

Article

From Technology Monopoly to Industrial Sharing: How Leading Manufacturers Realize Sustainable Value Circulation

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Abstract

Digital and intelligent transformation reshapes manufacturing ecosystems, and the synergy between technological innovation and sustainable business upgrading drives high-quality industrial development. Based on knowledge interaction theory, this paper adopts a longitudinal single-case design and the Gioia analytical framework to study BYD covering the period 2003–2025. With data triangulation realized through internal corporate archives, public industrial materials and five semi-structured interviews, this paper explores the staged evolution and value allocation mechanism of sustainable business model innovation driven by firms' proprietary core technologies. Three sequential phases of technological value circulation are summarized: value creation enabled by single-point core technologies, value addition realized through generic product technologies, and cross-industry value sharing facilitated by industrial technology openness. The traction, utilization and recombination of knowledge generate synergistic advantages of core technologies across the innovation chain, industrial chain and value chain, reconstructing a new value operation logic centered on value creation, value addition and cross-boundary value sharing. The extant literature decouples technological evolution and business model innovation, resulting in prominent theoretical gaps. This study improves relevant theoretical explanations and proposes operable industrial strategies, offering references for manufacturing enterprises to achieve long-term sustainable development relying on core technological capabilities.

Keywords: sustainable progress; manufacturing industry; core technology; sustainable business model; business model innovation



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1. Introduction

In the digital-intelligent economic era, industrial transformation has restructured the operational logic of manufacturing firms. The integration of knowledge diffusion and artificial intelligence facilitates the co-evolution of data-driven innovation and core technological upgrading [1] (p. 143080), [2] (p. 5793). By elevating the efficiency of in-house core technology R&D, industry frontrunners such as Kute Smart, Schneider Electric and Shangpin Home Collection have delivered tangible transformations of their business architectures and secured persistent market competitiveness over the long run [3] (p. 121508). The implementation of Made in China 2025 (2015) further accelerated business model innovation. Core technologies are reshaping operational structures and value creation methods in traditional manufacturing industries, thereby giving rise to innovative networked and platform-based business models [4] (p. 102853), [5] (p. 109282). For instance, the sharing economy enables precise alignment between supply and demand in business transactions [6] (pp. 85–100).

Platform-based business model innovation generates financial benefits while simultaneously presenting significant challenges [7] (p. 122606), such as reducing companies' social value and harming the ecological environment [8] (pp. 1942–1952). Therefore, companies must incorporate sustainable development principles into their daily operations to fulfill stakeholder expectations and create technological value [9] (p. 5561). However, existing research often treats technological advancement and business model change in isolation, lacking an integrative perspective on their reciprocal evolution. A systematic examination of their synchronized development is vital for guiding firms toward more resilient and sustainable innovation strategies.

Sustainable business model innovation aims to create social and environmental value while developing core technologies to fulfill corporate social responsibility commitments [10] (p. 123741), [11] (p. 5511). Through knowledge exchange, companies can advance core technologies while fostering shared technological value, which is vital for innovative and sustainable business models [12] (pp. 22–36) [13] (p. 123086), and thus contribute to society by advancing critical technological innovations [14] (p. 100462). Information integration promotes technology and knowledge transmission across the industrial chain [15] (p. 138848), enhancing communication between companies and their stakeholders to facilitate technical value creation [16] (p. 123897). Leading new energy vehicle manufacturers such as BYD (Guangdong Province, Shenzhen City, China) collaborate with universities to translate laboratory battery research into mass-produced automotive technologies and leverage intelligent in-vehicle systems to collect user feedback for product optimization [17] (pp. 287–304). Despite such practical observations, existing research lacks longitudinal evidence explaining manufacturers' staged value evolution from independent technological R&D to open industrial technology sharing.

The prior literature on technological and sustainable innovation splits into two siloed research streams with prominent theoretical limitations. One strand solely focuses on how R&D of core technologies drives corporate performance without linking such technological progress to the iteration of sustainable business models [18] (pp. 346–374). The other strand independently investigates the design of sustainable business models yet overlooks the endogenous iterative logic of proprietary core technologies owned by firms [19] (pp. 6716–673). Multiple systematic reviews centering on circular economy and sustainable business model innovation indicate that few scholars have constructed integrative analytical frameworks to dissect their co-evolutionary relationships. Most extant studies merely test their isolated linear correlations, failing to elaborate staged interactive circulation mechanisms between the two [20] (pp. 6182–6209). Second, scholars rarely examine the transition of proprietary core technologies from firm-exclusive assets to cross-industry shared resources, overlooking the dynamic circulation mechanism of technological value within manufacturing ecosystems [21] (p. 116414).

Against this backdrop, this paper puts forward its core research question: How can manufacturing enterprises construct sustainable business models relying on self-developed core technologies and realize equitable industrial-wide sharing of technological value? To answer this question, we select BYD, a representative new energy vehicle manufacturer with fully independent core technologies, as the longitudinal single-case research object. Grounded in knowledge interaction theory, this study adopts the Gioia analytical framework to investigate two core dimensions: how core technologies drive sustainable business model innovation, and how sustainable business model innovation unlocks the full value of core technologies. Beyond the traditional value logic of “value proposition, value creation and value capture”, this paper further develops a sustainable value circulation paradigm encompassing value creation, value elevation, and cross-boundary value dissemination. This research yields three marginal theoretical contributions: it constructs a co-evolutionary

framework integrating core technologies and sustainable business models; it refines the three-stage knowledge interaction mechanism of knowledge traction, utilization, and recombination; and it enriches the theoretical system of value co-creation and distribution within digital industrial ecosystems.

2. Theoretical Background

2.1. Knowledge Interaction Drives Core Technological Breakthroughs

Intertemporal knowledge interaction within enterprises fosters the co-evolution of stakeholders and drives multi-dimensional knowledge exchange [22] (p. 23638). The knowledge interaction framework depicts dynamic knowledge flows among internal R&D teams, supply chain partners and cross-industry participants, covering knowledge generation, absorption, recombination and spillover, and highlights two-way iterative exchanges between heterogeneous subjects [23] (pp. 497–527). Embedded in this framework is a three-stage logical chain of “application innovation–technology development–value sharing”. This chain delivers tiered knowledge interaction across external market participants, internal and upstream–downstream supply chain stakeholders, and cross-industry actors: application innovation advances market-demand-oriented product iteration and realizes two-way external knowledge interaction between firms and market participants; technology development integrates scattered practical experience via sustained R&D and forms proprietary core technologies through intra-firm and supply-chain knowledge interaction; value sharing opens mature generic technologies to the whole industry and enables bilateral interaction featuring technical knowledge spillover and reverse feedback across cross-industry participants [24] (pp. 355–380).

In dynamic and complex environments, robust knowledge interaction mechanisms enable innovation systems to pursue dual objectives: technological advancement and breakthroughs in core technologies [25] (p. 6328). Knowledge evolution stimulates technological innovation, raising product development efficiency and reinforcing competitive strength; knowledge recombination addresses critical technical bottlenecks, optimizes industrial structures and enriches user value [26] (pp. 698–723). Continuous knowledge sharing and interaction accelerate technological innovation to produce disruptive breakthroughs. Knowledge iteration reshapes innovation paradigms and feedback loops, transforming enterprises’ internal resource circulation modes [27] (pp. 1414–1443). These transformations propel business model innovation and organizational adaptation, underpinning long-term sustainable competitive advantages [28] (pp. 315–362). Ultimately, breakthroughs in core technologies bolster long-term enterprise viability and facilitate the open commercialization of core products to sustain ongoing value creation.

The extant literature has examined how knowledge drives corporate development, yet it generally overlooks the evolutionary path from generalized technologies to critical proprietary core technologies [29] (pp. 789–798). The impacts of digital and emerging knowledge interaction and recombination on core technological breakthroughs remain insufficiently explored [30] (p. 102905). Against the backdrop of the digital-intelligent economy, this paper takes the evolutionary path through which enterprises achieve core technology breakthroughs by leveraging knowledge interaction as its core research entry point.

2.2. Core Technologies Empowering Business Model Innovation

Digital transformation and iterative industrial knowledge evolution restructure traditional business paradigms and the value creation trajectories of manufacturers underpinned by proprietary core technologies [31] (p. 101890). Core technologies constitute non-imitable proprietary assets that dominate pivotal industrial links. Iterative advancement of such technologies remodels internal operational workflows, supply chain coordination systems

and cross-industry collaborative architectures, thereby overhauling enterprises' fundamental operational frameworks [32] (p. 124289). Against the backdrop of digital-intelligent transformation, manufacturing firms have shifted the focal point of market competition from standalone product competition to integrated sustainable business model innovation. Enterprises deprived of differentiated proprietary core technological capabilities fail to cultivate enduring sustainable competitive advantages [33] (pp. 1484–1513). Elaborating the endogenous coupling mechanism between core technologies and business model innovation carries pivotal theoretical and practical implications for the long-term resilient development of manufacturing entities.

Core technologies empower sustainable business model innovation across three foundational dimensions: participating stakeholders, organizational network structure, and value circulation logic, with concrete implementation layers covering value proposition design, industrial network architecture construction, and profit allocation mechanisms. Intelligent manufacturing facilitates the standardization and full digitization of corporate internal resources, enabling enterprises to formulate diversified strategic innovation pathways [34] (p. 8081). Stakeholder synergistic collaboration and personalized digital service systems elevate end-users' perceived value and facilitate multi-party joint technological value co-creation [35] (pp. 574–587).

The extant literature has empirically validated the causal influence of core technological breakthroughs on business model evolution; nevertheless, prior scholarship fails to unpack the complete endogenous driving mechanism of core technologies within digital-intelligent industrial scenarios [36] (pp. 1367–1392). Throughout the whole lifecycle of core technology R&D and industrial commercialization, firms are required to integrate internal and external heterogeneous resources to develop sustainable business models aligned with their long-term strategic positioning. Such strategic reconstruction broadens market coverage, boosts overall profitability, and optimizes the sustainability of corporate operational systems [37] (p. 124947). Further in-depth scholarly investigation is therefore warranted to dissect how iterative core technologies reconstruct the underlying logic of industrial innovation and establish equitable benefit distribution norms within multi-stakeholder industrial ecosystems.

2.3. Sustainable Business Model Innovation

Platform-based business models are capable of delivering economic gains for manufacturing enterprises, yet they inherently incur latent risks of platform monopolization [38] (pp. 2728–2740). Monopolistic behaviors dampen firms' incentives for technological innovation, undermine the fulfillment of corporate social responsibility commitments, and jeopardize the long-term sustainable interests of both focal enterprises and all ecosystem stakeholders [39] (p. 7071). Against this backdrop, firms must integrate foundational sustainability tenets into the architectural design of their platform operation frameworks from the outset [40] (pp. 5661–5680).

Sustainable business model innovation (SBMI) draws theoretical underpinnings from the triple bottom line paradigm, which systematically reconstructs firms' value propositions, multi-stakeholder value co-creation networks, and industrial benefit allocation mechanisms [41] (pp. 1477–1506). Distinct from conventional profit-oriented business models that prioritize singular economic returns, SBMI centers on the synergistic generation of economic, social, and environmental value. Enterprises ought to internalize heterogeneous stakeholder demands into routine operational governance and co-generate enduring technological value through sustained knowledge interaction and exchange [42] (pp. 1440–1459), [43] (p. 104949).

SBMI mandates that enterprises concurrently capture economic surpluses while delivering technological value to a broad spectrum of stakeholders—including internal employees, upstream and downstream suppliers, and governmental regulators—and further translate unmet market pain points into viable sustainable business opportunities [44] (pp. 217–240), [45] (p. 139294). Multilateral constraints imposed by interconnected stakeholders force firms to strike a balance between collective shared industrial benefits and long-term corporate growth trajectories, which in turn fosters interdependent value co-creation ecosystems [46] (p. 988). Following this operational logic, SBMI advances equitable technological value distribution across industrial boundaries and enables cross-boundary technological sharing spanning the entire industrial chain. Digital-intelligent transformation functions as a critical enabler that underpins the long-run sustainable deployment of proprietary core technological competencies and facilitates collaborative technological value spillover within industrial ecosystems.

Extant scholarly works merely incorporate sustainability notions as superficial additions to traditional business model elements, without unpacking the full sequential process of technological value creation, circulation and sharing driven by iterative core technological breakthroughs [47] (pp. 1794–1804). SBMI constitutes a holistic system-level innovation instead of a marginal supplementary extension to platform business models, encompassing two core functional orientations [48] (pp. 2296–2311). First, it consolidates enterprises' enduring operational foundations through large-scale, sustainable commercialization and deployment of proprietary core technologies. Second, it remodels the pathways governing the creation, circulation and cross-boundary sharing of technological value by leveraging digital-intelligent toolchains and infrastructure. In-depth dissection of the endogenous mechanism via which core technologies empower SBMI can effectively remedy the prominent theoretical gaps identified within this research domain.

3. Method

3.1. Research Approach

Our study adopts a longitudinal single-case study design integrated with the Gioia methodology [49] (pp. 15–31). This combined method is appropriate for three reasons:

1. The research is exploratory in nature, focusing on the complex relationships among core technologies, sustainable business model innovation, and technological value sharing, which requires in-depth and systematic case investigation;
2. The co-evolution of core technologies and business models is a long-term process. A longitudinal design supports continuous tracking of key events and causal mechanisms.
3. The single-case design is suitable for analyzing typical enterprises with rich empirical evidence, enabling comprehensive description and rigorous theoretical construction [50] (p. 137050).

3.2. Case Presentation

BYD Company Limited is a leading global manufacturer and core technological innovator within the new energy vehicle industry. Founded in 1995, the firm initially specialized in rechargeable batteries. It formally entered the complete vehicle manufacturing sector in 2003 via the acquisition of Qinchuan Automobile, by which time it had grown into the world's second-largest supplier of rechargeable batteries.

This study selects BYD as an extreme and revelatory single case on three grounds:

First, outstanding case representativeness. BYD has achieved self-developed breakthroughs in industrial pivotal core technologies and is widely recognized as a benchmark brand for sustainable clean-energy transportation. It has obtained an AA ESG rating, the

top tier among domestic vehicle manufacturers, rendering it a paradigmatic enterprise delivering iterative sustainable business model innovation.

Second, sufficient data accessibility. The firm has persisted in long-term technological R&D and innovative practice; it has deployed digital simulation engines to overcome bottlenecks in core technologies for four years, with the relevant technical solutions commercialized for three years. A wealth of chronological, multi-angle archival and interview materials has accumulated throughout this long-term practice, supporting rigorous longitudinal qualitative analysis.

Third, unique theoretical particularity and critical value. Unlike most firms that only partially realize technological value circulation, BYD has comprehensively undergone the full evolutionary chain: independent core technology breakthrough, internal industrialization, and cross-industry shared value realization. Its ecosystem covers diversified multi-stakeholder participants, including suppliers, downstream partners, end consumers and industrial policy institutions. This complete evolutionary trajectory provides critical empirical evidence to supplement and revise the existing fragmented theoretical frameworks on technological value sharing, thus carrying strong theoretical enlightenment and critical significance for this research field.

BYD's business model features continuous iteration and sustainable evolution, manifested in three core dimensions. The firm maintains intensive R&D investment, leverages digital simulation tools to achieve breakthroughs in multi-domain core technologies, and establishes a vertically integrated industrial knowledge system. Positioned as a clean-energy-oriented sustainable brand, BYD has attained an AA ESG rating. Furthermore, the enterprise translates proprietary core technological advantages into shared industrial value, constructing a sustainable ecosystem with coordinated participation of multi-stakeholder groups [51] (pp. 495–527).

3.3. Data Analysis and Quality Assurance

To guarantee the reliability, construct validity and credibility of qualitative findings, this study implements multiple quality control strategies in accordance with canonical case study standards [52] (pp. 243–267). First, data triangulation. This research integrates three distinct categories of data sources, including more than 50 pieces of internal corporate documents, over 100 sets of public industrial materials, and five semi-structured interviews with senior executives. All interviewees have long participated in corporate strategic decision-making and technological iteration, possessing systematic cognition of the firm's full-cycle developmental trajectory; their professional experience and strategic judgments are further corroborated by official public media reports. Cross-verification is conducted across multi-source data, and conflicting information is re-examined against original raw materials until full data convergence is reached.

Second, investigator triangulation. The first two authors independently complete full coding of all raw data following the Gioia paradigm. When the inter-coder reliability falls below the threshold of 0.80, the third author participates in group discussions as an impartial third-party arbitrator to unify coding criteria and resolve subjective discrepancies, ensuring objectivity and consistency of coding outputs.

Third, member checking. The complete coding system covering first-order concepts, second-order themes and aggregate dimensions is submitted to two senior managers of BYD for factual verification. Their feedback confirms the high accuracy and integrity of the coding logic, stage division and mechanistic interpretation proposed in this study.

Fourth, longitudinal temporal validation. The dataset of this research spans 2003 to 2025, sufficiently reflecting the long-term evolutionary trajectory of the firm's tech-

nologies and business models, and effectively mitigating the retrospective bias prevalent in cross-sectional research [53] (pp. 1–13).

The above multi-layered quality assurance mechanisms jointly consolidate the solid data foundation, standardized analytical procedures and trustworthy research conclusions of this paper. Detailed information on multi-source evidence is summarized in Table 1. (This table summarizes all original self-collected data sources of this case study. Encoding A, B1 and B2 are self-designed classification labels for internal data sorting, rather than markers of the external literature citation markers data (A) and internal corporate documents (B1) are kept confidential for privacy and corporate information protection; all materials under Code B2 are publicly available resources with accessible official website links.)

Table 1. Multiple sources of evidence.

Methods	Semi-Structured Interviews	Internal Documentation Analysis	Public Data Research
Period	2022–2025	2003–2025	2003–2025
Source	We conducted single 50–90 min interviews with senior managers familiar with BYD’s full development trajectory using a multi-doctor revised protocol centered on this study’s core themes. (This study selects senior executives as exclusive interview respondents based on the research theme positioning. Since the research focuses on the enterprise’s top-level strategic evolution of core technology opening and industrial value sharing, senior managers who participate in group strategic planning, R&D resource allocation and industrial ecological layout can provide systematic, long-term and holistic cognitive information matching the longitudinal case analysis demand. To avoid research scope divergence, grassroots technicians, suppliers and end users are not included in the interview scope of this paper.)	unpublished internal documents	Annual Reports; Public Media Reports; White Papers; China Automotive Technology and Research Center Co., Ltd. (Tianjin, China)
Amount of Data	Five interviews with the co-founders	>50 external conferences and internal company reports	>100 Resources Related to New Energy Vehicles
Encoding	A	B1	B2

To sort out milestone events for timeline construction, all validated interview and archival materials were arranged chronologically. Three screening criteria were adopted to identify pivotal turning points: breakthroughs in core technology R&D, large-scale restructuring of sustainable business models, and major adjustments to industrial ecological layout. For inconsistent time nodes or event descriptions across separate data sources, repeated cross-checks against original raw materials were carried out until unified factual conclusions were reached. All confirmed landmark incidents were ordered sequentially to form the complete evolutionary trajectory of BYD’s core technologies and sustainable business model innovation illustrated in Figure 1 (see Figure 1).

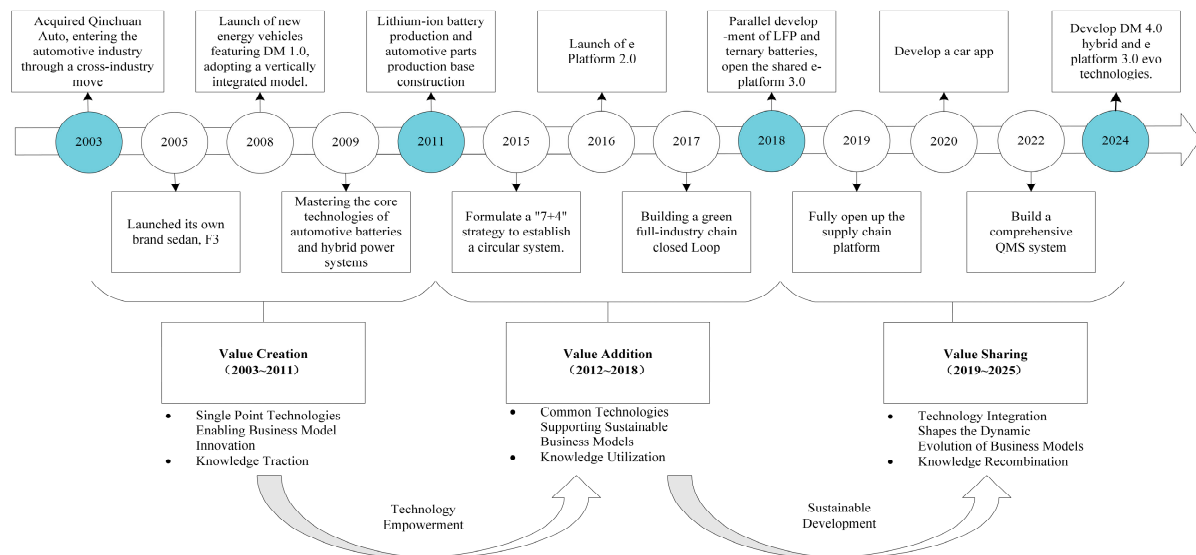


Figure 1. BYD's sustainable business model innovation development journey.

4. Results

This section is divided into two parts. The first part elaborates on the evolution of BYD's business model in detail, clarifying the temporal and contextual boundaries of the case study. The second part explains the data structure (see Figure 2) by deeply analyzing each key emerging concept and cites typical remarks from interviewees as evidence to ensure transparency in the data-to-theory conversion process.

4.1. Implementation Path of BYD's Technology Sharing

4.1.1. Single-Point Technology-Driven Value Creation (2003–2011)

(1) Fundamental Support of Technology. In 2003, BYD diversified into the automobile sector. Drawing on its mature consumer battery technologies, the firm gradually shifted its R&D focus to the three core electric systems of new energy vehicles: batteries, motors and electronic controls. BYD invested hundreds of millions of yuan in the R&D of its No.316 prototype vehicle, which was completed in 2004. Outdated design and poor market compatibility triggered uniformly negative feedback from internal dealer evaluations. The whole project was terminated to prevent damage to brand reputation.

Drawing practical lessons from this independent R&D failure, BYD revised its R&D logic. It benchmarked and disassembled mature mass-produced vehicles available on the market, then launched the cost-effective F3 sedan in 2005. This model delivered the company's first breakthrough in passenger vehicle sales. This strategic transformation was supported by proactive upstream resource arrangements. Such measures included equity investments in lithium resources and the construction of dedicated lithium iron phosphate production bases. During this phase, BYD steadily boosted resource utilization efficiency. By 2011, its industrial water reuse rate hit 82%, and the recycling rate of waste pole pieces reached 91.3. These figures effectively cut raw material and manufacturing costs.

The firm maintained consistent high-intensity R&D investment. Its R&D workforce expanded from 1200 employees in 2003 to 18,700 in 2011. Its R&D intensity consistently outperformed the automotive industry average, with over 5% of annual revenue allocated to technological research each year. Sustained R&D efforts enabled BYD to master key technologies for vehicle batteries and hybrid powertrains. In 2008, the F3DM equipped with the first-generation DM1.0 dual-mode hybrid system was launched. It achieved an urban fuel consumption of 3.7 L per 100 km, with 41% lower carbon emissions than conventional fuel vehicles of the same class. Cumulative sales from 2008 to 2011 reached 43,700 units,

delivering tangible carbon reduction outcomes. BYD's technological innovation covered the full spectrum of product development and manufacturing processes. It deployed semi-automatic human-machine collaborative production lines and a unified Product Data Management (PDM) system. This setup shortened vehicle development cycles by 32% and simultaneously accumulated product technology and manufacturing capabilities.

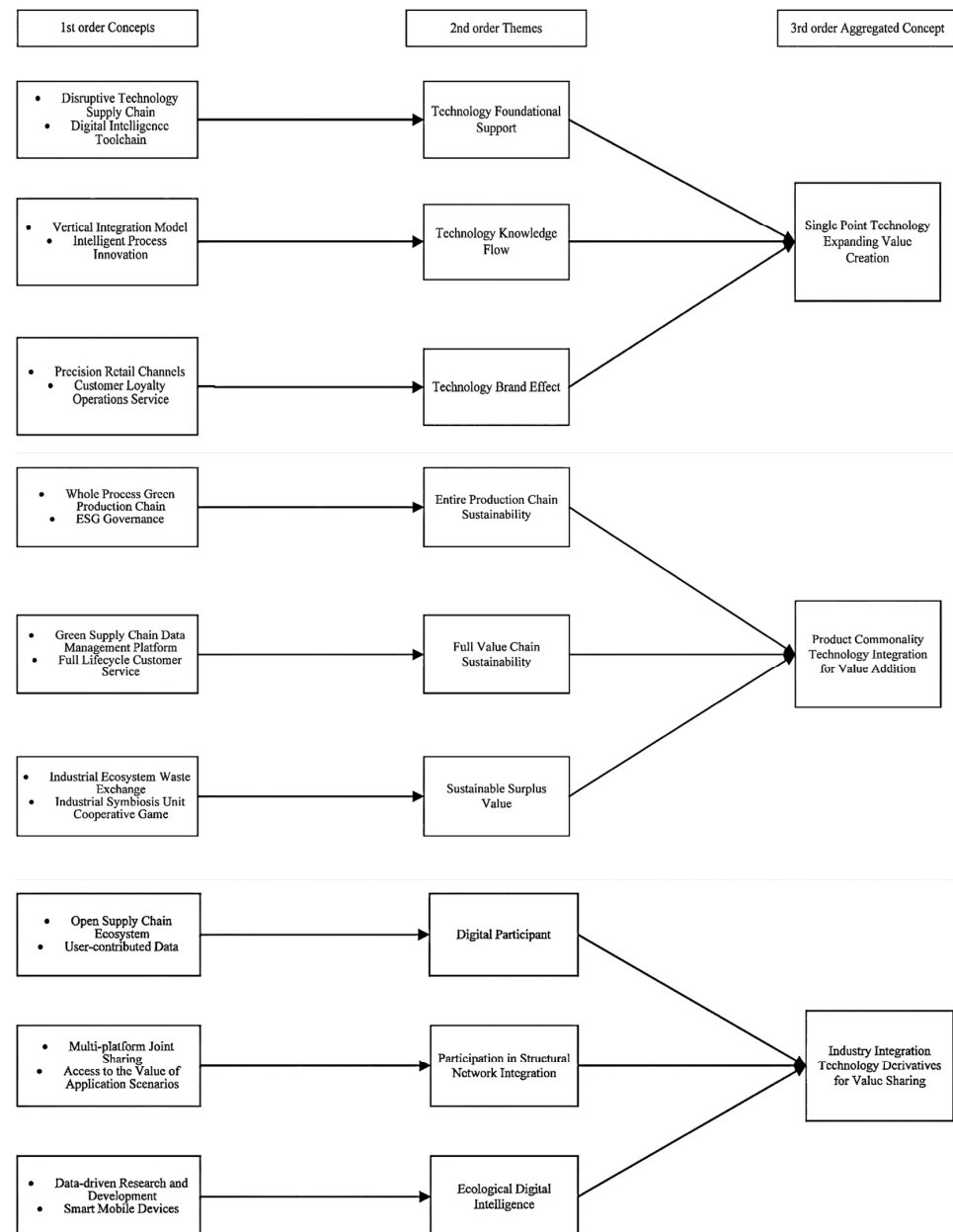


Figure 2. Data analysis structure diagram.

The technical reserves built in this period laid a solid foundation for subsequent flexible production line renovation and digital upgrading. This view aligns with existing research, which confirms that early technical reserves underpin the application of flexible manufacturing in the automotive industry [54] (pp. 1144–1159). Facing unstable market environments, BYD iterated materials, processes, and product technologies steadily. This stable technical iteration ensured continuous and reliable technical output during market fluctuations.

(2) Knowledge Flow of Technology. Breakthroughs in core technologies raised the specificity of automotive components. Starting in 2008, BYD optimized its industrial layout and adopted a vertical integration model. It built a complete industrial chain

covering upstream lithium raw material supply, midstream manufacturing of batteries, motors and electronic controls, and downstream vehicle sales and after-sales services. The vertical integration strategy yielded measurable practical benefits. First, BYD's reliance on external suppliers dropped from 78% in 2008 to 32% in 2011, with 27 self-owned component factories officially put into operation. Independent R&D and manufacturing capacities were significantly strengthened. Second, the internalized industrial chain facilitated information exchange and technical sharing across all links. It reduced technical transaction costs and generated basic economies of scale.

BYD also standardized upstream supply chain management. In 2010, it released a unified ESG code of conduct for all suppliers. The wastewater compliance rate of core suppliers rose from 86% in 2009 to 100% in 2011. In terms of market response optimization, BYD rolled out a comprehensive digital user feedback system in 2011. The demand response cycle was shortened from 45 days to 18 days, while customer satisfaction scores climbed from 76.2 in 2008 to 88.7 in 2011. Based on the DM1.0 framework, BYD continuously refined its hybrid technology architecture and formed a dual-platform iteration system. The unified platform enabled internal knowledge sharing and technical docking across the industrial chain.

Nevertheless, aggressive vertical expansion and overly ambitious sales targets between 2010 and 2011 sparked a nationwide dealer withdrawal crisis. Unreasonable mandatory inventory quotas and rigid assessment criteria imposed heavy financial pressure on distributors. More than 300 dealers terminated cooperation, leading to a sharp year-on-year decline in the firm's net profit in 2011. BYD summarized lessons from this channel management failure. It established tiered rebate incentive mechanisms for dealers and improved full-industry-chain quality control standards. Meanwhile, the firm adjusted its R&D priorities and allocated more resources to ternary lithium battery technology and intelligent manufacturing process upgrading.

Existing studies mostly focus on general knowledge-driven innovation yet rarely distinguish evolutionary differences between universal automotive electrification technologies and firm-specific proprietary core technologies. BYD's industrial practices verify an evolutionary path: enterprises can evolve from generic basic technologies to proprietary core technologies through systematic technical integration [55] (p. 121007). To meet diversified and upgraded consumer demands, BYD shifted its production and R&D logic toward user value orientation. Optimized matching between market demand and technical supply enabled stable value transmission and sustained improvements in end-user product experience.

(3) Brand Effect of Technology. The independent R&D and manufacturing capacity of China's traditional automotive industry used to lag behind that of Western developed markets. BYD's continuous technical layout in the new energy vehicle sector effectively narrowed the domestic gap in core vehicle manufacturing. The company transformed self-developed technologies into tangible product competitiveness and formed clear market differentiation based on technical advantages. The F3 sedan, launched in 2005, achieved a monthly sales peak of 21,300 units in 2008. It became the first Chinese independent brand sedan with monthly sales exceeding 10,000 units. BYD's cumulative vehicle sales reached 1.12 million units by 2011. Its market share increased from 0.8% in 2005 to 4.3% in 2011. Government procurement further validated the practical value of BYD's new energy products. Central institutions purchased 12,600 BYD new energy vehicles from 2007 to 2008. The application reduced the fuel consumption of official fleets by 38% and enhanced public recognition of the brand's technical practicability. In terms of industrial social value, BYD's industrial chain layout supported 127,000 jobs by 2011. Continuous technical iteration improved product stability and user recognition. The vehicle repurchase rate reached 27.3% in 2011, which was 11 percentage points higher than the average level of domestic independent brands. On the basis of mature internal technical systems, BYD carried out selective external technical

licensing. The output of internal core technologies was standardized to match the operational rules of its supply chain system. The steady accumulation of technical advantages, market recognition, and standardized technical output has gradually consolidated BYD's stable competitive position in the new energy vehicle market (see Table 2).

Table 2. Single-point technology-driven value creation core coding and evidence presentation.

Dimension	Key Constructs	Representative Code	Evidence Examples (Typical Citations)
Single-Point Technology-Driven Value Creation	Fundamental Support of Technology	Reserve of Disruptive Technology Chain	- We consistently uphold the concept of 'Technology First' and make deep layouts and continuous investments in multiple cutting-edge fields. Our technology reserve strategy is a systematic plan for the next 10 years or even longer. (A) - It mainly includes several core areas. First is battery technology, where our Blade Battery technology has achieved breakthroughs in safety and energy density. Second is the electric drive system, where our independently developed DM-i super hybrid technology and e-platform 3.0 both represent disruptive innovations. Additionally, we have important layouts in intelligent driving, automotive-grade chips, new materials, and other fields. (B1)
		Digital Intelligence Toolchain	We have built a comprehensive tooling system covering the entire value chain, including R&D, manufacturing, supply chain, and sales, achieving end-to-end digital collaboration. First, we integrated design tools like CAD/CAE/CAM to support collaborative product design. Second, we implemented a simulation and verification platform that enables performance testing in virtual environments, significantly reducing development cycles. We have also established a unified Product Data Management (PDM) system to ensure design data consistency and traceability. (B2)
	Knowledge Flow of Technology	Vertically Integrated Model	- Vertical integration is one of our core competitive advantages. In the emerging new energy vehicle industry, we have chosen to establish a complete industrial chain layout from core components like batteries, motors, and electronic controls to complete vehicles. This enables us to better control product quality and maintain leadership in technological innovation. (A) - This model has many advantages: first, cost control, as the internal supply chain can effectively reduce overall costs. Second, innovation synergy allows rapid integration of technological innovations from components to complete vehicles. Most importantly, supply chain security means having independent control over the supply of key components. (A)
		Intelligent Process Innovation	- We have built a tool system covering the entire value chain of R&D, manufacturing, supply chain, and sales, and achieved end-to-end digital collaboration. The first is the integrated application of CAD/CAE/CAM and other design tools to support the collaborative design of products. The second is the simulation verification platform, which can perform performance tests in a virtual environment, greatly shortening the development cycle. (B2) - We have also established a unified product data management (PDM) system to ensure consistency and traceability of design data. (B2)
	The Brand Effect of the Technology	Precision Retail Channels	We implement a 'user-oriented, data-driven' retail strategy. Through digital tools and big data analytics, we achieve precise channel layout planning, accurate understanding of user needs, and precise service delivery. (B2)
		User Retention Operations Service	- We consistently uphold a 'user-centric' philosophy, continuously improving the user experience through innovative service systems and operational methods, while fostering brand recognition and loyalty. (A) - We have established a multi-dimensional evaluation system, including metrics such as user satisfaction, repurchase rate, and recommendation rate. Through regular user research and data analysis, we can promptly understand changes in user needs and adjust operational strategies. (A)

4.1.2. Integration of Generic Product Technologies for Value Addition (2012–2018)

(1) Full Production Chain Sustainability. Driven by the knowledge utilization logic, BYD has internalized ESG governance as a constitutive element of its industrial chain governance, establishing a green full-production-chain closed loop anchored by core technologies [56] (p. 104118). This closed loop covers all the links, including upstream lithium mineral raw materials, power battery manufacturing, complete vehicle assembly and retired battery recycling, and realizes the structural coupling of forward resource

utilization and reverse resource regeneration at the material flow level. BYD implements ESG management and control across all production and operation links. From 2012 to 2018, it invested a total of 1.41 billion RMB in three-waste treatment, and all production bases maintained stable pollutant discharge compliance. The photovoltaic power station at the headquarters, which was put into operation in 2016, generates 120 million kWh of electricity annually, lifting the factory's energy self-sufficiency rate to 31%. The rainwater recycling facilities at the Xi'an Base supply 500,000 tons of reclaimed water each year, and the group's industrial water reuse rate reached 94.7% in that year. In 2017, BYD put into operation China's first full-process power battery recycling production line, with a lithium iron phosphate material recovery rate of 95.2% and a non-ferrous metal recovery rate of 98.1%. A total of 112,000 tons of retired power batteries were recycled during 2012–2018, equivalent to saving 236,000 tons of lithium ore resources. The corporate carbon intensity per ten million RMB operating revenue kept improving, falling from 32.6 tCO₂e in 2012 to 24.15 tCO₂e in 2018, with a cumulative decline of 25.9%. All production workshops cut volatile organic compound (VOC) emissions by 1740 tons in 2018.

Official SGS carbon footprint certification data indicate that the full life cycle carbon footprint of the BYD Yuan UP ranges from 93.05 to 138.68 gCO₂e per kilometer, which is far below the general benchmark of 200 gCO₂e/km for equivalent fuel-powered vehicles. The retired battery recycling segment delivers negative carbon benefits, reducing the overall full-life-cycle carbon emissions of a single vehicle by approximately 22%. Two long-term environmental indicators tracked in BYD's annual ESG reports further demonstrate its continuous pollution reduction performance. First, the group's industrial water reuse rate rose steadily from 94.7% in 2018 and remained above 95% throughout 2019–2025, drastically curbing the exploitation of fresh water resources. Second, the lithium iron phosphate recovery rate of the dedicated battery recycling line increased from 95.2% in 2018 to 95.6% in 2025, continuously alleviating the ecological pressure caused by mineral extraction and solid waste disposal. Standardized LCA calculation results and continuous quantitative ESG indicators jointly verify that the stage of generic product technology integration can continuously generate environmental value via closed-loop manufacturing systems. Meanwhile, LCA tests conducted by CATARC verified that the full-cycle carbon emission of the DM3.0 hybrid system is 189 gCO₂e/km, 43% lower than that of fuel vehicles with the same displacement.

While the industry did not start paying close attention to ESG rating indicators until 2020, BYD had rolled out systematic low-carbon layouts as early as 2012 and embedded sustainability into the underlying operational logic of its production system. The “reverse productivity” generated after core technologies empower flexible production lines is reflected in the bidirectional closed-loop iteration between technical systems and production processes. Flexible production lines enable two-way data interaction between R&D and manufacturing departments. Automated control and intelligent logistics systems monitor full-process product quality and feed operational data back to technology R&D and process design in real time. The parallel advancement of lithium iron phosphate and ternary battery technology routes facilitates the continuous optimization of generic battery technologies, upgrading the sustainability of production chains from scattered technical breakthroughs to the establishment of systematic technical foundations.

(2) Full Value Chain Sustainability. Full value chain sustainability represents the systematic extension of the production closed loop into the digital-intelligent dimension. The digital-intelligent process chain of “green production chain management—supply chain management—user service management” constructed by BYD is centered on the synergistic coupling of internal control and external service. Internally, the green supply chain data management platform enables the standardization of internal value chain information flows and the precision of decision-making. BYD built a unified digital management framework covering green manufac-

turing, supply chain supervision and user service. By 2018, the DiChain platform covered more than 8000 primary suppliers. The platform required all partners to complete carbon inventory accounting and formulate carbon peaking implementation plans. Intelligent logistics route optimization reduced carbon emissions per unit of goods by 46%. Externally, the evolution from e-Platform 2.0 to the open sharing of e-Platform 3.0 marks BYD's transformation of closed proprietary knowledge assets into generic technological resources accessible to heterogeneous actors, thereby breaking through the constraints of firm boundaries on the transmission of sustainability at the level of knowledge governance [57] (p. 114606). The upgrade from closed e-Platform 2.0 to partially open e-Platform 3.0 eliminated internal knowledge barriers within the supply ecosystem. From 2016 to 2018, the DiLink intelligent cockpit collected 2.7 billion pieces of user feedback data, supporting 19 rounds of DM hybrid system iteration. The penetration rate of personalized vehicle configuration rose from 11% in 2016 to 34.6% in 2018. The construction of the DiChain supply chain information platform embeds digital tools into supply chain governance, reshaping the trust structure and institutional arrangements between the firm and its cooperative suppliers through contract digital capital flow transparency. To stabilize cash flow for upstream suppliers, BYD capped supplier payment cycles at 130 days. Technology spillover brought a cumulative profit increase of 7.2 billion RMB to upstream component manufacturers from 2012 to 2018. Green procurement rules demand that all suppliers provide full social insurance coverage for all employees. The full-path autonomous industrial chain built upon DM3.0 core technology, together with the DiLink intelligent connected system, transforms users from passive service recipients into active value co-creation nodes: structured data streams generated by user behavior are continuously fed back into R&D and service processes, achieving a closed-loop coupling of demand sensing, service customization, and technology iteration. The "Future Fund" policy alleviates user concerns regarding uneven local subsidies at the institutional level, extending value chain sustainability from the technological operational level to institutional safeguards at the governance level.

(3) Surplus Value Sustainability. Surplus value sustainability reflects a paradigmatic shift in sustainable business models from value creation and capture toward value sharing and regeneration. BYD's internal technology sharing platform distributes redundant technical capacity to industrial chain partners, shifting the logic of value distribution from closed appropriation to open industrial empowerment at the institutional level [58] (pp. 4561–4580). At the physical dimension, the "material re-manufacturing—battery re-manufacturing—vehicle manufacturing—power battery recycling" circular system jointly established with GEM Group endows decommissioned traction batteries with the economic attribute of active resources. The cooperation delivered a 62% residual value recovery rate for retired power batteries. The cascade energy storage business generated 3.16 billion RMB in operating revenue from 2015 to 2018 and cut solid waste discharge by 87,000 tons. In 2018, BYD recycled 160,000 tons of waste aluminum, lowering annual upstream carbon emissions by roughly 142,000 tons. The formulation of the "5-4-2" strategy and the "7 + 4" strategy defines the direction and pathway for surplus value reallocation at the strategic level. At the level of industrial boundary expansion, the "New Energy Vehicle+" concept and the "Electric-Future" initiative, grounded in the modular characteristics of the core technology platform, systematically integrate technological surplus with complementary assets through cross-industry collaboration with heterogeneous actors such as Huawei. By 2018, BYD licensed general DM hybrid technologies to 12 non-automotive enterprises and launched 37 joint R&D projects, lifting partners' overall energy efficiency by 28.3%. Modular technology only enables limited cross-industry resource coordination within the cooperative network. This enables sustainability transitions from a firm-specific capability to a co-evolutionary driver of the

industrial ecosystem, ultimately enabling resource interoperability and value appreciation among cross-industry actors (see Table 3).

Table 3. Integration of generic product technologies for value addition core coding and evidence presentation.

Dimension	Key Constructs	Representative Code	Evidence Examples (Typical Citations)
Integration of Generic Product Technologies for Value Addition	Sustainability Across the Entire Production Chain	Full-process Green Production Chain	- We have strict environmental standards for our suppliers. From raw material procurement to manufacturing, everything must comply with environmental requirements. (A) - We also help suppliers implement technical improvements to reduce energy consumption and emissions. This is our important initiative to promote sustainable industrial development. (A)
		ESG Governance	- While creating economic value, we are committed to maximizing environmental benefits and social value. (B2) - We implement a ‘green development’ strategy that covers the entire product lifecycle. In production, we invest substantial resources in clean production transformation, build photovoltaic power facilities, and promote waste recycling. All our new factories adopt green building standards and have established comprehensive environmental management systems. (B1)
	Sustainability Across the Full Value Chain	Green Supply Chain Data Management Platform	- We have developed an intelligent supply chain management platform that integrates multiple modules, including order management, inventory management, and logistics management. Through big data analysis, we can accurately predict demand and optimize inventory levels. Meanwhile, the application of blockchain technology ensures transparency and traceability of supply chain information. (B2) - With the current emphasis on sustainable development, the green transformation of supply chains has become an inevitable trend. Our supply chain platform is also undergoing green innovation. (B2)
		Full Lifecycle User Service	- We have built a ‘full lifecycle’ user operation system. From pre-purchase interactive experiences and professional services during the purchase process to continuous post-purchase care, we have formed a complete service loop. Particularly through digital means, we can better understand user needs and provide personalized services. (B2) - For example, we have created a digital product experience system. Through AR/VR technology, users can gain in-depth understanding of vehicle features online. Our intelligent advisor system provides personalized recommendations based on user needs. Meanwhile, we also offer professional new energy vehicle replacement evaluation services to help users make optimal choices. Our one-stop car purchase service includes comprehensive support such as insurance, vehicle registration, and charging pile installation. (B2)
	Sustainable Surplus Value	Industrial Chain Ecosystem Resource Exchange	- We have established a comprehensive battery material recycling system. Production scrap and defective products can be reprocessed and reintegrated into the production flow through professional treatment. We have also developed innovative material purification technology to improve the quality of recycled materials. Through platform matching, these recycled materials can efficiently circulate between different factories. (A) - We adopt an ‘energy cascade’ model. For example, excess heat from high-temperature processes can be used for low-temperature processes or office heating. (A)
		Cooperative Game of Industrial Symbiotic Units	- We have established close partnerships with upstream battery material suppliers, power battery manufacturers, as well as downstream charging station operators and automobile dealers. (A) - We have built an open innovation platform where all parties can share R&D resources and conduct joint research. (A)

4.1.3. Value Sharing Derived from Industrial Technology Integration (2019–2025)

(1) Digital Participants. Digital-intelligent technologies serve as a critical technological foundation for new energy vehicle industry participants to maintain operational stability. Currently, intelligent manufacturing and remote collaboration have become core approaches for firms to address manpower constraints and ensure the operation of the entire chain covering design, supply chain, manufacturing, marketing, and after-sales services. Firms engage in the market along the knowledge linkage chain of “technology digitalization—supply chain opening—user participation in data construction,” thereby forming a value innovation structure with technology as the key driving factor and co-creating technological value with participants including users, employees, and the internal environment [59] (p. 9290).

Digital operation platforms support stable cross-industry chain coordination. BYD opened its supplier technology platform in 2019, shifting its strategic focus from internal technology absorption to selective external technology licensing. BYD’s new energy passenger vehicles faced tight market supply, which pushed component suppliers to expand production and accelerated the full opening of its supply chain system. This transformation from passive technology introduction to active technology export lifted the operational management capacity of power battery suppliers and reserved growth room for other value-chain partners. By the end of 2025, BYD had authorized core three-electric technologies to 47 vehicle and component manufacturers, which effectively cut the average R&D expenditure of cooperating enterprises.

BYD relies on data systems to analyze user demands, divide consumer groups, and carry out targeted product positioning and personalized service matching. Vehicle intelligent terminals collect massive user operation data annually, and over 100,000 core users take part in vehicle function real-world testing. When user feedback from automotive mobile applications reflected market demand for stronger power and lower fuel consumption, BYD accelerated powertrain R&D and launched the 1.5 TID integrated drive assembly. Models built on the fifth-generation DM hybrid system, including the Qin L DM-i and Seal 06 DM-i, reach a WLTC fuel consumption of 2.9 L/100 km under low-battery conditions; the optimized version further reduces the figure to 2.6 L/100 km. Calculated based on the 3.6 million DM hybrid vehicles in stock in 2025, this hybrid system generates steady annual fuel savings and carbon emission reductions.

As of October 2025, BYD’s cumulative global sales of new energy vehicles surpassed 12 million units, yielding substantial total CO₂ equivalent emission reductions. Emission reductions generated solely in 2025 occupied a notable share of the annual emission reduction increment of China’s passenger vehicle sector. However, divergent demands among multiple stakeholders limit large-scale, full-industry spillover of technological value. The fragmented nature of stakeholder demands constitutes a potential constraint on the sustained output of firm value. By transforming discrete data resources into systematized data capabilities and aligning them with the diverse needs of participants within the industrial ecosystem, firms can provide knowledge resource support for technology integration innovation and technology value sharing within the ecosystem [60] (p. 101771).

(2) Networked Participation Structure. Since 2021, China’s automotive industry has achieved breakthroughs in intelligent connected technologies. Some autonomous vehicles developed through collaborations between firms and technology institutions have entered the consumer market, propelling the industry into a new development stage characterized by intelligent connectivity [61] (p. 5880). Digital-intelligent technologies endow new energy vehicles with attributes such as autonomous driving, intelligent cockpits, and the intelligent Internet, driving knowledge recombination in three dimensions: “overall structure—application scenario—mobile space.”

Mass-produced intelligent connected vehicles were formally launched after 2021. BYD constructed an integrated full-digital QMS covering MES, PLM, WMS, LIMS, closed-loop platforms and data acquisition modules, realizing full-lifecycle traceability of power battery quality data. Key production equipment achieves full digitalization and full networking. Through cross-domain joint development of motors, electronic controls and reducers, as well as cross-department collaborative design, BYD developed a three-in-one electric drive platform covering power specifications of 40 kW, 70 kW, 120 kW and 180 kW, matching power, acceleration and climbing demands of all vehicle series. Platformized powertrain development enables all models to share R&D design outcomes and intelligent manufacturing resources. The Frigate 07 SUV, launched in 2022, provides two pure electric range variants: 100 km and 200 km, covering medium–short pure electric commuting and long-distance hybrid travel demands. BYD also signed technical service agreements with China Software International to develop intelligent connected vehicle mobile terminals, pushing the participation structure toward deeper intelligent networking.

BYD built an industrial collaborative network covering 13 categories of raw materials, 29 types of auto parts and 8 mobility service formats. From 2019 to 2025, the firm delivered 216 joint R&D projects and co-formulated 41 national and industrial technical standards. The total quantity of self-operated and shared charging piles exceeded 1.2 million units in 2025. The layout of shared mobility services integrates new energy vehicles and charging infrastructure, expanding industrial chain scenarios to vehicle manufacturing, charging operation and battery recycling. Shared mobility vehicles raise average annual single-car mileage and cut carbon emissions per passenger kilometer. Networked collaboration only releases scale economic benefits within internal cooperative partners.

This indicates that the networking of participation structure is not merely an outcome of technology R&D, but rather a systematic realization path through which firms embed technological capabilities into multi-scenario applications and release knowledge recombination and scale effects via platform-based design, cross-domain collaboration, and intelligent terminal deployment.

(3) Ecological Digital Intelligence. Automotive services are deeply integrated into the product system, reflecting the ecological digital-intelligent concept of “product as a service.” Driven by the “new four modernizations” of electrification, connectivity, intelligence, and sharing, the definition of automobiles is transforming from “transportation tools” to “super intelligent mobile terminals,” and the core competitiveness is evolving from single mechanical capability to multi-dimensional software service capability [62] (p. 107135). Firms achieve sustainable technological value creation along the logical chain of “data-driven core technology R&D—smart mobile terminal creation—ecological digital-intelligent upgrading.”

Under the “product-as-a-service” theoretical framework, automobiles evolve into mobile intelligent terminals. In 2025, BYD’s annual R&D intensity reached 7.88%, far above the automotive industry average of 3.1%. BYD continuously allocates R&D funds to differentiated ecological innovation supported by industrial chain data and algorithms. Multi-business data create space for diversified service demands, and data assets are defined as productive factors with economic value, accelerating ecological digital transformation.

The e-Platform 3.0 Evo platform integrates five original global technology clusters and delivers a high automatic parking success rate. Models equipped with this platform carry upgraded intelligent motion control and DiPilot intelligent driving systems. BYD rolled out an open intelligent driving cooperation program, sharing perception and control hardware technologies with industrial partners. By 2025, three production parks had passed national zero-carbon park certification and consumed large volumes of renewable power each year. The enterprise released clear dual-carbon targets: cutting carbon intensity of self-owned factories by 50% by 2030 and realizing full-value-chain carbon neutrality by 2045.

Selective licensing of three-electric core technologies lowers market entry thresholds for small- and medium-sized auto manufacturers. Guided by unified shared recycling standards, the industrial average recovery rate of battery materials grew steadily from 82% in 2019 to 95.6% in 2025. The application of fifth-generation DM technology expands the depth of plug-in hybrid technology, widens product coverage and completes supporting industrial chains, realizing cluster upgrading of core technologies and improvements in vehicle integration performance. On the product basis, BYD launched the “Co-Creation of Autonomous Driving Open Industry Chain Initiative” and further opened vehicle perception and execution hardware, forming an “open + collaborative” industrial ecosystem supported by proprietary core technologies.

Data platforms and modular technology coordinate the value circulation of multiple participants inside the BYD-led collaborative ecosystem. Thus, the essence of ecological digital intelligence lies in using data as a link and platform-based technology as a foundation, driving firms to shift from single-point product manufacturing to systematic service provision covering the entire industry chain, thereby constructing a networked pattern of multi-actor coordination and continuous value generation within the industrial ecosystem [63] (p. 969) (see Table 4).

Table 4. Value sharing derived from industrial technology integration core coding and evidence presentation.

Dimension	Key Constructs	Representative Code	Evidence Examples (Typical Citations)
Value Sharing Derived from Industrial Technology Integration	Digital Participants	Supply Chain System Opening	- Supply chain openness is our important strategic direction. With the rapid development of the new energy vehicle industry, no single company can complete all aspects alone. We need to grow together with partners to create a healthy industrial ecosystem. (A) - We are advancing this on several levels. First, at the technical level, we have opened up multiple core technologies, including blade batteries, to the industry chain. Through technology licensing and deep cooperation, we help suppliers improve their R&D and manufacturing capabilities. (A)
		User Participation in Data Construction	- We adopt a ‘Smart + Interactive’ data collection model. Basic operational data are automatically collected through the vehicle’s intelligent system, while user experience feedback is gathered through app interactions. Particularly during new feature testing phases, we invite core users to participate and provide detailed feedback data. (A) - We maintain regular communication with users. Through deep interaction, we can better understand user needs and develop more popular products. (A)
	Participate in Networked Infrastructure	Multi-platform Joint Sharing	- By integrating the advantageous resources from different platforms, we can provide users with more comprehensive travel solutions while improving resource utilization efficiency. We have launched a ‘scenario-based service’ model. (B2) - Through integrating service capabilities across platforms, we offer users all-scenario solutions. For example, we can seamlessly combine charging, sharing, and financial services to meet users’ diverse needs. (B2)
		Application Scenario Value Integration	We have many car usage scenarios, including smart mobility scenarios, mobile office scenarios, leisure and entertainment scenarios, smart home integration scenarios, etc. Each scenario has undergone in-depth user research to ensure precise fulfillment of user needs. (B2)
	Ecological Digital Intelligence	Data-driven Development	- Through systematic collection and analysis of user data, vehicle operation data, and market feedback data, we accurately grasp user needs, optimize product performance, and improve R&D efficiency. (A) - Particularly during new vehicle testing phases, we deploy more intensive data collection points to ensure comprehensive performance data acquisition. Meanwhile, we also emphasize the collection of market research data to gain deep insights into evolving user needs. (A)
		Smart Mobile Device	- We no longer view cars simply as means of transportation, but position them as mobile smart terminals. Through scenario-based innovation, we continuously expand the application boundaries of vehicles to create more value for users. We have achieved the capability of ‘continuous evolution.’ (B2) - Through OTA technology, we can remotely update vehicle software and functions. Based on user feedback and usage data, we continuously optimize system performance and functional experience. This dynamic upgrade mechanism ensures the constant improvement of vehicle intelligence. (B2)

5. Discussion

Although the three-stage value circulation framework constructed in this study possesses strong explanatory power, other theories are insufficient to fully interpret BYD's evolutionary trajectory from technology monopoly to industry-wide technology sharing [64] (p. 8972). Closed innovation theory only applies to the early stage of vertical integration and independent R&D. It merely explains closed internal R&D behaviors in the knowledge traction phase yet cannot account for BYD's post-2019 strategy of proactive external technology licensing and shared platform construction driven by knowledge recombination and overlooks the ecological technology value spillover generated by technology sharing within a complete full-industry-chain system. Platform monopoly theory mainly focuses on the adverse outcomes of platform rent-seeking, fails to incorporate the coupling logic between industrial policies and staged knowledge spillover, and cannot adequately explain the unique development path adopted by leading Chinese vehicle manufacturers to construct balanced value distribution systems through phased technology opening. Meanwhile, the static analytical framework of "value proposition–value creation–value capture" centers on intra-firm profit capture and lacks analytical logic to interpret cross-stakeholder and cross-industry value distribution enabled by cross-agent knowledge flows.

This study constructs a dynamic, stagewise evolutionary logic driven by three-tier knowledge interaction processes, integrating the distribution of economic, environmental and social value across industrial boundaries. It also fully depicts the complete lifecycle of enterprises transforming from technology monopoly to open industrial knowledge sharing. This paper elaborates on how staged knowledge output and phased technology opening mitigate monopoly drawbacks and realize balanced value distribution across the whole industry.

In the course of corporate development, technological iteration and business model transformation only advance synchronously along a temporal axis. Such synchronicity merely establishes a correlation between the two, which is inadequate for drawing robust causal inferences. Therefore, this paper sets aside superficial temporal phenomena to delineate the causal mechanism from two dimensions: internal transmission logic and external interfering factors.

External contextual factors encompass policy incentives, market expansion, fiscal subsidies, and industrial competition. These factors can modulate the pace and scale of technological value release yet cannot independently drive firms to restructure their sustainable business architectures systematically across sequential developmental stages. Without hierarchically controlled proprietary core technologies, most automotive manufacturers operating under identical external institutional conditions are limited to incremental short-term product adjustments and unable to build a holistic full-industry-chain value circulation system. External factors are therefore precluded from serving as the primary causal driver. For illustration, existing research on CATL solely examines technology licensing confined to the battery segment, which yields only localized knowledge spillover without forming a full-chain technology sharing system covering vehicle manufacturing and downstream vehicle application. Even with sound industrial support policies, established overseas automakers merely adopt closed cross-licensing of patents among limited partners; knowledge flows are restricted to a small group of cooperative firms and fail to generate inclusive cross-industry technological value spillovers across the whole sector.

BYD's stable causal relationship is rooted in the function of knowledge interaction. The iterative upgrading of a firm's core technologies sequentially undergoes three progressive processes: knowledge traction, knowledge utilization, and knowledge recombination. First, knowledge traction, supported by exclusive single-point proprietary core technologies, facilitates enterprises in building vertically integrated industrial systems to realize value creation. Second, knowledge utilization, empowered by the integration of generic product

technologies, enables enterprises to construct complete green full-production chains to deliver value addition. Third, knowledge recombination, enabled by modular and open industrial technologies, allows enterprises to nurture cross-industry collaborative ecosystems to achieve cross-boundary value sharing. (see Figure 3).

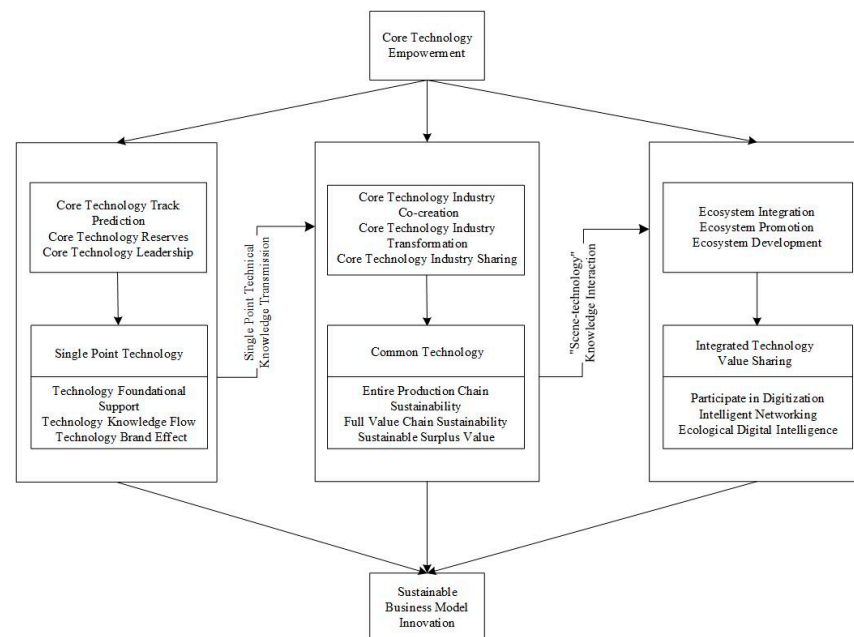


Figure 3. Sustainable business model innovation mechanism.

Key core technologies, characterized by their strategic and long-term nature, constitute the primary source of a firm's core competitiveness and exert a catalytic effect on the expansion of the industrial chain [65] (p. 2980). Accordingly, core technologies persistently act as a fundamental driving force throughout the entire process of sustainable business model innovation. Knowledge flows link all participants within the industrial chain. The industrial chain coordinates differentiated demands from diverse stakeholders and consolidates the foundation for sustainable technological value. Driven by knowledge recombination, the value chain continuously expands the boundary of industrial ecosystems and forms a sustainable development pattern featuring industry-wide shared technological value.

This evolutionary process can be decomposed into three sequential progressive stages. Stage 1: Sustainable design of technological breakthrough directions (Knowledge Traction Stage)—Enterprises conduct foundational research targeting technological bottlenecks arising from market demands. After small-batch trial verification, firms scale up R&D input to build solid technological reserves, which lay the foundational support for subsequent sustainable business model innovation. This stage centers on tackling core technical choke points and capturing initial corporate economic returns, with enterprises maintaining relatively low market share.

Stage 2: Sustainable identification of technology application scenarios (Knowledge Utilization Stage)—Enterprises launch upgraded vehicles embedded with disruptive core technologies to the market, continuously explore and expand diversified application scenarios, and deliver tangible technological value to all stakeholders. The bidirectional expansion of high-performance products and their matching scenarios consolidates the full-industry-chain sustainable layout. Enterprises obtain compound economic and social benefits simultaneously, and their market share climbs to a medium level alongside continuous market expansion and technological iteration.

Stage 3: Sustainable synergy of technology coupling with industrial chains (Knowledge Recombination Stage)—Driven by sustained core technology empowerment and repeated market validation, enterprises develop mature integrated core technologies adaptable to multiple scenarios. On this basis, firms fulfill corporate social responsibilities and elevate user well-being and ultimately realize industry-wide shared technological value within cross-industry collaborative ecosystems. Supported by technology leapfrogging, enterprises reach market leadership and lay the groundwork for the R&D of forward-looking next-generation core technologies.

Independent R&D and breakthroughs in core technologies constitute the decisive driver behind the transformation of China's new energy vehicle industry from vulnerability to global competitiveness; they also serve as the fundamental prerequisite for BYD to fulfill social responsibilities and implement long-term forward-looking missions. Along its battery technology evolution path, BYD has secured successive breakthroughs in Blade Battery and DM hybrid series technologies and holds dominant full-industry-chain core technological advantages. It is the sole domestic enterprise that fully masters complete “three-electrics” systems and disruptive DM-i super hybrid technologies. Supported by digital-intelligent technologies, BYD embeds its proprietary core technologies into a four-dimensional composite product system covering four dimensions: the enterprise itself, stakeholder groups, natural environment, and social environment. This system underpins sustainable business model innovation marked by dual high-value output of robust economic performance and comprehensive social benefits and facilitates multi-dimensional symbiotic sharing of core technological value.

In practical operation, BYD deploys digital simulation engines to parallelize traditional sequential R&D workflows and enhance the iteration efficiency of battery core technologies. BYD also expands its business boundaries to provide integrated system solutions and engineering consulting services and iteratively optimizes its battery technological competence while delivering user-oriented services. Ultimately, BYD co-creates high-quality life value with end users and achieves symbiotic technological value distribution with all industrial stakeholders (see Figure 4).

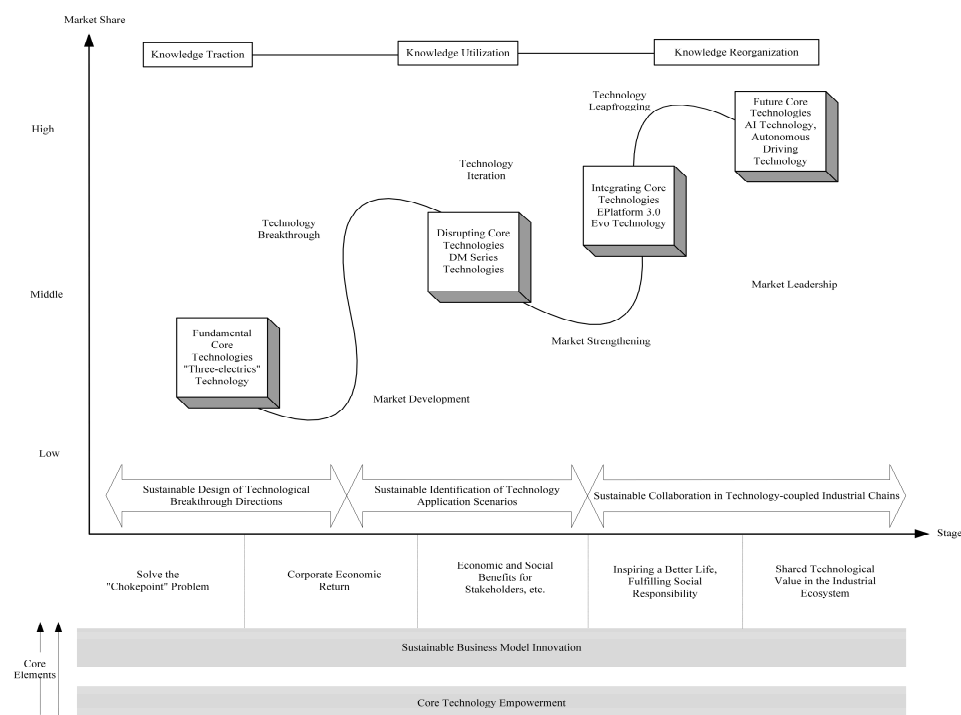


Figure 4. Breakthrough mechanism of the core technology system.

6. Conclusions

Our study adopts a longitudinal case analysis of BYD to systematically investigate the evolutionary path and value-sharing mechanism of sustainable business model innovation empowered by core technologies under China's new energy vehicle institutional background. The results reveal a three-stage development path observed in this specific enterprise within the digital-intelligent economy: single-point technology-driven value creation, value increment through general product technology integration, and value sharing originating from industrial technology integration, which together form a full-lifecycle system of sustainable technological value applicable to this type of domestic integrated new energy manufacturer.

Core technologies jointly drive sustainable business model innovation along the innovation chain, industrial chain and value chain. On the innovation chain, persistent R&D consolidates the technical foundation; on the industrial chain, diverse stakeholder demands are coordinated and resource allocation is optimized; on the value chain, the industrial ecosystem expands its boundaries to realize value symbiosis among multiple participants. Through three knowledge interaction processes including knowledge traction, utilization and recombination, the enterprise's core technologies transform from exclusive proprietary assets into common technologies shared by the industry, and eventually evolve into technologies integrated into the industrial ecosystem—an evolutionary path formed under local industrial conditions.

Accordingly, its value logic shifts from the traditional paradigm of “value proposition–value creation–value capture” to a localized sustainable framework of “value creation–value addition–value sharing”. In this industrial context, data assets accelerate value circulation, self-controlled core technologies support long-term stable value symbiosis, and the industrial ecosystem coordinates value distribution among all parties. These three elements collectively promote the dynamic iteration of sustainable business models, and the above mechanism is characteristic of China's domestic new energy vehicle industry.

6.1. Theoretical Implications

Distinct from fragmented research separating technological innovation and business model innovation, this study takes knowledge interaction as the analytical framework and fully illustrates the two-way co-evolution path across three stages, filling the research gap regarding their temporal coupling mechanism.

Distinct from single-stage theories, including closed innovation theory and platform monopoly theory, this research covers the full lifecycle of closed independent R&D, modular integration and cross-industry technology openness, and interprets the value reconstruction logic of enterprises shifting from technological monopoly to technological openness. It delivers unique explanatory power for policy-driven technology spillover under China's industrial scenario.

Theoretical contributions: This paper refines the sequential operation mechanism of three-tier knowledge interaction, constructs a three-stage value circulation paradigm suitable for manufacturing sectors within China's industrial scenario, and provides standardized analytical tools for full-chain manufacturing enterprises.

6.2. Practical Implications

6.2.1. Recommendations for Leading Manufacturers

(1) Hierarchical technology control and phased technology opening mechanism: Enterprises shall sustain steady long-term R&D investment to construct a digital simulation R&D system. Internally, technologies are classified into top-confidential underlying core algorithms and standardized modules available for external licensing. Firms shall adopt

three evaluation dimensions (mass production maturity, industrial chain security, and industry supply and demand balance) to implement gradient technology opening. When the supply chain faces bottleneck risks, only encapsulated black-box modules shall be authorized externally to prevent leakage of proprietary core knowledge.

(2) Co-construction of industrial collaborative systems and multi-dimensional value measurement: Enterprises shall sign tiered cooperation contracts with strategic industrial chain partners and build a unified digital collaboration platform equipped with a dispute mediation mechanism. A weighted accounting system covering economic returns, technological innovation gains and ecological benefits shall be established. The input–output ratio of technology sharing shall be calculated regularly to dynamically adjust technology licensing prices and the scope of open technologies.

6.2.2. Recommendations for Stakeholders in the Industrial Ecosystem

(1) Differentiated innovation positioning and platform collaborative participation: Suppliers shall abandon full independent R&D of the underlying three-electric core technologies and carry out applied iterative innovation in segmented scenarios such as echelon utilization of power batteries and lightweight components. They shall proactively access digital supply chain platforms opened by leading manufacturers, participate in the co-construction of user data, and shorten R&D cycles and cut costs by utilizing shared modular technologies.

(2) Embedding into industrial circular networks and standardized benefit allocation: Partners shall fully comply with green production and ESG management standards formulated by leading firms and deeply engage in the closed-loop recycling system covering the full lifecycle of complete vehicles. Tiered revenue-sharing agreements shall be signed with leading manufacturers, and partners shall take part in the formulation of general industrial technical standards to stabilize revenue in segmented markets relying on the industrial ecosystem.

6.2.3. Recommendations for Industrial Policymakers

Form standardized industrial technology licensing and IP balance policies: Policymakers shall formulate unified industry norms for modular core technology authorization, set reasonable royalty rate ranges and licensing term standards for shared generic technologies, and build a balanced intellectual property governance framework that strictly protects enterprises' confidential underlying algorithms while restraining malicious patent hoarding and market monopoly. Meanwhile, deploy special fiscal subsidies to reward leading manufacturers that open mature technical modules to SMEs, reducing the R&D threshold of the whole industry and boosting the spillover of core technological value across industrial chains.

6.3. Limitations and Future Research

This study carries several inherent constraints that deserve explicit discussion. First, the research adopts a single-case design focusing exclusively on BYD, a vertically integrated new energy vehicle manufacturer with full independent three-electric core technologies under China's supportive industrial policies. The staged value circulation mechanism summarized in this paper cannot be directly generalized to SMEs, multinational automakers or manufacturing sectors without complete self-developed core technologies. Second, the dataset only includes five semi-structured interviews with senior executives. Although all informants possess full knowledge of corporate development and their statements are cross-validated with internal and public documents, the limited number of interviewees may restrict the richness of multi-stakeholder perspectives such as grassroots technicians, suppliers and end users, which may weaken the saturation of qualitative data. Third, part of the evidence relies on publicly released corporate materials; undisclosed internal strategic documents and confidential cost data are inaccessible, which may lead to incomplete

observation of hidden risks behind technology sharing strategies. Fourth, the whole analysis is embedded within China's unique institutional and industrial context, and the regulatory, subsidy and industrial chain conditions in other countries will change the incentive logic of enterprises' voluntary technology openness, limiting the cross-national transferability of our findings. For future research, scholars can select enterprises from different countries and regional contexts to conduct replicative tests, so as to examine whether this three-stage value circulation framework remains valid and applicable under alternative institutional settings.

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Institutional Review Board Statement: This study only adopts case analysis and public industry data for research, does not involve minors, does not collect personal names, private information and other sensitive data, causes no physical or psychological harm to any subjects, and has no commercial interest orientation. Therefore, this research is exempt from formal ethical review by the relevant academic management department of Anhui University of Finance and Economics.

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study.

Data Availability Statement: All data used in this study were obtained from public domain resources, mainly including official releases from BYD's official website. Part of the original data and research contributions are available in the article. For additional data access and inquiries, please contact the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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