

Digital Platform Architecture for Collaborative Innovation in Engineering and Industrial Systems

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Abstract

The accelerating convergence of physical production systems and digital computation has elevated digital platforms into the primary coordination infrastructure for collaborative innovation in engineering and industrial domains. This paper presents a comprehensive architectural examination of such platforms, treating them not as monolithic software applications but as evolving socio-technical assemblages that orchestrate heterogeneous actors, data flows, physical assets, and institutional rules. We argue that the capacity for sustained collaborative innovation depends on deliberate architectural choices that reconcile competing tensions: modularity against integration, controlled governance against generativity, and localized efficiency against ecosystem-wide fairness. The discussion develops a multi-layer architectural frame, progressing from infrastructure substrates through data interoperability mechanisms, governance structures, deployment lifecycles, and finally to the long-term policy and sustainability dimensions. Across these layers, the paper identifies critical structural trade-offs, including the coupling between platform cores and application boundaries, the dynamics of boundary resources, the role of semantic integration in enabling cross-organizational learning, and the emergence of algorithmic biases when optimization criteria are not collectively negotiated. Through an analysis grounded in systems thinking, we illustrate how architectural decisions cascade into implications for robustness, security, fairness, and the capacity for evolutionary adaptation. The paper concludes by outlining directions for policy-aware platform engineering that treats collaborative industrial platforms as partially public digital utilities, requiring institutional design to complement architectural design. The synthesis contributes a coherent framework for researchers and practitioners seeking to construct and govern platforms that enable genuine distributed innovation in engineering and industrial systems.

Keywords

digital platform architecture, collaborative innovation, industrial systems, platform governance, socio-technical infrastructure, interoperability, digital twin.

1. Introduction

Contemporary engineering and industrial systems are undergoing a fundamental transformation driven by the pervasive digitization of physical assets, processes, and organizational boundaries. Within this transformation, the digital platform has emerged as the central organizing logic that enables multiple autonomous actors—manufacturers, suppliers,

maintenance providers, engineering firms, and regulatory bodies—to co-create value through shared digital resources. Rather than acting as a single-purpose software product, an industrial digital platform functions as an extensible codebase and associated institutional framework around which an ecosystem of complementary innovations can crystallize [1]. Such platforms rewire the division of labor in engineering collaboration by unbundling traditional vertical integration and recomposing activities through modular, interoperable services [2]. Yet the design and long-term governance of these architectures present deep challenges that are insufficiently addressed by treating them solely as IT projects; they demand a systemic perspective that spans infrastructure engineering, organizational theory, data governance, and public policy.

The motivation for this paper stems from the observation that many industrial platform initiatives fail to sustain collaborative innovation despite substantial initial investments. Failures are frequently attributed to narrow architectural scoping—focusing exclusively on technical interoperability while neglecting governance, incentive alignment, and the evolution of institutional rules. Successful platforms in complex engineering systems, such as those orchestrating multi-tier supply chains or enabling joint digital twin development across firms, require an intricate alignment between modular architecture, decentralized decision rights, and robust socio-legal frameworks [3]. The paper therefore positions the digital platform as a layered, evolving socio-technical system and interrogates the structural trade-offs embedded in each architectural layer. By examining infrastructure, data semantics, governance mechanisms, deployment evolution, fairness, and sustainability in an integrated manner, the analysis offers a holistic framework that bridges engineering system design and collaborative innovation theory. The scope covers industrial platforms in domains including manufacturing, energy systems, construction, and transportation, where cyber-physical integration and multi-stakeholder coordination are paramount.

2. Architectural Foundations and Structural Paradigms

Understanding the architecture of collaborative industrial platforms requires moving beyond the traditional client-server or three-tier software models toward a conception of platform architecture as a set of partitioning decisions that assign functionalities between the stable platform core and the variable complement periphery. The foundational principle of modularity enables heterogeneous firms to contribute innovations without redesigning the platform backbone, but the granularity of modular boundaries is a critical design variable [4]. If modules are defined too coarsely, the platform becomes overly rigid and fails to accommodate specialized engineering workflows; if defined too finely, integration overhead escalates and the platform loses its value as a coordination device. The architecture must also accommodate the profound heterogeneity inherent in industrial systems, where legacy equipment, real-time control loops, and safety-critical functions coexist with data-intensive analytics and machine learning pipelines [5].

A layered architectural model has proven influential in this context. It commonly distinguishes an infrastructure layer providing computational and networking resources, a data and service layer enabling information exchange and semantic interoperability, an application layer hosting domain-specific engineering tools, and an institutional layer encoding the rules of engagement, contracting, and intellectual property management [1]. The cyber-physical nature of industrial systems introduces a further substrate layer consisting of sensors, actuators, and edge devices, which must be represented and managed as first-class architectural components [6]. The digital twin paradigm extends this model by creating virtual

representations of physical assets that synchronize with their real-world counterparts, thereby enabling simulation, predictive analytics, and cross-enterprise asset collaboration [7]. The architectural integration of digital twins into a multi-party platform raises profound questions about data ownership, model fidelity, and the synchronization cadence required for different engineering decisions.

A significant structural tension arises between the desire for a unified, centralized platform and the reality of federated industrial environments. In many engineering sectors, no single actor possesses the authority or capability to impose a monolithic architecture across all participants. Consequently, architectural paradigms are shifting toward systems of systems, federated data spaces, and distributed ledger-based coordination mechanisms that preserve local autonomy while enabling collective intelligence [8]. In a federated architecture, each participant maintains its own platform instance with locally governed data and services, while a minimal shared layer provides cross-organizational discovery, identity management, and coordination protocols. The trade-off between global optimization enabled by centralization and the resilience, privacy, and adoption incentives enabled by federation represents a recurring architectural dilemma that must be resolved contextually based on industry structure, regulatory constraints, and the nature of collaborative work.

The architectural choices also encode assumptions about innovation pathways. A platform designed with stable, well-documented application programming interfaces and software development kits lowers the entry barrier for third-party engineering firms and fosters a wider ecosystem of complementary tools [9]. However, the design of boundary resources involves a delicate balancing act: overly restrictive interfaces stifle emergent innovation, while excessively permissive ones risk fragmentation and compromise the integrity of the platform core [10]. In engineering contexts, boundary resources must not only expose software services but also encapsulate domain-specific physical models, calibration data, and compliance constraints, making their design a deeply interdisciplinary activity that spans software architecture and domain engineering.

3. Governance Mechanisms and Stakeholder Alignment

Governance in industrial digital platforms is the set of mechanisms by which authority, decision rights, and value allocation are structured among platform owners and complementors. Governance is not an afterthought to architecture; rather, architectural partitioning decisions are inherently governance decisions because they allocate the capacity to act and innovate across different stakeholder groups [11]. Effective collaborative innovation depends on a governance framework that balances centralized control required for architectural coherence and security with decentralized autonomy required for domain-specific creativity and responsiveness. In large-scale engineering ecosystems, governance typically operates at multiple levels: the technical governance of code contributions and interface evolution, the organizational governance of partnership agreements and service-level contracts, and the institutional governance of regulatory compliance and liability allocation.

A central governance challenge is the management of platform evolution in the presence of powerful legacy actors and entrenched technical standards. Industrial systems often have lifecycles measured in decades, and existing engineering workflows, certifications, and safety regimes cannot be disrupted overnight. Platform governance must therefore accommodate gradual migration paths, dual-mode operations, and backward compatibility guarantees that reduce switching costs for incumbent participants while gradually aligning them with new digital capabilities [12]. This temporal dimension of governance is frequently overlooked in

platform literature that emphasizes rapid growth and winner-take-all dynamics; industrial platforms must instead internalize a generational perspective that respects physical asset lifetimes and workforce retraining cycles.

The distribution of value and risk constitutes another critical governance dimension. Collaborative innovation platforms generate data and insights that are jointly produced but asymmetrically appropriable. Governance frameworks must define data access policies, revenue-sharing models, and intellectual property arrangements that are perceived as sufficiently fair to sustain participation over the long term [13]. When governance is perceived as exploitative—for instance, when the platform owner uses ecosystem-generated data to compete with complementors—trust erodes and collaborative innovation collapses. Institutional mechanisms such as independent data trusts, participatory decision-making bodies, and transparent algorithmic auditing are emerging as complements to traditional contractual governance in addressing these fairness challenges.

The concept of platform boundary resources further intertwines architecture and governance. The rules governing access to interfaces, the processes for proposing and ratifying changes, and the mechanisms for deprecating obsolete features all shape the evolutionary trajectory of the ecosystem [10]. In industrial contexts, where safety and reliability are paramount, governance must incorporate rigorous verification and validation protocols for third-party modules, requiring close coupling between technical gatekeeping and regulatory compliance functions. The design of certification sandboxes and staged deployment pipelines that allow components to be tested under realistic conditions before integration into safety-critical environments illustrates how architectural infrastructure and governance processes can be co-designed to manage risk while preserving an open innovation aperture.

4. Infrastructure Design, Security, and Interoperability

The infrastructure layer of an industrial digital platform must integrate a highly heterogeneous collection of computational resources spanning cloud data centers, edge nodes on factory floors, embedded controllers on machinery, and mobile interfaces for field engineers. The architectural challenge is to provide a coherent abstraction over this distributed fabric that enables seamless data flows and service compositions while respecting the physical constraints of latency, reliability, and energy consumption imposed by industrial processes [14]. The rise of edge-cloud continuum architectures reflects an attempt to partition computation between centralized facilities optimized for large-scale analytics and distributed nodes optimized for real-time control, with dynamic orchestration that can relocate workloads in response to changing conditions.

Security architecture in collaborative industrial platforms must contend with an expanded threat surface that bridges information technology and operational technology. Cyberattacks on industrial platforms can have kinetic consequences, making security a functional safety concern rather than merely a data protection issue. The architecture must therefore embed defense-in-depth principles, strong identity and access management grounded in zero-trust models, and cryptographic integrity protections that extend from sensor readings to derived analytical outputs [15]. The multi-party nature of collaboration introduces additional complexities: participants may be simultaneously collaborators and competitors, necessitating architectures that can support selective data sharing, verifiable computation, and confidential analytics that reveal insights without exposing raw data. Technologies such as secure multi-party computation and hardware-assisted trusted execution environments are gaining

relevance in this space, though their scalability and real-time performance characteristics remain active areas of research and engineering refinement.

Interoperability is the linchpin of collaborative innovation, as the value of the platform grows with its capacity to connect previously siloed data, models, and workflows. Traditional syntactic interoperability, where systems agree on data formats and communication protocols, is necessary but wholly insufficient. Industrial platforms require semantic interoperability—shared, machine-understandable meaning that enables automated reasoning, cross-domain inference, and the discovery of relevant services across organizational boundaries [16]. The development of industry-specific ontologies, standardized asset administration shells, and semantic descriptions of digital twin capabilities represents a major investment in platform infrastructure that pays dividends through reduced integration costs and increased opportunities for emergent innovation.

Data sovereignty is a particularly acute concern in cross-organizational industrial collaboration. Firms are often willing to participate in data sharing only if they can maintain fine-grained control over who accesses their data, for what purposes, and under which contractual constraints. Architectural patterns such as the International Data Spaces reference model address this by decoupling data storage from data usage, with a clear separation between data providers, data consumers, and intermediary brokering and clearing services [17]. These architectures embed usage control policies directly into the data exchange fabric, enabling enforcement that persists beyond initial transmission. The design of such trusted data sharing infrastructure requires careful alignment between technical mechanisms, legal contracts, and sectoral governance rules, making it a quintessential socio-technical enterprise.

5. Deployment Strategies, Lifecycle Evolution, and Robustness

The deployment of an industrial digital platform is not a singular event but a protracted process of co-evolution between the technical platform, the participating organizations, and the broader institutional environment. Premature attempts to enforce uniform adoption across all participants frequently generate resistance, workarounds, and eventual abandonment. Evolutionary deployment strategies that begin with well-bounded use cases delivering demonstrable value, then expand scope along technical and organizational dimensions as trust and capabilities mature, have proven more resilient in practice. This incremental expansion must be guided by a target architectural vision to avoid technical debt accumulation and path-dependent lock-in to suboptimal integration patterns. The platform architecture must therefore be designed for evolvability from the outset, with explicit provisions for versioning, extensibility, and the graceful deprecation of legacy components [18].

The robustness of a collaborative industrial platform refers to its ability to maintain essential functions and performance levels in the face of disturbances, including component failures, demand surges, adversarial attacks, and changes in the regulatory or market environment. Robustness is achieved not merely through redundancy at the infrastructure level but through architectural strategies that enhance loose coupling, graceful degradation, and the dynamic reconstitution of workflows. In engineering collaborations where work spans multiple organizational domains, a platform must be able to isolate faults and prevent cascading failures while preserving the overall progress of collaborative projects. Mechanisms such as circuit breakers in service interactions, asynchronous communication patterns with durable buffers, and decentralized state management all contribute to this architectural robustness.

Lifecycle management in long-lived industrial platforms must address the tension between stability and innovation. The platform core requires a rate of change that is slow and predictable enough to give complementors confidence, while the ecosystem must retain the capacity to rapidly incorporate new sensing modalities, analytical methods, and regulatory requirements. This tension is often managed through a differentiated architecture where the core platform services evolve at a deliberate cadence governed by community processes, while innovation occurs at the periphery through a marketplace of pluggable modules and services [18]. The distinction between core and periphery is itself a governance decision that must be periodically revisited as technologies mature and the strategic priorities of the ecosystem shift.

Testing, verification, and validation in multi-party industrial platforms present challenges that transcend traditional software engineering. The behavior of the composite system depends on the complex interactions of independently developed components, physical dynamics of equipment, and human decision-making. Creating representative test environments that encompass this heterogeneity is expensive and inherently imperfect. Approaches such as co-simulation frameworks that integrate physical process simulators with software-in-the-loop testing, combined with staged deployment in digital twin environments, offer promising pathways to manage quality assurance without stifling innovation speed [7]. The architecture must explicitly support the instrumentation, monitoring, and tracing necessary to detect emergent misbehaviors in production and to identify their root causes across organizational boundaries.

6. Fairness, Inclusivity, and Policy Implications

As industrial digital platforms assume a more central role in coordinating engineering work, they increasingly function as market-shaping infrastructures whose design has distributional consequences for the participating firms, workers, and communities. Fairness in this context extends beyond nondiscrimination in algorithmic decisions to encompass the procedural fairness of platform governance, the distributive fairness of value appropriation, and the representational fairness of whose interests shape the platform's evolutionary trajectory [19]. The architectural design of a recommender system that matches engineering tasks to suppliers, for instance, embodies implicit criteria about what constitutes a good match that can systematically advantage certain types of firms or geographies. Designing platforms that render these criteria transparent, contestable, and adjustable is an architectural requirement with profound ethical and competitive implications.

The inclusivity of collaborative innovation platforms determines the diversity of knowledge, resources, and perspectives that can be brought to bear on industrial challenges. Architectural decisions about interface complexity, data access granularity, and the cost structure of API access directly impact the ability of small and medium enterprises, startups, and public research institutions to participate meaningfully. High integration costs and opaque governance processes tend to limit participation to well-resourced incumbents, reducing the innovative potential and resilience of the ecosystem overall. A deliberately inclusive architecture might provide low-barrier entry points such as sandbox environments with synthetic datasets, streamlined certification processes for non-safety-critical modules, and tiered participation models that allow firms to engage at different levels of commitment [20].

Policy frameworks for industrial platforms are still nascent and fragmented across sectors and jurisdictions. However, several policy dimensions are becoming clear. Competition policy must grapple with the tendency of industrial platforms to concentrate market power through

data network effects and the control of critical interoperability standards. Data governance policy must negotiate between the legitimate interests of data holders, the societal benefits of cross-organizational data sharing for purposes such as sustainability monitoring and public safety, and the protection of trade secrets [21]. Sector-specific regulation, particularly in infrastructure industries such as energy, water, and transportation, increasingly requires platform operators to provide nondiscriminatory access and to demonstrate that algorithmic coordination does not inadvertently create systemic risks or anticompetitive outcomes.

Looking forward, a growing body of thought argues that certain industrial platforms, especially those providing critical digital coordination infrastructure for entire sectors, should be treated as digital public utilities or at least as entities with special responsibilities [22]. This perspective suggests that platform architecture should be subject to public oversight regarding openness, interoperability, and fair pricing, much as physical infrastructure networks have been regulated. The architectural implication is significant: platforms must be designed from the outset to support auditing, third-party access, and modular substitution of components, preventing the emergence of inescapable proprietary lock-in. The tension between the efficiency of integrated proprietary platforms and the societal benefits of open, contestable architectures will remain a central policy question in the coming decade.

7. Sustainability and Long-Term Viability

Sustainability in industrial digital platforms manifests in two intertwined dimensions: the environmental sustainability of the industrial processes coordinated by the platform, and the organizational and economic sustainability of the platform ecosystem itself. Digital platforms hold exceptional potential to enhance resource efficiency across supply chains by enabling circular economy models, optimizing energy consumption through predictive coordination, and reducing material waste through digital simulation and quality control [23]. However, the energy and material footprint of the digital infrastructure itself—data centers, communication networks, and edge devices—must also be accounted for. An architecture oriented toward sustainability would disaggregate computation based on energy availability, caching and data reduction strategies, and the use of life-cycle assessment data as a first-class input to platform optimization algorithms.

The long-term viability of a collaborative innovation platform depends on its ability to maintain relevance as technologies, regulations, and participant needs evolve. This requires a governance model that can credibly commit to continuity while retaining the adaptability to redirect priorities. Platform architectures that depend on a single dominant commercial sponsor face the risk of abandonment or strategic repurposing when corporate priorities shift, undermining the investments of complementors. Multi-stakeholder governance structures, including industry consortia, cooperative models, and foundations that own key platform assets, offer alternative institutional arrangements that can enhance perceived durability [24]. The architecture must align with the chosen sustainability model, for example, by ensuring that critical platform services have open-source reference implementations and standardized interfaces that prevent single-vendor dependency.

The workforce implications of collaborative industrial platforms also factor into long-term viability. Platforms that successfully augment and empower the engineering workforce by providing accessible tools, shared knowledge bases, and decision-support capabilities are more likely to sustain participation and social legitimacy than platforms perceived as automating away professional judgment and tacit knowledge [25]. Architecture can support workforce sustainability by embedding explanation facilities, skill-aware interfaces, and

learning resources that help engineers transition into new digitally augmented roles. Addressing the socio-economic adjustments triggered by platform-mediated industrial transformation is not merely a matter of corporate social responsibility but a prerequisite for the stable, legitimate operation of the platform over multi-decade lifecycles.

8. Conclusion

This paper has developed a multi-layered analysis of digital platform architecture for collaborative innovation in engineering and industrial systems, moving from foundational architectural paradigms through governance, infrastructure, lifecycle evolution, fairness, and sustainability. The overarching argument is that the capacity for sustained collaborative innovation is not a property that can be added on after architectural and governance decisions are made; it is an emergent outcome of coherent design across these interdependent layers. The architectural partitioning of a platform, the design of its boundary resources, the allocation of decision rights, the mechanisms for trust and security, the strategy for incremental deployment, and the institutional embedding each play a constitutive role in shaping what kinds of collaboration become possible, for whom, and under what conditions.

The analysis highlights several recurring structural trade-offs that must be navigated contextually rather than resolved universally. The tension between centralized efficiency and federated resilience, between sufficient openness to foster innovation and sufficient closure to maintain coherence, and between the stability required for safety-critical engineering and the adaptability required for continuous innovation represents the core architectural dilemmas of the field. A recurring insight is that these technical trade-offs map onto governance and institutional trade-offs, requiring a genuinely interdisciplinary design practice that engages engineers, organizational designers, legal scholars, and domain experts in a shared architectural discourse.

Looking ahead, several directions merit further research and practical experimentation. The integration of formal architectural description languages with semi-formal governance rule representations could enable more rigorous reasoning about the consequences of architectural choices for ecosystem-level properties such as fairness, resilience, and innovation velocity. The development of modular, reusable institutional patterns—comparable to architectural design patterns in software engineering—could accelerate the construction of well-governed industrial platforms without requiring each initiative to reinvent foundational governance mechanisms. Finally, the role of public policy in shaping platform architecture through interoperability mandates, open-access requirements, and sustainability criteria deserves sustained attention, as the architectural decisions embedded in today's industrial platforms will structure competitive dynamics, innovation trajectories, and environmental outcomes for decades. The engineering of collaborative industrial platforms must therefore be understood as an ongoing act of institutional design as much as of technical construction.

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