design choices.

This orientation is rooted in broader socio-economic dynamics. Since the 1990s, rural–urban migration has expanded China's informal sector, encompassing workers excluded from formal employment, welfare, and labour protections. By the late 2000s, it exceeded 300 million workers, three-quarters of the urban labour force (Huang, 2011). Although poverty persisted, discretionary consumption began to grow. In early industrialisation, stratification and imitation consumption emerge: elites follow global fashions, while lower strata emulate them to signal aspiration (Baudrillard, 1988). In the Chinese context, this structural dynamic was similarly observed, albeit with distinctive socio-institutional characteristics. Operating within the rigid framework of the household registration (hukou) system, rural-to-urban migrants faced systemic exclusion from essential urban welfare entitlements – including education, healthcare, and pension benefits. This institutional marginalisation fundamentally shaped their subjective identity, fostering a pronounced sense of alienation and cementing their status as structural outsiders within the urban social fabric (Ngai, 2005).

Imitation goods proliferated across clothing, electronics, and household items. Over time, this Shanzhai economy became a cultural phenomenon, reflecting both precarious livelihoods and parody-like resistance to formal authority (Yin, 2010; Wu, 2011).

In essence, the Shanzhai economy was not merely about imitation, but rather served as a parodic resistance by informal sector workers against the dominant formal sector (Anagnost, 1997), while also functioning as an expression of their psychological need to assert their existence and distinctiveness. As a result, during the era of informal sector expansion since the 1990s, the tendency to redefine oneself through products became established, leading consumers to direct their consumption freedom toward goods with high symbolic differentiation (de Certeau, 1984). However, in an uncontrolled competitive environment, consumers' latent demands were diverse and unclear. Thus, Chinese companies repeatedly adopted a swarm economy trajectory, flooding the market with multiple products designed to resonate with consumer psychology and rapidly converging toward best-selling models. This dynamic involves users, companies, capital, and policies simultaneously focusing on new technologies and features, fundamentally reshaping the market structure in a short period.

Within SDV consumption, vehicles are no longer static objects but platforms for self-expression, evolving through software updates and enabling lifestyle renewal. This experience-driven orientation underpins architectural flexibility, making China the most radical SDV market. For example, NIO's introduction of the voice AI NOMI drew immediate attention, triggering competitive imitation and differentiation by other OEMs (Qu and Yang, 2024). Such user-driven dynamics accelerate cycles of imitation (me-too), homogenisation, and differentiation, positioning the Chinese market as a testing ground for swarm strategies shaped jointly by consumer psychology and policy.

4.3 Corporate behaviour: core tensions in the competitive landscape and the swarm strategy

The global evolution of SDV architectures is progressing in parallel, but in China a defining feature is the swarm strategy of indigenous automobile manufacturers. In economics and behavioural studies, this refers to firms imitating others and moving collectively in uncertain, high-risk markets, where such behaviour can be more rational than relying on heuristics. For latecomer firms with limited technological or organisational capabilities, success often depends on rapidly launching products that mirror competitors' successes, while simultaneously enhancing flexibility and experimenting with alternatives. In this process, repeated cycles of imitation and differentiation allow firms to broaden their perspective and identify latent demand through collective, iterative exploration.

Around 2000, indigenous firms entered the market by imitating foreign OEMs and offering affordable mass-market vehicles. They then advanced by creating non-competing segments such as City SUVs and by adopting designs that meet the Chinese aesthetic taste. Their growth followed a rapid cycle of imitation (me-too), homogenisation, differentiation, elimination, and standardisation (Li, 2023). This same dynamic now shapes the SDV domain, where firms pursue a trajectory from follower behaviour to homogenisation, and ultimately to breakthrough differentiation, using agile collective behaviour to explore and define emerging architectures.

Beyond consumption practices, the contemporaneous industrial structure intensified competitive fluidity. China's SDV market is highly decentralised, with legacy OEMs, EV start-ups, Tier 1s, Tech Giants, and chip makers all coexisting. A monopoly model like Tesla's was not feasible. Multiple coalitions were continuously reconfigured. Unlike Bosch or Continental, China lacks absolute Tier 1s capable of guiding the entire industry. Consequently, OEMs, Tier 1s, and Tech Giants operate in parallel without fixed roles, fostering an industrial culture of constant reconfiguration.

Another critical factor was the compatibility with China's digital industry. Internet giants such as Baidu, Alibaba, and Tencent (BAT) transplanted the iteration and A/B testing cultures of smartphone and online service development into the automotive sector. Concepts such as OTA updates, user – experience-centric design, and open application programming interface (APIs) – previously foreign to automakers – became mainstream. Weekly software updates began to shape vehicle development. With Huawei, Baidu, and Alibaba entering OS, cloud, and HMI domains, the boundaries between IT and automotive blurred. Design decisions could no longer be made solely by the auto industry.

Within this structure, a tripartite contest has emerged over control of product definition:

1 From emerging OEMs like BYD, NIO, and XPeng to incumbents like SAIC and Changan, manufacturers are resisting becoming mere metal shell factories and assertively pursuing full-stack in-house development.

2 Tech Giants, aiming to function as Tier 0.5, are vying to control the software layer, seeking to define vehicle intelligence through OS and cloud infrastructure.

3 Traditional Tier 1 suppliers, previously central to ECU and system integration, are repositioning themselves as middleware and software integration service providers, attempting a strategic comeback.

These tensions have simultaneously accelerated decentralisation and re-centralisation, resulting in a fluid hierarchy across the supply chain.

The swarm strategy observed among Chinese automakers should not be regarded as an anomaly, but as a universal logic of industrial adaptation under technological transformation. A similar pattern was evident in the early 20th-century US automobile industry, epitomised by Ford. Although often celebrated as the icon of modern mass production, Ford's origins were not unique. Like Olds Motor Works, founded in 1899, Ford initially operated as an assembler within Detroit's established supplier ecosystem. By 1905, its annual production was around 2,000 units.

What distinguished Ford was its capacity to generate emergent heterogeneity through swarm-based evolution. The launch of the Model T in 1908, coupled with a strategic focus on affordability, marked a turning point. Ford progressively internalised production through vertical integration – casting, machining, and assembly – and by 1915 annual output had reached 500,000 units. This created new logistical bottlenecks, which were resolved through adaptation of conveyor systems from other industries, leading to synchronised flow production aligned with takt time.

Thus, Ford's trajectory illustrates how emergent heterogeneity can crystallise from within a swarm. Its systemic innovation was not an isolated feat but a strategic resolution to the emergent challenges common to the entire adaptive field. It advanced by not just solving shared problems, but by defining a new resolution path that reordered the industry's logic. Other firms faced the same challenges of cost and logistics, but Ford provided a systemic resolution. By analogy, the collective and adaptive behaviours of Chinese OEMs in the SDV transition should be understood not as mere imitation but as efforts to accumulate emergent heterogeneity – just as Ford once did.

4.4 Techno-social dynamics: the five-layer structural challenge

China's SDV transition cannot be explained by technological innovation alone; it represents a process of reproducing complexity within a five-layer structure – technology, firm, industrial chain, market, and institutions – where each layer interacts dynamically.

At the technological level, the move from distributed to centralised E/E architectures requires advances from discrete microcontroller units (MCUs) towards high-performance SoCs, backbone adoption of automotive Ethernet, and enhanced safety redundancy. Each step towards software – hardware decoupling is countered by recoupling, revealing the paradox of rising complexity. At the firm level, OEMs oscillate between ambitions for full-stack development and reliance on Tier 1s or Tech Giants. Within the industrial chain, Tier 1s lose influence as OEMs assume integration roles, while Tech Giants ascend to Tier 0.5 status, intensifying tensions between standardisation and differentiation.

On the market side, consumers purchase evolving experiences via OTA rather than static products, compressing development lead time to 12–24 months. Institutionally, NEV and dual-credit policies accelerate transformation, while standards like ISO 26262 and data sovereignty regulations present a critical dilemma: increased openness can compromise security. These regulations forcibly impose design boundaries, creating a fundamental tension between innovation and safety.

The interplay of institutions, industrial structure, Tech Giants ascent, swarm dynamics, five-layer interdependence, and the paradox of decoupling/recoupling has normalised a fluid design mode in China's SDV industry. In theory, SDV development aspires to layer separation; in practice, each decoupling invites recoupling, making complexity reproduction the central driver of evolution (Colfer and Baldwin, 2016). Ultimately, this process converges on an experience-oriented architectural strategy, where shifting between decoupling and recoupling according to user experience requirements becomes the engine of progress. This produces a full-spectrum reconfiguration engaging corporate organisation, industrial power, institutional frameworks, and user psychology, positioning the Chinese model as a distinctive case in global SDV evolution.

5 Conclusions: from mirroring to orchestration – architecture as strategy in the SDV era

5.1 Reorienting the mirroring hypothesis: the limits of the structuralist model

The mirroring hypothesis has long served as a foundational framework in automotive product architecture theory, positing that a firm's organisational structure and information-processing systems are reflected in its product architecture. This perspective asserts that flows of design information and hierarchical structures determine physical modularity and integration (Colfer and Baldwin, 2016). In studies of Japanese manufacturing in the 1990s and analyses of German OEMs' modular strategies, such as Volkswagen's MQB platform (Li, 2018), the causal chain wherein the organisation defines the product, and its structure materialises into performance held strong explanatory power (Ulrich, 1995; Baldwin and Clark, 2000).

However, the emergence of the SDV has fundamentally destabilised this premise. In the SDV era, software-driven feature updates (OTA), cloud computing, and AI-driven user experience optimisation disperse design information flows beyond firm boundaries. Architecture is now dynamically reconstituted through external nodes – cloud service providers, regulators, data centres, and infrastructure managers. The static relationship where product equals corporate mirror image no longer holds; instead, product architecture manifests as a projection surface for the external world.

Furthermore, it is noteworthy that the shift to SDVs superficially suggests a return to integral architecture. As multiple software functions intersect with numerous hardware elements, increasing structural interdependence, the system may appear to be converging again toward an integrated form. However, this integrality does not stem from a firm's internal integration capabilities, as in the past. It is a reactive integrality formed as a consequence of sequential adaptation to external institutional, market, and user experience requirements – a phenomenon that transcends the framework assumed by existing product modularity theory.

5.2 Introducing the inverted mirroring path

To explain this structural change, this study defines the reversal of the causal pathway as the Inverted Mirroring Path. The traditional mirroring hypothesis depicted a sequence where a firm's capabilities and design philosophy shape the product architecture, which is then reflected in performance and market value (Clark and Fujimoto, 1991). In the SDV era, however, exogenous factors – user expectations, policy requirements, and data regulations – primarily dictate the architecture, and corporate organisations are subsequently reconfigured accordingly. For instance, in the Chinese market, the logic of design now originates from OTA update frequency and user interface/experience consistency, prompting OEMs to redesign SoC configurations, E/E architectures, and chip selections to meet these demands. This structure represents a shift in the causal path from firm → product → market to market/institutions → product → firm, marking a pivotal moment for redefining traditional manufacturing theory.

5.3 Experience-oriented architecture strategy: positioning architecture as strategy

Building on the inverted mirroring path, this study introduces the concept of experience-oriented architecture strategy (EOAS). EOAS regards product architecture not as an efficient design structure but as a strategic apparatus for maximising user experience (Holweg and Oliver, 2015). While decoupling and coupling have traditionally been discussed along the axes of cost reduction and manageability, in SDV development they function as levers to be dynamically switched based on user experience demands. Tight coupling is required for the HMI and inference systems, whereas flexible decoupling is applied to infotainment and the battery management system (BMS). Thus, from the EOAS perspective, architecture is positioned not as a fixed design but as a framework for context-dependent reconfiguration.

5.4 Conclusions: electrification strategy and swarm intelligence – the rapid growth of china's auto industry and the transformation of global competition

EOAS treats institutions not merely as external constraints but as starting points that shape design preferences. China's NEV policies and the dual-credit policy directed initial architectural design toward a BEV-centric trajectory. Concurrently, data sovereignty regulations and ISO 26262 established boundary conditions, institutionalising a semi-decoupled/semi-coupled structure by stipulating that excessive decoupling increases safety risks. This institutional influence should be understood in conjunction with the concept of dynamic capabilities (Teece, 2018). Firms' architectural strategies are effectively reinterpreted, treating institutions not as entities to be complied with but as a design foundation to be utilised.

Within this framework, the significance of the Chinese model becomes clear. China's SDV evolution has emerged as a third pole, distinct from Tesla's pure software-led trajectory and Volkswagen's hardware-legacy-constrained trajectory. Its evolution is shaped by three factors: historical (a tradition of lightweight development stemming from a reliance on foreign joint ventures), institutional (NEV policies and data sovereignty regulations), and industrial structural (the rise of IT and telecommunications giants as Tier 0.5).

Particularly noteworthy is how swarm strategy drives the dynamics of China's SDV evolution. OEMs collectively emulate Tesla's centralised E/E architecture or Volkswagen's MQB modular philosophy while continuously attempting their own differentiation. This cycle of imitation and differentiation perpetually reproduces decoupling and recoupling, creating a dynamic that constantly amplifies complexity. Consequently, the Chinese SDV model has become a system that harnesses the very cycle of decoupling and recoupling as its engine of evolution, unfolding as a comprehensive restructuring process that engulfs user experience, institutions, industrial power, and organisational structures.

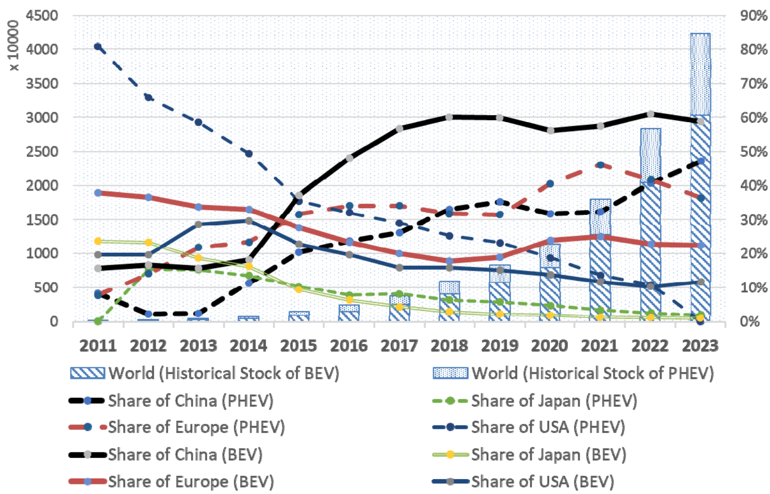
In conclusion, the Chinese model presents the following three theoretical turning points for SDV research:

1 Product architecture is not a mirror of the firm's interior but a projection surface for exogenous institutions, markets, and user experience.

2 Decoupling and coupling are not fixed design principles but strategic parameters to be switched according to user experience.

3 SDV evolution is a dynamic process that reproduces complexity through cycles of decoupling and recoupling, making a unified, convergent global endpoint unlikely.

Figure 1 Global stock and regional composition of electric vehicles (see online version for colours)



Note: BEV + PHEV, excluding HEVs.

Source: IEA (2024)

Consequently, China's SDV evolution represents a decisive theoretical rupture – a shift from endogenous design determinism to an exogenously-led architecture strategy. This mandates a fundamental redefinition of product architecture: no longer a static mirror of the firm, but a dynamic strategic interface where institutions, markets, and user experience continuously negotiate and reconfigure the very foundations of industrial power, value creation, and competitive advantage. Embracing this perspective allows for a deeper interpretation of the success factors behind China's NEV policies and provides a compelling explanation for the growth disparities among Chinese automakers – between indigenous brands and joint ventures, and within the indigenous brand group itself. A key future challenge is to apply this strategic architecture theory to models in other countries, using comparative analysis to elucidate why different markets follow distinct evolutionary paths and why a unified endpoint remains elusive.

Declarations

I declare that I used ChatGPT (OpenAI) to improve the clarity of the English language during the editing phase of this paper. All authors declare that they have no conflicts of interest.

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