Digital Twin-Assisted Capacity Sharing and Reciprocity Optimization in Smart Factories

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Abstract

The increasing volatility of global demand and the rising complexity of production systems are compelling smart factories to explore collaborative capacity sharing as a fundamental strategy for improving asset utilization and operational resilience. This paper presents an interdisciplinary study on the convergence of digital twin technology and reciprocity-based governance models to enable optimized capacity sharing across federated manufacturing networks. Departing from conventional transactional resource allocation, the proposed framework leverages high-fidelity virtual representations to enable real-time visibility of machine states, predictive synchronization of capacity surpluses and deficits, and the formulation of dynamic sharing agreements governed by reciprocity principles. We examine system-level architectural trade-offs involving edge-cloud orchestration, industrial interoperability standards, and the integration of legacy equipment. A detailed analysis of reciprocal mechanisms is provided, highlighting how direct and indirect reciprocity, encoded through smart contracts and tokenized reputation systems, transforms distributed capacity sharing into a self-sustaining cooperative equilibrium. The discussion is extended to infrastructure scalability, sustainability outcomes, algorithmic fairness, and the policy implications of cross-enterprise data governance. By synthesizing insights from industrial informatics, behavioral economics, and distributed systems, the paper outlines a comprehensive socio-technical roadmap for digital twin-assisted manufacturing commons. The work underscores that technical capability alone is insufficient; long-term viability depends on embedding robust reciprocity structures that align individual firm rationality with collective welfare, thereby redefining competition and cooperation in the era of hyperconnected production.

Keywords

Digital twin, capacity sharing, smart manufacturing, reciprocity optimization, industrial interoperability, manufacturing commons, cyber-physical production systems.

1. Introduction

The contemporary manufacturing landscape is shaped by an acute tension between the need for highly specialized capital equipment and the relentless fluctuation of market demand. Individual firms, especially small and medium-sized enterprises, often struggle with capacity underutilization during demand troughs while simultaneously facing capacity bottlenecks during peaks. This structural inefficiency has motivated a shift from rigid, vertically integrated production models toward networked, shared-resource ecosystems that can fluidly redistribute manufacturing workloads. The broader sharing economy paradigm, already transformative in mobility and accommodation sectors, is gradually permeating industrial production under the rubric of shared factories and manufacturing-as-a-service. However, realizing efficient capacity sharing among autonomous factories introduces profound coordination challenges that span technical, economic, and behavioral domains. These challenges cannot be adequately addressed by static scheduling heuristics or conventional enterprise resource planning systems, which lack the real-time situational awareness and inter-organizational trust mechanisms essential for dynamic resource pooling.

Digital twin technology has emerged as a cornerstone enabler for next-generation smart manufacturing systems. Originally conceptualized as a virtual mirror of physical products, the digital twin has evolved into a comprehensive, multi-scale simulation environment that continuously synchronizes operational data from physical assets with their digital counterparts through pervasive sensing and communication fabrics [1, 2]. In the context of shared production capacity, a digital twin can represent not merely a single machine but an entire production line or factory module, exposing its instantaneous availability, processing capabilities, energy consumption, and maintenance schedules as a set of queryable, composable digital services. When multiple such twins are interconnected, a federated digital representation of a manufacturing network emerges, within which capacity exchange can be simulated, negotiated, and executed with unprecedented granularity. Extensive reviews of digital twin applications in manufacturing confirm the technology's potential to bridge the physical-to-virtual gap in ways that earlier simulation and monitoring tools could not achieve [3].

Parallel to advances in digital representation, research on capacity sharing has increasingly recognized that the sustainability of collaborative production networks depends critically on the governance of reciprocal behavior. Game-theoretic analyses of capacity sharing among independent factories have demonstrated that cooperative outcomes are achievable when repeated interactions and enforceable commitments are present; without appropriate incentive structures, however, the rational strategy for participants often degenerates into opportunistic free-riding that undermines collective efficiency [4]. The concept of the shared factory as a new manufacturing pattern formalizes these insights by proposing institutional and platform-level mechanisms to support distributed ownership of manufacturing resources [5]. Yet bridging the gap between the virtualized visibility offered by digital twins and the behavioral requirements of reciprocity optimization remains an open challenge. The present paper addresses this gap by developing a holistic framework that treats capacity sharing not as a mere technical data-exchange problem but as a socio-technical system in which digital twins provide the informational substrate and reciprocity-based governance supplies the normative logic. The following sections elaborate the foundations of digital twins for manufacturing capacity representation, examine integration architectures and their trade-offs, dissect reciprocity mechanisms, and evaluate sustainability, fairness, and policy dimensions.

2. Digital Twin Foundations for Capacity Sharing

The effective sharing of manufacturing capacity presupposes a shared understanding of what capacity means in a particular context, how its state evolves over time, and what constraints govern its use. A digital twin that faithfully reflects these aspects must integrate heterogeneous data streams from programmable logic controllers, sensors, actuators, and manufacturing execution systems into a unified semantic model. Industrial communication architectures have undergone significant modernization to support such integration, moving from hierarchical fieldbus structures toward converged Ethernet-based networks that enable seamless, high-bandwidth connectivity from the shop floor to the cloud [6]. The digital twin ingests these data to maintain a live model of each piece of equipment, including its current run status, remaining useful life, tool wear, setup requirements, and energy profile. When applied to capacity sharing, this live model allows a factory to publish a dynamic capacity profile that potential partners can inspect and reserve through automated brokerage protocols, thereby reducing the transaction costs that traditionally inhibit spot-market for manufacturing services.

However, the value of a digital twin in a multi-party sharing network hinges on more than raw data fidelity; it requires semantic interoperability across organizational boundaries. The Asset Administration Shell concept, central to the Reference Architecture Model for Industrie 4.0, provides a standardized meta-model for describing industrial assets in a vendor-agnostic and domain-independent manner [7]. By encapsulating submodels that specify technical functionality, operational limits, and contractual interfaces, the Asset Administration Shell enables digital twins from different manufacturers to discover each other's capabilities and negotiate capacity transfers without requiring manually crafted integration code. The convergence of such standardization efforts with digital twin technology paves the way for a marketplace of manufacturing services where capacity is traded much like cloud computing instances, with the crucial difference that physical execution carries tangible quality, safety, and regulatory implications. Complementary research on the interplay between digital twins and big data analytics has emphasized that the simulated what-if analysis enabled by virtual copies can dramatically improve the accuracy of capacity forecasting and the pre-qualification of sharing arrangements before they are physically enacted [8].

A further foundational consideration is the multi-granular nature of capacity representation. At the finest granularity, a digital twin may represent a single spindle or robotic arm; at a coarser level, it may abstract an entire assembly cell as a capability bundle described in terms of throughput, tolerance, and lead time. The choice of granularity involves a trade-off between fidelity and computational tractability, particularly when sharing networks scale to hundreds of geographically distributed nodes. Furthermore, the digital twin must accommodate not only steady-state capacity but also transient dynamics such as ramp-up periods after changeovers and stochastic breakdowns that must be communicated in near-real time to avoid coordination failures. The integration of these dynamic representations with back-end planning systems enables what-if explorations where a factory can simulate lending a subset of its capacity to a partner while meeting its own primary commitments, thereby moving capacity sharing from an ad hoc remedial measure to a continuously optimized strategic lever.

3. System Architecture and Integration Trade-offs

Deploying a digital twin-assisted capacity sharing platform across multiple autonomous factories raises a series of architectural questions that touch upon compute placement, communication patterns, and system governance. A fully centralized model in which all digital twin instances and the capacity brokerage logic reside in a cloud environment offers advantages in terms of global optimization potential and ease of maintenance, echoing the cloud manufacturing paradigm that abstracts distributed manufacturing resources as a unified service pool [9]. Under such a model, a central orchestrator can gather capacity availability data from every participant, solve large-scale matching and scheduling problems, and disseminate instructions. The chief drawback, however, lies in latency sensitivity and data sovereignty concerns. Many production processes require sub-second control loops that cannot tolerate the round-trip delays inherent in wide-area cloud interactions. Moreover, factory operators are reluctant to export fine-grained operational data to external infrastructures, as this could expose proprietary process knowledge or create competitive vulnerabilities.

To resolve these tensions, a hybrid edge-cloud architecture becomes necessary. In this arrangement, each factory maintains an on-premises edge computing layer that hosts the digital twins of its internal assets and manages local capacity optimization in real time. A subset of aggregated, non-sensitive information is then forwarded to a cloud-based or consortium-governed layer that performs inter-factory matching, enforces reciprocity rules, and maintains a distributed ledger of sharing transactions. The edge layer guarantees that time-critical control decisions remain within the plant, while the cloud layer provides the global coordination needed to discover capacity surpluses across the network. Industrial communication standards such as Time-Sensitive Networking and OPC UA over 5G are gradually maturing to support deterministic data exchange across these layers [6]. The design of such a split architecture must also account for intermittent connectivity and partial network failures, incorporating buffering and graceful degradation strategies that prevent cascading production stoppages when a remote twin becomes temporarily unreachable.

Integration with legacy systems constitutes another pervasive challenge. Many active factories operate with a heterogeneous mix of modern cyber-physical systems and older equipment that lacks native digital communication interfaces. Retrofitting these machines with edge gateways and lightweight digital twin wrappers is often the only practical path, but this introduces semantic gaps that must be bridged through standardized translation layers. The Asset Administration Shell framework can be leveraged here by creating an administrative shell for each legacy asset that exposes a compliant interface to the sharing platform, even if the underlying machine has no concept of such abstractions [7]. The architectural decision of where to run these translation services, whether on the gateway, on the edge server, or in the cloud, further complicates the design space and must be evaluated against criteria of reliability, maintainability, and the ability to support plug-and-produce reconfigurations when sharing relationships change. It is precisely at these integration seams that many industrial digitalization projects falter, underscoring the importance of a well-thought-out architectural blueprint that separates concerns cleanly while preserving the agility to incorporate new participants with minimal friction.

4. Reciprocity Mechanisms and Governance Structures

While technical interoperability establishes the physical and informational preconditions for capacity sharing, sustained participation is fundamentally a behavioral and institutional problem. In the absence of enforceable contracts and trusted norms, individual factories are likely to prioritize their own immediate needs over network-wide efficiency, leading to outcomes that are suboptimal for the collective. The economics of reciprocity provides a powerful lens to understand how cooperation can emerge even among self-interested agents in repeated interactions. Experimental behavioral economics has established that many human and institutional actors exhibit a propensity for conditional cooperation, rewarding generous behavior and punishing defection, which sustains cooperative equilibria over time [10]. The translation of these insights into automated manufacturing systems requires embedding reciprocation rules directly into the capacity sharing platform.

The foundational work on trust and reciprocity in firms' capacity sharing demonstrates that informal reciprocal arrangements, when properly structured, can achieve efficiency levels comparable to those of full contract-based coordination while preserving flexibility [11]. Within a digital twin-assisted ecosystem, such arrangements can be operationalized through smart contracts that automatically track contributions and withdrawals from the shared capacity pool and adjust future access privileges accordingly. For instance, a factory that has consistently lent capacity to partners during past peak seasons may earn priority tokens that allow it to draw on the network's resources during its own surge periods without renegotiating terms. A decentralized reputation system, possibly backed by a permissioned blockchain, can maintain an immutable, tamper-evident record of sharing transactions, enabling the computation of reciprocity scores that serve as digital trust proxies [12]. The integration of blockchain with cloud manufacturing architectures has been shown to provide the decentralized trust infrastructure necessary for multi-party industrial collaborations without requiring a centralized trusted third party, which is often politically infeasible across competing firms.

Governance extends beyond individual transactional fairness to encompass the collective design of sharing rules, admission criteria, and dispute resolution procedures. A purely decentralized market mechanism may inadvertently favor large firms with greater bargaining power, eroding the participation incentives of smaller entities which are often the primary beneficiaries of shared capacity. To counteract this, governance structures may incorporate weighted voting mechanisms or constitutional rules that embed fairness constraints into the protocol itself. For example, a minimum guaranteed share of network capacity could be reserved for qualifying small and medium-sized manufacturers, funded by a small transaction fee collected from all trades. The digital twin environment facilitates the auditing and enforcement of such rules by making the history of capacity offers, acceptances, and actual deliveries transparent to all consortium members while preserving the confidentiality of proprietary process parameters. The interplay between automated reciprocity algorithms and human oversight remains a critical design dimension; purely algorithmic governance may fail to accommodate exceptional circumstances such as force majeure events, necessitating an appeal layer where human stewards can exercise contextual judgment without undermining the overall rule credibility.

5. Infrastructure, Deployment, and Scalability

The physical infrastructure underpinning digital twin-assisted capacity sharing must support ubiquitous, reliable, and low-latency connectivity across a geographically distributed manufacturing base. The advent of 5G wireless technology, with its support for ultra-reliable low-latency communication and massive machine-type communication, is widely regarded as a critical enabler for industrial IoT applications that demand deterministic behavior [13]. A 5G-enabled factory can stream high-frequency sensor data from hundreds of machines to an edge computing cluster that hosts their digital twins, maintaining synchronization within the millisecond tolerances required for closed-loop control. The deployment of private 5G networks further allows a single factory or an industrial park to customize its connectivity fabric in terms of bandwidth partitioning, security policies, and quality-of-service guarantees. When multiple such factory networks are federated into a capacity sharing consortium, the interconnection can be realized through network slicing techniques that create logically isolated, performance-assured virtual networks over a shared physical infrastructure.

Scalability concerns extend beyond communication to the computational demands of maintaining and querying thousands of digital twin instances. The computational load can be distributed by partitioning the global digital twin graph along geographical or organizational boundaries and by employing caching mechanisms that precompute aggregations of capacity availability for matchmaking purposes. The predictive capabilities of digital twins also expand the scalability envelope by enabling capacity trading to be conducted based on forecasted rather than instantaneous states, thereby relaxing the real-time synchronization requirements for non-critical resource allocation [14]. A forward-looking approach might involve a hierarchical federation of capacity brokers wherein local edge brokers handle intra-park sharing, regional brokers coordinate among industrial clusters, and a global broker manages the residual long-horizon exchanges. Each level operates at a different timescale and data granularity, a design pattern already applied in multi-tier cloud architectures.

The practical deployment of such infrastructure must also contend with the heterogeneity of industrial sites and the constraints of brownfield environments. Retrofitting an existing factory with the necessary sensing, edge compute, and security infrastructure demands significant capital expenditure, which must be justified by a credible return-on-investment projection. A phased deployment strategy, starting with high-value bottleneck machines and progressively extending connectivity to auxiliary resources, can reduce the initial barrier. Pilot consortia that bring together non-competing companies with complementary demand profiles have proven to be an effective method for demonstrating tangible benefits before wider adoption. Additionally, regulatory approvals for sharing production data across borders, particularly in sectors such as aerospace or medical devices subject to stringent traceability and confidentiality regulations, must be addressed through technology-encoded data governance frameworks that enforce sharing scopes and usage limits at the digital twin interface layer.

6. Sustainability, Robustness, and Fairness Considerations

Capacity sharing, facilitated by digital twins, carries significant implications for the environmental sustainability of manufacturing. By raising the average utilization rate of capital equipment across a network of firms, it directly reduces the need for redundant machine investments and the associated embodied carbon from manufacturing, transporting, and commissioning those additional assets. Moreover, digital twins can model energy consumption patterns during different production tasks, enabling capacity exchanges to be routed preferentially toward factories with lower carbon intensity or access to renewable energy sources at a given time. This integration of carbon-aware scheduling with capacity sharing extends the optimization objective from purely economic metrics to a multi-dimensional sustainability score, aligning industrial efficiency with climate goals. The sharing of specialized high-value equipment, such as additive manufacturing machines for complex geometries, can prevent the proliferation of underutilized resources that otherwise would operate well below their energy-efficient load ranges, highlighting the circular economic potential of digital twin-governed manufacturing commons.

Robustness in capacity sharing networks describes the ability of the system to maintain its core functionality in the face of disruptions, be they machine breakdowns, supply chain shocks, or adversarial behaviors. The digital twin framework enhances robustness by providing continuous visibility into the health status of all resources in the network, enabling rapid reconfiguration and reallocation of capacity when a node fails. Predictive maintenance algorithms that run within the twin environment can forecast failures before they occur, allowing preemptive load transfers that avoid unplanned downtime for the relying partners [14]. Furthermore, a distributed consensus mechanism for the shared ledger ensures that no single point of failure can compromise the integrity of the transaction history or the reciprocity records. The network graph of sharing relationships should be designed to avoid a hub-and-spoke topology where the failure of a dominant node fragments the entire ecosystem; instead, a mesh-like interconnection with sufficient redundancy can be encouraged through reciprocity weightings that favor diversified partnership portfolios over excessive dependence on a single partner. The resulting economic topology is both more resilient and more competitive, reducing systemic risk.

Fairness is an equally indispensable design parameter. In any multi-agent sharing system, the distribution of costs and benefits must be perceived as equitable to sustain voluntary participation. Algorithmic fairness in capacity allocation involves ensuring that no participant is systematically disadvantaged by the matching and scheduling policies embedded in the platform. Techniques from cooperative game theory, such as the computation of the Shapley value for the contribution of each factory to the collective surplus, can be embedded in the platform's analytics layer to verify that the implicit reciprocity weights do not drift toward structurally biased outcomes [4]. Behavioral experiments in supply chain contracting have confirmed that human decision makers exhibit a strong aversion to disadvantageous inequity and will often sacrifice immediate economic gain to punish unfair behavior [15]. In a fully automated digital twin marketplace, these fairness concerns must be encoded as explicit constraints; for instance, an algorithm might be prohibited from allocating the entire surge capacity of a network to a single high-bidding firm if doing so would leave other loyal members critically constrained. The sharing economy literature further emphasizes that the framing of participation terms and the transparency of allocation rules significantly influence perceived legitimacy and long-term community cohesion [16]. Robustness and fairness, therefore, are not merely ancillary virtues but are deeply intertwined with the sustainability and scalability of the entire capacity sharing paradigm.

7. Policy Implications and Future Research Directions

The emergence of digital twin-assisted manufacturing commons carries profound implications for industrial policy, antitrust regulation, and data governance. Policymakers must navigate the delicate balance between fostering collaborative efficiency and preventing collusion that could harm market competition. The real-time visibility into competitor capacity and demand that digital twins provide, while essential for sharing optimization, could potentially be misused for coordinated output restriction or price signaling. Regulatory frameworks may need to evolve toward a principle-based approach that distinguishes between legitimate capacity pooling and anticompetitive information exchange, perhaps by mandating that sharing platforms implement algorithmic firewall layers that restrict the propagation of strategically sensitive signals to governance-monitored aggregation endpoints. Cross-jurisdictional data transfer rules further complicate scenarios where manufacturing consortia span multiple nations with divergent privacy and industrial data protection regimes. The European Union's emerging data governance initiatives, which seek to create common data spaces for industrial data, offer a potential template but their interaction with autonomous capacity sharing protocols remains an active area of policy exploration.

Future research must delve deeper into the behavioral dynamics of automated reciprocity systems when deployed at scale. While game-theoretic models and laboratory studies such as the exploration of trust and reciprocity in capacity sharing [11] provide foundational insights, field experiments with real manufacturing networks are needed to observe how reciprocity norms evolve when human managers interact with algorithmically generated recommendations. The degree to which factory decision makers accept or override automated capacity sharing proposals constitutes a critical human-in-the-loop factor that could substantially alter the equilibrium properties of the system. Another essential research direction is the application of advanced artificial intelligence techniques, particularly multi-agent reinforcement learning, to enable factories to autonomously negotiate capacity sharing agreements while learning and adapting their reciprocity strategies in response to evolving partner behaviors [17, 18]. This opens a future where digital twins are not passive mirrors but active agents that participate in virtual marketplaces on behalf of their physical counterparts, continuously trading capacity options and futures to optimize multi-objective functions spanning profit, sustainability, and risk.

A further frontier concerns the interoperability of capacity sharing protocols across disparate industrial sectors and geographical regions. While this paper has focused on manufacturing, analogous capacity sharing problems exist in healthcare with expensive diagnostic equipment, in logistics with warehousing and transportation fleets, and in energy systems with distributed generation assets. Developing a cross-domain ontology for capacity representation would unlock new forms of symbiotic sharing, for example, using the thermal load flexibility of a data center to offset the power demand peaks of an adjacent factory. The standardization of digital twin interfaces through international bodies and industrial consortia will be a prerequisite for such expansive interoperability [19]. Simultaneously, research on zero-knowledge proofs and secure multi-party computation applied to digital twin data could address the persistent tension between transparency and confidentiality, enabling capacity matching and reciprocity verification without revealing the underlying sensitive operational data. The synthesis of these technological and governance innovations will define whether digital twin-assisted capacity sharing evolves into a niche efficiency tool or becomes a foundational principle for future resilient, sustainable, and equitable industrial ecosystems.

8. Conclusion

This paper has presented a comprehensive interdisciplinary examination of how digital twin technology can be harnessed to enable optimized capacity sharing and reciprocity-driven governance in smart factories. We have argued that the digital twin serves as an indispensable informational backbone that transforms opaque, siloed production resources into transparent, composable, and dynamically queryable capacity modules. When combined with architectural patterns that respect the heterogeneous realities of industrial plant floor environments, these virtual representations allow capacity sharing to be conducted with a level of real-time awareness and operational granularity unparalleled in previous manufacturing epochs. Crucially, the long-term viability of such networks cannot be secured by technology alone. The integration of reciprocity mechanisms, grounded in behavioral economics and operationalized through smart contracts and decentralized trust infrastructure, is essential to align individual incentives with collective outcomes and to prevent the erosion of cooperative norms. The analysis has further demonstrated that sustainability, robustness, and fairness are not peripheral concerns but central design criteria that must be systematically embedded into the architecture of any large-scale capacity sharing system. As manufacturing ecosystems move toward federated, service-oriented models, the successful marriage of high-fidelity digital twinning with principled reciprocity governance will be a decisive factor in creating industrial commons that are not only technically efficient but also organizationally resilient and socially legitimate. The path forward requires sustained interdisciplinary collaboration among engineers, computer scientists, economists, and policymakers to engineer the socio-technical scaffolds upon which the next generation of collaborative production will be built.

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