Article | Received 23 September 2025; Revised 23 January 2026; Accepted 28 January 2026; Published 14 February 2026
https://doi.org/10.55092/am20260005

Integrating Future Factory-to-Factory (F2F) Manufacturing through System of Systems Engineering (SoSE): a framework for capability beyond constituent systems

Polinpapilinho F. Katina[1,*], Hengtao Tang[2] and Anouar Hallioui[3]

[1] Departments of Informatics and Engineering Systems, University of South Carolina Upstate, Spartanburg, South Carolina, USA
[2] Department of Leadership, Learning Design, and Inquiry, University of South Carolina, Columbia, South Carolina, USA
[3] Department of Energy, Politecnico di Torino, Turin, Italy

* Correspondence author; E-mail: pkatina@uscupstate.edu.

Highlights:

- Unlike traditional monolithic systems, SoS capabilities arise from the dynamic interaction of independently designed, managed, and operated subsystems.
- Integration needs to account for several layers, including physical, communication, service, coordination, and governance.
- Industrial implications for using SoSE to integrate factories include moving from siloed operations to interoperable ecosystems.

Abstract: System of Systems Engineering (SoSE) is an emerging discipline focused on the design, integration, and evolution of metasystems—composed of multiple autonomous yet interdependent systems. These systems of systems (SoS) offer capabilities that exceed those of any individual constituent systems by enabling synergistic coordination, interoperability, and dynamic adaptation across diverse operational contexts. This study pursued three primary objectives: (i) to examine the role of integration in enabling emergent capabilities beyond those of individual systems, (ii) to explore SoSE as a framework for orchestrating Future Factory-to-Factory (F2F) Manufacturing, and (iii) to assess the implications of SoSE to address volatile, uncertain, complex, and ambiguous (VUCA) manufacturing environments. Data for this study were drawn from the Web of Science Core Collection—a globally recognized citation database that informs research evaluation and planning across more than 7000 institutions. Our analysis revealed that SoSE is gaining importance as a unifying paradigm for managing enhanced capability of complex, distributed systems characterized by operational and managerial independence, evolutionary development, and emergent behaviors. Findings indicated persistent challenges across technical, operational, economic, governance, and strategic domains, underscoring the need for holistic integration strategies. In the context of Future F2F Manufacturing, SoSE holds a significant promise for enhancing system-wide coordination, resilience, and adaptability. The study concludes by emphasizing the importance of embedding Systems Theory principles to guide the sustainable and scalable integration of interconnected manufacturing ecosystems to maintain viability.

Keywords: System of Systems Engineering; future manufacturing; interoperability; digital twins; VUCA; cyber-physical systems

1. Introduction

The increasing complexity, dynamism, and interconnectivity of modern technological and industrial landscapes have given rise to a more holistic and adaptive engineering paradigm—System of Systems (SoS). A System of Systems is not merely a large or complex system; rather, it is a configuration of multiple independent and operational systems, each of which is not only capable of functioning on its own to achieve a specific purpose but also can interact to produce emergent behaviors and capabilities not attainable by a single constituent system alone [1]. The U.S. Department of Defense [2] formally defined SoS as "a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities". SoS are characterized by five commonly accepted traits [3]:

- Operational Independence—Each constituent system can operate independently.
- Managerial Independence—Each system is managed separately and may pursue its own goals.
- Evolutionary Development—Systems evolve independently over time.
- Emergent Behavior—New capabilities emerge over time only through system interactions.
- Geographical Distribution—Systems are often distributed over large physical areas.

1.1. Framing manufacturing integration through the lens of SoS

In the context of modern manufacturing, the characteristics of a SoS align closely with the shift toward distributed, digitally connected, and autonomous production ecosystems. Factories today are no longer isolated units; instead, they are part of increasingly complex networks of cyber-physical systems which incorporate advanced sensing, robotics, machine learning, supply chain logistics, and real-time data analytics. Each factory—equipped with its enterprise systems, operational technologies, and decision-making processes—functions autonomously. When coordinated as part of a broader Factory-to-Factory (F2F) manufacturing system, they form a SoS capable of achieving greater efficiency, resilience, and innovation than any individual factory.

The rise of Industry 4.0 accelerates this evolution, driven by the Internet of Things (IoT) and the servitization of manufacturing, which demands integration across platforms, geographies, and domains. Modern manufacturing environments must dynamically respond to Volatile, Uncertain, Complex, and Ambiguous (VUCA) conditions—ranging from supply chain disruptions to rapid shifts in market demand. SoS thinking enables manufacturers to move beyond local optimization and siloed operations toward globally optimized, adaptive, and collaborative manufacturing ecosystems.

In this context, System of Systems Engineering (SoSE) emerges as a critical discipline of Future F2F Manufacturing. It provides the methodologies, tools, and governance structures necessary to design, manage, and evolve complex manufacturing configurations where constituent systems are not centrally controlled by any singular entity, but must still interoperate effectively. SoSE emphasizes interoperability, coordination, scalability, and lifecycle adaptability, making it ideally suited to manage the integration challenges inherent in Future F2F Manufacturing.

By framing manufacturing integration through the lens of SoS, we can better understand how independent systems—factories, digital twins, supply nodes, and maintenance networks—can be designed and coordinated to deliver capability beyond any individual entity.

The transition from standalone manufacturing plants to interconnected, intelligent ecosystems introduces a host of challenges across technical, operational, organizational, and governance domains. While the promise of enhanced efficiency, flexibility, and resilience speaks to the need for integration, the reality is that complex and autonomous systems often bring deeply entrenched barriers to seamless coordination, cooperation, and integration. These challenges are further amplified in SoS contexts, where constituent systems evolve independently and possess their own goals, authorities, and technologies, as evidenced by Katina [4]:

- Heterogeneity of Systems and Technologie: Modern factories operate using a broad mix of equipment, software platforms, protocols, and vendor-specific technologies—many of which are proprietary or legacy-based. This technical heterogeneity complicates data exchange, system orchestration, and interoperability across factories. For example, the integration between a legacy PLC-controlled machining line and a modern MES with IoT interfaces may require custom middleware or data translation layers.
- Lack of Standardized Data Models and Interfaces: The absence of common data standards, ontologies, and interface definitions across industrial platforms prevents accurate and meaningful exchange of information. Differences in data formats, units, semantics, and context create semantic interoperability gaps that impede system coordination. For example, one factory may define "machine availability" differently than another, affecting scheduling and capacity planning at the system level.
- Distributed Control and Autonomy: Unlike centralized systems, SoS involve independently operated entities that may maintain control over their internal functions. This independence—while advantageous for flexibility—poses challenges in achieving global optimization, coordinating joint decisions, or establishing consistent performance standards. This suggests that challenges still exist, such as coordinating production schedules and quality standards across multiple independent factories with different objectives.
- Integration of Legacy Systems: Many factories continue to rely on decades-old legacy control systems, often without internet connectivity or modern Application Programming Interface (APIs). Retrofitting such systems to operate in a connected, intelligent SoS environment can be prohibitively expensive or technically unfeasible. This suggests, for example, that older SCADA systems may lack cybersecurity protections or data export capabilities needed for integration, potentially placing the larger SoS at risk.
- Cybersecurity and Data Governance: As manufacturing systems become more connected, the attack surface expands. Protecting sensitive operational data, intellectual property, and coordination mechanisms across organizational boundaries demands robust, distributed cybersecurity and governance frameworks. Therefore, there remains a challenge of balancing the need for real-time data sharing with confidentiality and data ownership concerns among competitive entities.

- Coordination and Synchronization Complexity: Synchronizing the operations of multiple autonomous systems—each with their own production cycles, constraints, and failure modes—requires sophisticated orchestration algorithms and real-time decision support. Misalignments can cause bottlenecks, delays, or systemic inefficiencies. For example, delays in one factory's output can disrupt the downstream scheduling of another, causing cascading failures.
- Organizational and Cultural Barriers: Beyond technology, organizational silos, differing management priorities, and resistance to change hinder collaborative integration. It is not uncommon for factories to be unwilling to share proprietary data or allow external influence over internal processes. Therefore, there remains a challenge of achieving trust and consensus on shared goals, processes, and value distribution across independent factories.
- Scalability and Evolution Management: In a dynamic SoS environment, constituent systems may be added, removed, or upgraded independently. Ensuring that the overall system can scale, adapt, and evolve without downtime or re-engineering is a major systems engineering challenge. Modular architectures, service-oriented platforms, and version control protocols are thus needed to enable "plug-and-play" integration of different systems into the SoS.

These challenges underscore the importance of adopting a SoSE approach, which is uniquely equipped to handle decentralized coordination, system heterogeneity, and evolving integration requirements in Future F2F Manufacturing ecosystems.

1.2. Future F2F Manufacturing

The accelerating convergence of digital technologies, intelligent automation, and advanced connectivity has transformed manufacturing ecosystems into highly dynamic and networked environments. Within this transformation, the concept of F2F manufacturing is emerging as a foundational element of next-generation industrial architectures—characterized by distributed coordination, collaborative production, and shared decision-making across geographically and organizationally independent factories.

F2F manufacturing refers to the interconnection and integration of multiple autonomous factories into a coordinated production ecosystem, where each factory retains operational independence but participates in system-level activities such as (i) dynamic workload sharing, (ii) joint resource optimization, (iii) collaborative scheduling and supply chain orchestration, and (iv) cross-factory quality assurance and analytics [5,6]. In contrast to traditional linear supply chains, F2F manufacturing adopts a network-centric structure which is more resilient and adaptive to real-time disruptions. Factories act as intelligent nodes within a broader SoS, enabling emergent capabilities such as predictive maintenance across facilities, global performance optimization, and seamless product customization.

Under the umbrella of Industry 4.0, F2F manufacturing is powered by enabling technologies such as Industrial Internet of Things (IIoT) (*i.e.*, Sensors, devices, and machinery connected for real-time monitoring and control), Digital Twins (*i.e.*, Virtual representations of factory assets and processes used for simulation, diagnostics, and decision-making), Edge and Cloud Computing (*i.e.*, Distributing computational tasks between local and centralized infrastructure to enable responsiveness and scalability), and Artificial Intelligence (AI) and Machine Learning (ML) (*i.e.*, Supporting predictive analytics, anomaly detection, and autonomous optimization).

Together, these technologies provide the infrastructure for interoperability, data sharing, and automated collaboration between factories—allowing F2F manufacturing systems to function as dynamic cyber-physical systems capable of adapting to shifting conditions. Moreover, the emergence of VUCA as a defining feature of global manufacturing environments reinforces the strategic need for F2F capabilities as indicated in Table 1.

Table 1. Navigating VUCA Conditions through F2F.

VUCA Element	Challenge	F2F Manufacturing Response
Volatility	Rapid shifts in demand, supply, or production capacity	Real-time load balancing and distributed manufacturing execution
Uncertainty	Disruptions from pandemics, politics, or raw material shocks	Redundant manufacturing nodes and data-driven situational awareness
Complexity	Interdependent global supply chains and technology stacks	Modular system architecture with decentralized intelligence and redundancy
Ambiguity	Incomplete or contradictory data and shifting requirements	AI-supported decision tools and digital twin simulations to promote clarity and transparency

F2F manufacturing adopts a network-centric structure, making factories more resilient and adaptive to real-time disruptions. However, there is a scarcity of literature discussing how SoSE can be used to enable factories to act as intelligent nodes within a broader SoS. SoSE seeks to offer capabilities that exceed those of any individual constituent factory systems. Therefore, the objective of this research is to examine how SoSE can be used as a framework to integrate Future F2F manufacturing. To fulfil this objective, the remainder of this article is organized as follows: Section 2 provides background information on SoS/E and how it can be used to integrate complex systems. It also explores how modern manufacturing can be viewed as a SoS as well as the potential benefits of such a viewpoint. Section 3 discusses drivers for emergent capabilities in SoSE, including interoperability, modularity, and orchestration. Based on these drivers, the implications of SoSE as an integrating framework are discussed for Future F2F manufacturing. Section 4 further elaborates on the implications of using SoSE as a framework for integrating Future F2F manufacturing along industry, policymaking, academic research, and workforce development. Section 5 discusses key research insights and conclusions stemming from the current research effort. Finally, Section 6 articulates streams of research ranging from the need for empirical validation of the framework to developing diagnostic approaches rooted in systems pathologies that allow decision-makers to identify, map, and mitigate systemic weaknesses across technical, operational, and organizational layers of SoS.

2. Background and literature review

2.1. SoSE: System of Systems Engineering

SoSE is a specialized sub-discipline of systems engineering that addresses the design, integration, governance, and lifecycle management of SoS—that is, configurations of multiple, independent systems that collaborate to achieve capabilities that none of the individual systems can achieve alone [3].

SoSE emerged to address increasingly complex challenges in domains such as defense, aerospace, transportation, healthcare, energy, and manufacturing, where systems are no longer developed in isolation but must interoperate across organizational, technological, and geographic boundaries [2]. Traditional systems engineering approaches, which typically assume centralized control and bounded system architectures, are inadequate for managing the distributed, dynamic nature of present and future SoS.

The literature consistently identifies five core characteristics that distinguish SoS from traditional monolithic systems [1,7]:

- Operational Independence of Elements: Each constituent system can operate independently and continue to deliver value even if detached from the SoS.
- Managerial Independence: Constituent systems are developed, managed, and evolved by different stakeholders or organizations with independent governance structures.
- Evolutionary Development: The SoS and its constituent systems evolve asynchronously. New systems may be added, old ones retired, and interfaces modified without system-wide redesign.
- Emergent Behavior: Capabilities arise from interactions among systems—capabilities that no single system possesses in isolation.
- Geographic Distribution: Systems are physically distributed and interact via networks and communication protocols, often across long distances and jurisdictions.

These characteristics necessitate engineering methods that accommodate heterogeneity, decentralization, interoperability, resilience, and adaptability, all of which are central to the SoSE paradigm. A critical distinction between SoSE and traditional systems engineering lies in their assumptions about control, ownership, boundaries, and complexity. Table 2 below summarizes key differences.

Table 2. Comparison between Traditional Systems Engineering and SoSE.

Aspect	Traditional Systems Engineering	SoSE
System Boundaries	Clearly defined and stable	Open, dynamic, and often fuzzy
Governance	Centralized authority and ownership	Distributed governance and stakeholder independence
Development Timeline	Unified and synchronized	Asynchronous evolution of constituent systems
Interoperability	Engineered into a single system	Must be established between heterogeneous, pre-existing systems
Emergent Behavior	Often minimized or controlled	Expected and leveraged as a source of new capability
Lifecycle Management	Managed centrally with unified upgrades	Requires modularity, backward compatibility, and flexible integration
Primary Engineering Focus	Design and optimization of a single system	Coordination, integration, and orchestration across multiple systems

Seminal works by Maier [1], Jamshidi [3], and Boardman and Sauser [8] have laid the theoretical groundwork for SoSE. Recent literature emphasizes additional constructs such as Complex System Governance [9] with focus on the need to align independently governed systems toward common objectives, the Viable System Model [10], used to conceptualize the recursive structure and adaptability of SoS [11], and Dynamic Systems Integration [12], incorporating methods for dealing with architectural evolution, digital thread continuity, and modular scalability. However, from these theoretical underpinnings, the reach to F2F has not been achieved.

A basic search for the term “System of Systems” yields 1312 results in Web of Science. While in Google Scholar, the term “System of Systems” yields 163,000 results. These outcomes lacked both clarity and consistency; additional refinement was required. Accordingly, advanced search functionalities of the selected databases were employed. Although multiple Boolean operators are available (e.g., AND, OR, NOT, SAME, NEAR), this study is restricted to the term “System of Systems” and its closely related variants, such as “System of Systems Engineering”. Table 3 presents the results of enhanced searches for the search term System of Systems” and its variations. These findings and all subsequent searches are current as of 12 December 2025.

Table 3. Comparison of retrieval results between Web of Science and Google Scholar.

Searchers	Terms	Web of Science	Google Scholar
Set 1 search	“System of Systems”	1312	163,000
Set 2 search	“System of Systems” AND “System of Systems Engineering”	64	163,000

Several conclusions can be drawn from this search. However, relevant to current research is that, first, these results are not congruent. There exists a disparity among the databases, as indicated by the outputs of the search for the different terms. However, this is not a surprise since these databases rely on distinct parameters. For instance, unlike Google Scholar, Web of Science is a human-curated database [13]. Second, although approximately 163,000 references initially seem relevant to this study, a closed inspection of the dataset reveals notable inaccuracies. As an example, the set of 163,000 records contains irrelevant materials, including book reviews, published indexes, and redundancies. Third, recalling that one of the aims of this study is to examine the role of integration in enabling emergent capabilities beyond those of individual systems, a handful of peer-reviewed literature was selected. VOSviewer was used to visualize the 64 peer-reviewed literature. The visualization in Figure 1 reveals terms that appear in the most relevant literature, with enhanced “capability” being a key theme in the literature.

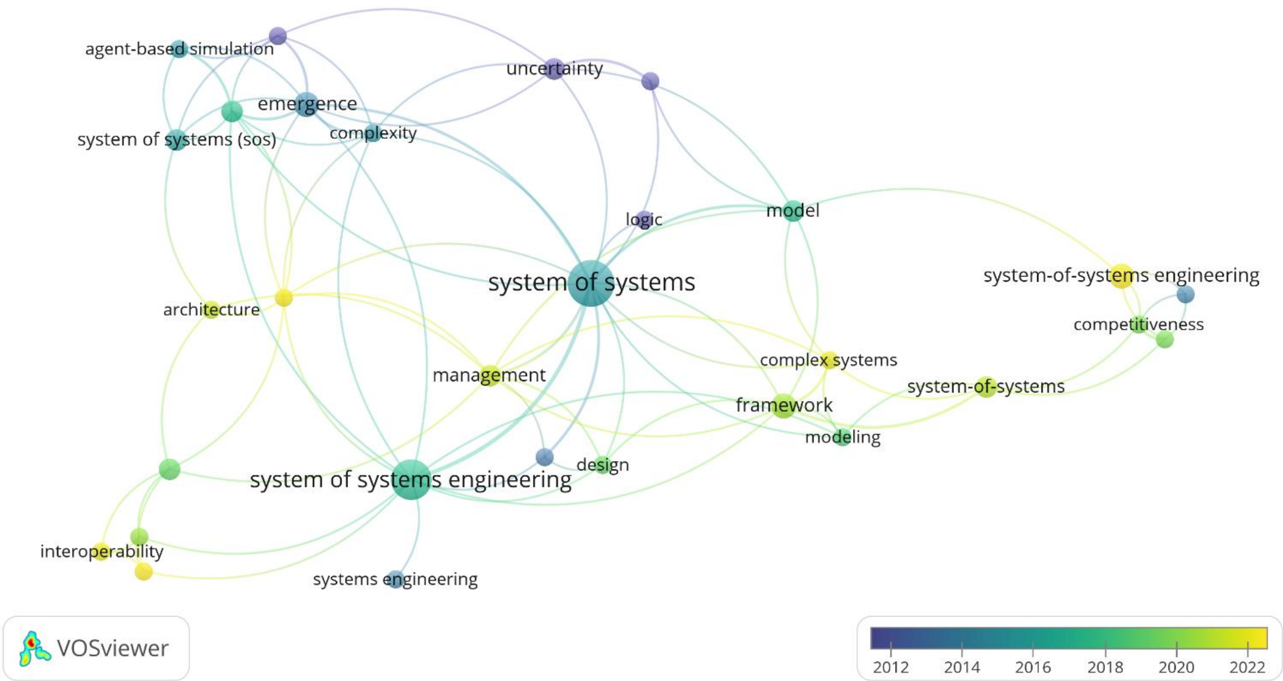

Figure 1. VOSviewer network visualization for co-occurrence and keywords in the literature about System of Systems.

Applications of SoSE in smart manufacturing—particularly under the Industry 4.0 paradigm—highlight its relevance to managing F2F integration, digital twins, real-time analytics, and cyber-physical coordination across global production networks [14]. In fact, we suggest that modern manufacturing environments increasingly resemble SoS in the sense that factories act as autonomous systems that must be dynamically integrated into larger, loosely coupled, interoperable production ecosystems. These systems face VUCA (Volatile, Uncertain, Complex, Ambiguous) challenges and require a shift from optimizing individual facilities to engineering coordination and capability at the ecosystem level. We suggest that SoSE may provide the tools and principles necessary to:

- Engineer interoperability and adaptability across digital supply chains.
- Manage the lifecycle of evolving components and interfaces.
- Support governance structures for multi-stakeholder collaboration.
- Design for emergent performance and cross-factory intelligence.

Thus, SoSE is not just relevant—it is essential—for designing and managing Future F2F Manufacturing Systems of Systems.

2.2. Manufacturing as a System of Systems

Modern manufacturing is transforming isolated, vertically integrated factories toward distributed, digitally connected ecosystems. This shift is catalyzed by advances in cyber-physical systems (CPS), the IIoT, and Industry 4.0. These shifts collectively enable real-time sensing, decentralized control, predictive analytics, and machine-to-machine communication. In this context, manufacturing environments are increasingly best understood not as singular systems, but as SoS—networks of autonomous yet interoperable systems collaborating to achieve capabilities beyond what any single entity can deliver.

As noted by Maier [1] and further extended by Jamshidi [3], a System of Systems is composed of multiple, independently managed systems that are operationally and managerially autonomous, evolve independently, and interact to produce emergent behavior. Manufacturing SoS can include constituent systems such as smart factories, digital twins, supply chain nodes, additive and subtractive manufacturing cells, robotic subsystems, quality control and maintenance platforms, enterprise resource planning (ERP), and manufacturing execution systems (MES). Each of these components (systems) functions independently, yet their integration yields emergent capabilities such as dynamic scheduling, shared predictive maintenance, and adaptive supply chain optimization. From a complexity management perspective, the complexity of manufacturing systems has been a grand challenge since the advent of industrial production due to the growing interdependence among their diverse subsystems and resources [15]. The issue of multiple systems integration and coordination is not new, but still poses a challenge for modern society. Several of these challenged systems (of systems) include:

- Smart Factories and Industry 4.0: The smart factory is a cornerstone of Industry 4.0, defined by its use of automation, connectivity, and data analytics to optimize operations [16–21]. Smart factories integrate CPS with embedded computing, enabling machines and systems to interact with humans and other machines through the internet and real-time platforms.
- CPS: Cyber-physical systems—comprising sensors, actuators, computing devices, and communication technologies—form the technical foundation for autonomous coordination in modern manufacturing. CPS-enabled systems can sense their environments, make decisions, and take actions autonomously [22], thereby allowing distributed manufacturing operations to self-organize and optimize in real time [23–27].

- F2F Manufacturing: More recently, the F2F manufacturing concept has emerged to address the need for multi-factory integration and coordination [5]. F2F manufacturing recognizes that future production networks will involve multiple factories—often geographically distributed and organizationally independent—interacting as participatory peers in collaborative ecosystems. This requires systems engineering approaches that support inter-factory resource sharing, collaborative planning, and real-time interoperability [14,28,29].

Despite technological advancements, integrating manufacturing systems into a cohesive SoS continues to pose multi-dimensional challenges, which can be grouped into three main categories of technical (*i.e.*, knowledge, machines, artifacts, or methods used in industry) (Table 4), semantic (*i.e.*, specific meaning embedded in language or logic) (Table 5), and organizational (*i.e.*, structure, configuration, and processes that support pursuit of purpose) (Table 6) challenges.

Table 4. Technical integration challenges.

Aspect	Description
Heterogeneous Technologies	Factories use diverse hardware and software, often from different vendors and generations.
Legacy Systems	Many facilities still operate legacy PLCs or SCADA systems not designed for IIoT compatibility.
Lack of Common Interfaces	Varying protocols (e.g., OPC-UA, MQTT), data formats, and middleware lead to high costs and complexity in integration.

An example of a technical integration challenge is an attempt to integrate a modern cloud-based MES with a 20-year-old CNC machine lacking a digital interface. It may require custom-developed APIs or retrofit hardware to properly function.

Table 5. Technical integration challenges.

Aspect	Description
Inconsistent Data Models	Different systems may represent the same concept (e.g., “temperature”, “machine status”) using different terminologies, units, or contexts.
Lack of Ontological Alignment	Without shared vocabularies or semantic frameworks, systems cannot interpret exchanged data meaningfully.
Ambiguous Metadata	Incomplete or ambiguous metadata can cause failures in automated decision systems and analytics pipelines.

An example of semantic integration challenges includes a production delay flag in one factory that may be recorded as a binary value, while another uses textual codes to describe the same delay—impeding a shared interpretation.

Table 6. Organizational integration challenges.

Aspect	Description
Decentralized Ownership	Factories often belong to different organizations, making coordinated governance and data sharing difficult
Trust and Confidentiality	Competitive concerns limit willingness to expose internal operational data or cede control to shared platforms
Alignment of Goals	Different factories may have conflicting objectives, operational cultures, or maturity levels for digital transformation

An example of an organizational integration challenge includes prioritization. One factory may prioritize lead-time reduction, while another focuses on cost minimization—complicating joint scheduling efforts.

These integration challenges demonstrate the need for a SoSE approach in manufacturing—one that explicitly addresses aspects of (i) technical interoperability across platforms and standards, (ii) semantic integration using ontologies and standard data models (e.g., AutomationML, RAMI 4.0), and (iii) organizational governance through contracts, protocols, and federated control structures. By framing manufacturing through an SoS lens, stakeholders can better coordinate distributed operations, enable emergent capabilities, and ensure resilience in the face of VUCA (volatile, uncertain, complex, and ambiguous) conditions.

2.3. Viability and resilience in manufacturing SoS

As manufacturing evolves into interconnected ecosystems of cyber-physical, autonomous, and digitally enabled systems, ensuring viability and resilience becomes increasingly essential. These two concepts are interdependent: viability ensures that a system can survive and thrive over time irrespective of shifting contexts and environments [30–33], while resilience enables it to respond to and recover from disruptions [34–39], shocks [40,41], stresses [42–44], external perturbations [45], turbulence/discontinuities [46] or changes [47]. For manufacturing SoS as critical infrastructures operating within multihazard environments, from a holistic design perspective, resilience can be defined as the capacity to prepare for and adapt to changing conditions, and to withstand and recover rapidly from disruptions [48,49]. The recent literature on systemic resilience defines three resilience stages, notably anticipating, coping with, and adapting to disruptions [50]. Manufacturing SoS are vulnerable to disruptions such as external social, economic, and geopolitical changes [51,52] and extreme natural hazards, including distinct high-impact, low-probability (HILP)—severe and unexpected—events (e.g., climate change-induced extreme natural conditions, supply chain cyber-attacks, terrorist attacks, pandemics, and global economic crises) [53–59], introducing volatility and uncertainty [60–63]. Furthermore, regarding the nexus between viability and resilience, Mosayebi *et al.* [64] showed that manufacturing systems' operations are generally vulnerable to material and operational risks due to their reliance on external sources and supply chain networks. Within this nexus, recognizing the creative evolution-driven holistic behavior of SoS—including manufacturing SoS—resilience has long been defined as the ability of a system to effectively adapt to disruptions that jeopardize its operation, viability, or development [65]. In the context of manufacturing SoS, where constituent factories operate independently yet are interlinked, maintaining system-wide coherence and adaptability under volatile and uncertain conditions is both a technical and a governance challenge. Addressing these challenges enhances both viability and resilience.

The Viable System Model (VSM), developed by Stafford Beer [66], provides a foundational cybernetic framework for understanding organizational viability in complex, adaptive systems. VSM posits that a system maintains viability through five interacting subsystems that manage operations, coordination, control, intelligence, and policy. Applied to manufacturing SoS, the VSM enables:

- Recursive structure for governance (*i.e.*, factories nested within regions, divisions, or supply networks), each performing the five essential functions, but through different mechanisms.
- Balance of autonomy (*i.e.*, freedom and independence of decision, action, and interpretation) at the local level with integration (strategic alignment requiring some surrender of autonomy) to be part of a larger system.

- Monitoring and control loops that provide regulatory capacity to support adaptation without invoking centralized command directives.

This suggests that in a network of smart factories, VSM principles can guide the design of coordination mechanisms that preserve each factory's autonomy while enabling system-wide optimization and adaptation (integration).

Complex System Governance (CSG) is an emerging framework, derived in part from the VSM, aimed at managing socio-technical systems characterized by heterogeneity, distributed authority, and emergent behavior [67]. CSG extends traditional governance models by emphasizing:

- Shared accountability across autonomous actors.
- Negotiated decision rights and value flows.
- Adaptive coordination mechanisms rather than hierarchical control.

CSG is particularly relevant to F2F manufacturing SoS, where independent factories must collaborate across organizational boundaries to achieve collective performance and resilience. The CSG framework encourages co-evolutionary governance, stakeholder engagement, and systemic situational awareness. In a regional manufacturing alliance, CSG can support collaborative protocols for resource sharing, data governance, and risk management. Combining VSM and CSG provides a robust theoretical basis for designing and managing a manufacturing SoS that is viable and resilient. This dual focus is essential for the long-term success of F2F manufacturing ecosystems, particularly under the VUCA conditions of modern global industry.

3. Findings and synthesis

3.1. Drivers for emergent capabilities in SoSE

While there are many good works and convergence areas in the SoSE field, there are also several areas of criticism for the current state of the field. For example, Keating *et al.* [68] submit that there is very limited recognition of the distinction between SoS and SoSE and that the definition of SoSE is far from having widespread agreement in the literature. These criticisms may seem to cast a shadow on the value of SoS and SoSE, but they also suggest unrealized potential for the emerging field has not yet been sufficiently addressed, such as offering a mechanism for greater integration of complex systems [69].

In a SoS context, integration is not merely a technical necessity—it is the enabler of emergent capability. Unlike traditional monolithic systems, SoS capabilities arise from the dynamic interaction of independently designed, managed, and operated subsystems. These emergent capabilities—such as distributed optimization, real-time adaptability, and predictive intelligence—can only be realized through sophisticated integration mechanisms that support coordinated behavior across system boundaries [1,70]. These emergent capabilities can be enabled through technical drivers, including interoperability, modularity, and orchestration [4].

Interoperability is the foundation of SoS integration and refers to the capacity of disparate systems to communicate, interpret, and act upon shared data. This includes (i) syntactic interoperability (e.g., use of data standards like OPC UA, B2MML), (ii) semantic interoperability (e.g., shared ontologies or models via RAMI 4.0 or Asset Administration Shell), and (iii) organizational interoperability (alignment of goals, workflows, and governance mechanisms). Interoperability enables real-time system coordination and mutual comprehension, both technically and operationally [14,71]. Without effective interoperability, constituent systems in an SoS act as isolated silos, incapable of achieving the desired level of collective outcomes.

Modularity provides the architectural basis for integrating evolving systems without redesigning the whole. It is meant to allow for new components or factories to be 'plugged' into the larger SoS with minimal disruption, supporting (i) independent upgrades of constituent systems, (ii) reusability of components and interfaces, and (iii) fault containment that enhances system resilience. In essence, modularity facilitates scalability and long-term adaptability, particularly in manufacturing SoS where technology lifecycles vary significantly [72,73]. Modular-based approaches align with the principles of service-oriented architecture and microservices, which enable decoupled yet coordinated operations.

Orchestration involves the dynamic coordination of services, processes, and decision-making across the SoS. In a distributed manufacturing ecosystem, orchestration ensures that (i) systems negotiate roles and tasks (e.g., via multi-agent systems), (ii) resources are dynamically allocated (e.g., through AI-driven scheduling), and (iii) mission-level goals are met while preserving subsystem autonomy. In this case, orchestration can be centralized, decentralized, or hybrid—depending on performance, resilience, and governance requirements [3,74]. Enabling orchestration requires platforms such as digital twins, distributed ledgers, and interoperable APIs.

When interoperability, modularity, and orchestration are engineered into an SoS architecture, constituent systems can collectively generate capabilities—such as predictive maintenance, adaptive logistics, or collaborative production scheduling—that are not achievable individually. Integration, therefore, is not merely technical alignment; it is the engine that manages emergence and strategic advantage in modern manufacturing systems.

3.2. SoSE as a framework for F2F manufacturing

The growing complexity and distributed nature of modern manufacturing systems suggest a SoSE approach—one that supports interoperability, resilience, and coordinated autonomy among independently managed factories. Table 7 provides a possible mapping of SoSE Elements to F2F Manufacturing. In this context, SoSE serves as a powerful engineering and governance framework for integrating multiple cyber-physical factories into a cooperative, value-generating network.

Table 7. Mapping SoSE elements to F2F manufacturing.

SoSE Element	Description in F2F Manufacturing Context	Real-World Alignment
Agents (Constituent Systems)	Independent smart factories, each with its own production capabilities, decision-making authority, and lifecycle.	Automotive plants, contract manufacturers, tiered suppliers
Nodes	Cyber-physical assets and digital infrastructure within and across factories (e.g., machines, robots, sensors, cloud platforms).	PLCs, MES, IoT gateways, digital twins
Coordination Mechanisms	Distributed control protocols, shared scheduling platforms, digital twins, and multi-agent systems for task negotiation and workflow alignment.	API-driven orchestration, federated ERP, ROS or JADE-based MAS
Governance Structures	Models that define rules of engagement, trust, data sharing, and conflict resolution among autonomous entities.	Coalition charters, smart contracts, standards bodies (e.g., OPC UA, ISO 23247)

In the above mapping, SoSE principles are aligned with F2F manufacturing as indicated in Table 8 below.

Table 8. Alignment with SoSE principles.

SoSE Principle	F2F Manufacturing Alignment
Operational Independence	Each factory operates autonomously and can independently fulfill its local mission.
Managerial Independence	Factories are governed by different organizations or corporate entities with distinct goals.
Geographic Distribution	Factories are dispersed globally and connected digitally (e.g., via 5G, cloud, edge).
Emergent Behavior	New capabilities (e.g., distributed inventory balancing, adaptive routing) arise only through integration.
Evolutionary Development	Factories and subsystems upgrade independently, requiring modular, forward-compatible integration.

Integration needs to account for several layers, including:

- Physical Layer: address machines, sensors, production lines (Cyber-Physical Systems).
- Communication Layer: addressing industrial IoT protocols (e.g., MQTT, OPC UA).
- Service Layer: addressing Digital twins, AI optimization agents, analytics platforms.
- Coordination Layer: addressing scheduling engines, MES/ERP integrations, distributed ledgers.
- Governance Layer: address smart contracts, value sharing models, system-of-systems governance (e.g., Complex System Governance).

3.3. Cross-domain implications

There are cross-domain implications of applying a SoSE framework to Future F2F Manufacturing, covering four key domains: technical, operational, economic, and governance [4]. Technical implications are indicated in Table 9 and address issues of interoperability standards, digital twins, and cybersecurity. In this case, SoSE offers a structured path to overcome technical fragmentation in F2F manufacturing ecosystems by emphasizing standardization, integration, and system-level awareness.

Table 9. Technical implications.

Aspect	Implication
Interoperability Standards	SoSE drives adoption of cross-factory standards (e.g., OPC UA, AutomationML, B2MML), enabling seamless machine-to-machine (M2M) and human-to-machine (H2M) communication.
Digital Twins	Integrated digital twins allow each factory to mirror its physical operations while contributing to a federated system-level twin, enabling real-time situational awareness and coordination.
Cybersecurity	Increased interconnectivity expands the attack surface. SoSE frameworks promote layered, distributed security models, zero-trust architectures, and real-time threat detection aligned with cross-factory communication protocols.

Operational implications are indicated in Table 10 and address distributed control, adaptive logistics, and fault tolerance. In this case, SoSE transforms operations from isolated processes to interdependent, adaptable workflows, enabling global coordination and local autonomy.

Economic implications include manufacturing-as-a-service, value-sharing models, and cost, as indicated in Table 11. In this case, the SoSE framework supports new business models and cost structures, reflecting the shift from ownership to shared services and dynamic collaboration.

Table 10. Operational implications.

Aspect	Implication
Distributed Control	Each factory retains autonomy while contributing to collaborative decision-making via multi-agent systems, service orchestration, and decentralized scheduling.
Adaptive Logistics	SoSE enables factories to reallocate tasks dynamically based on real-time demand, capacity, or disruptions—minimizing downtime and enhancing supply chain resilience.
Fault Tolerance	Resilience is increased through redundancy and failover capabilities embedded at the SoS level, allowing one factory to take over if another fails.

Table 12 focuses on governance implications along elements of accountability, ecosystem coordination, and trust mechanisms. Governance in SoSE-driven F2F manufacturing requires novel structures that support distributed authority, shared responsibility, and mutual trust.

Table 11. Economic implications.

Aspect	Implication
Manufacturing-as-a-Service (MaaS)	Factories can offer production capabilities on-demand via digital platforms—monetizing idle capacity and improving utilization.
Value Sharing Models	Revenue and cost allocation must be transparent and equitable across networked factories, especially when collaborating across organizational boundaries.
Cost Optimization	Joint R&D, shared infrastructure (e.g., cloud services), and collective procurement reduce overall cost and risk for participating factories.

Table 12. Governance implications.

Aspect	Implication
Accountability	In decentralized ecosystems, SoSE promotes traceability and auditability through digital ledgers and system-of-systems monitoring tools.
Ecosystem Coordination	SoSE enables coalition-based governance (e.g., federations or alliances of factories), allowing for collaborative rule-setting, resource sharing, and dispute resolution.
Trust Mechanisms	Tools such as blockchain, smart contracts, and common data models foster trust without central control, critical in collaborations involving SMEs, global partners, or competitors.

4. Implications and recommendations

There are implications of using SoSE as a framework for integrating Future F2F manufacturing along industry, policymaking, academic research, and workforce development. In this article, industry implications focus on practical steps for adopting SoSE in F2F contexts. For policymakers, we focus on support for standards and governance models. For academia, we emphasize directions for interdisciplinary research. And for workforce development, we focus on training aligned to SoSE principles. Each implication is followed by a list of recommendations.

4.1. Industry: practical steps for adopting SoSE in F2F contexts

Industrial implications for using SoSE to integrate factories include:

- Manufacturers must move from siloed operations to interoperable ecosystems.
- Legacy systems and proprietary technologies challenge seamless SoS integration.
- Inter-factory trust, data sharing, and collaboration are prerequisites for value creation.

To enable the adoption of SoSE in F2F contexts, the following recommendations are suggested:

- Adopt interoperable platforms (e.g., OPC UA, MQTT, B2MML) to enable real-time machine-to-machine and system-to-system communication.
- Invest in federated digital twin frameworks to enable cross-factory simulations, predictive analytics, and situational awareness.
- Pilot Manufacturing-as-a-Service (MaaS) models to monetize idle capacity and explore new revenue streams through shared production networks.
- Form coalitions or manufacturing consortia (e.g., regional SME alliances) for joint innovation, shared R&D, and cost-effective standard adoption.

4.2. Policy makers: support for standards, governance, and infrastructure

There are also implications for using SoSE to integrate factories for policymakers. These include:

- F2F SoS initiatives operate across jurisdictions and are therefore often lacking aligned policies or governance.
- Data sharing, IP protection, and digital infrastructure remain uneven across regions.
- There is a risk of fragmentation without common frameworks and incentives.

To enable the adoption of SoSE in F2F contexts, the following recommendations are suggested with policymakers in mind:

- Support development and adoption of international standards (e.g., ISO 23247, RAMI 4.0, Asset Administration Shell) for interoperability and compliance.
- Create funding programs to support SoSE-based transformation in SMEs, especially for digital retrofitting and cybersecurity upgrades.
- Facilitate neutral governance platforms or intermediaries for ecosystem coordination, certification, dispute resolution, and compliance monitoring.
- Incentivize shared infrastructure (e.g., digital innovation hubs, common data platforms) that enable cross-factory integration and experimentation.

4.3. Academia: directions for interdisciplinary research

Academic implications using SoSE to integrate factories include:

- SoSE in manufacturing spans systems engineering, computer science, management, cyber-physical systems, and policy domains.
- Gaps exist in theory-to-practice translation, especially for governance and system resilience.

To enable the adoption of SoSE in F2F contexts, the following academic research streams are recommended:

- Advance interdisciplinary SoS research combining systems thinking, AI, control theory, and industrial engineering.
- Develop simulation and testbed environments to model, validate, and optimize F2F SoS scenarios under VUCA conditions.
- Explore emergent behavior modeling, lifecycle co-evolution, and policy implications in distributed smart manufacturing systems.
- Publish open-access training materials, datasets, and SoSE toolkits for industry uptake and continuous academic-practice exchange.

4.4. Workforce development: training aligned to SoSE principles

Adopting the use of SoSE to integrate factories has implications for workforce development:

- F2F manufacturing requires workers who understand system interdependencies, digital tools, and adaptive decision-making.
- Traditional training models do not scale for the agility and interdisciplinarity demanded by SoSE.

To enable the adoption of SoSE in F2F, the following recommendations are suggested for workforce development in mind:

- Adopt a tiered training framework: foundational (systems literacy), intermediate (engineering integration), and advanced (project-based SoS simulation).
- Develop micro-credentialing and certification programs in IoT integration, digital twins, AI-based orchestration, and cyber-physical system management.
- Integrate soft skills training (e.g., interdisciplinary collaboration, systems thinking, communication across organizational boundaries).
- Partner with industry and academia to co-design responsive curricula and hands-on learning aligned to real F2F SoSE environments.

5. Conclusion

This study explored the transformative role of SoSE in enabling integration and coordination across independently operated factories within the emerging paradigm of Future F2F Manufacturing. Three insights from this research are noteworthy:

- SoSE provides the structural, technical, and governance foundations necessary to integrate heterogeneous, autonomous systems in a coordinated ecosystem.
- Emergent capabilities—such as dynamic resource allocation, predictive logistics, and collaborative quality assurance—are only possible through purposeful SoS integration, not achievable by any individual factory in isolation.
- Realizing these capabilities requires addressing cross-domain challenges across technical (e.g., interoperability, digital twins), operational (e.g., distributed control), economic (e.g., value-sharing), and governance (e.g., accountability and trust) domains.

By adopting a layered SoSE framework, industries can unlock greater resilience, agility, and scalability—key traits needed to thrive under conditions of VUCA. This approach enables not only technical interoperability but also facilitates new collaborative business models such as Manufacturing-as-a-Service (MaaS) and federated innovation networks.

Ultimately, SoSE offers a powerful conceptual and operational toolset to transition from isolated smart factories to coordinated, intelligent factory networks, helping industry, policymakers, academia, and workforce leaders collaboratively shape the next generation of resilient, interconnected manufacturing ecosystems.

6. Future work

While this study offers a conceptual and analytical foundation for applying SoSE to Future F2F Manufacturing, several areas remain for further exploration and empirical validation.

6.1. Empirical validation and implementation

Future research should conduct real-world implementation case studies across diverse manufacturing sectors (e.g., aerospace, automotive, electronics) to assess the effectiveness, scalability, and adaptability of the SoSE framework in live operational contexts. Pilot programs and testbeds involving multiple smart factories can demonstrate how interoperability standards, digital twins, and distributed coordination manifest in practice. Research should also focus on evaluating the economic impact and return on investment (ROI) from system-level integration *versus* siloed modernization efforts.

6.2. Simulation and modeling

Development of agent-based, systems dynamics, or discrete event simulations can be used to model emergent behavior, system resilience, and performance trade-offs across F2F SoS configurations. Simulation environments should reflect VUCA conditions and explore how factories respond to disruptions, supply chain volatility, and dynamic reconfiguration scenarios.

6.3. Longitudinal and evolutionary studies

There is a strong need for longitudinal studies to observe the co-evolution of constituent factories and their integration platforms over time. These studies can help understand technical debt, organizational inertia, and innovation diffusion in SoSE-enabled ecosystems.

6.4. Transdisciplinary collaboration

Advancing this field requires collaboration across systems engineers, manufacturing experts, computer scientists, sociotechnical researchers, and policy analysts. Joint efforts should aim to create open-source tools, standards, and shared data sets to accelerate knowledge exchange and technology transfer.

6.5. Metasystem concept in manufacturing SoS

Building on foundational work in Management Cybernetics [10,66,75], the metasystem is conceptualized as the set of coordinating functions (*i.e.*, policy, development, operations, and coordination) that oversee and manage the interaction between autonomous components within a larger system. In the context of SoSE for F2F manufacturing, there remains a need to investigate how metasystem structures may enable situational awareness across distributed factories through shared digital twins and sensor networks, provide feedback and control mechanisms, and serve as the backbone for systemic alignment—ensuring that local optimizations do not undermine global performance. Metasystemic functions are especially critical in manufacturing SoS because constituent systems (factories) evolve independently, often driven by local goals. Without a metasystem, coordination, adaptability, and system-level viability are jeopardized.

6.6. Governance perspective in SoSE

Governance extends beyond control to include direction-setting, oversight, policy design, and accountability [76–78]. Within manufacturing SoS, there is a need to examine (i) how governance structures can enable shared rule-making without compromising factory autonomy, (ii) how it balances short-term efficiency with long-term sustainability and evolution, and (iii) how to incorporate non-hierarchical mechanisms—such as federated decision-making and coalition governance. SoSE governance theory emphasizes a long-term perspective, which is in line with the challenges faced in F2F coordination. These challenges require ongoing collaboration, the ability to adapt to market changes, and the accommodation of diverse stakeholder interests. However, there is still a need to clarify how principles from CSG can guide the development of adaptive, stakeholder-inclusive oversight for manufacturing ecosystems.

6.7. Systems pathology in manufacturing SoS

Pathological behaviors in SoS arise when underlying principles of systems theory are violated, leading to reduced performance, fragility, or failure. Drawing from Beer [66] and extended in Katina's research [79–82], Systems Pathology examines dysfunctions such as coordination breakdowns, interoperability failures stemming from architectural incoherence, and overcentralization or underregulation, reducing adaptability or increasing risk. In manufacturing SoS, there remains a need to understand how pathologies may manifest and what mechanisms might be developed in response. Of vital importance is developing diagnostic approaches rooted in systems pathology that allow decision-makers to identify, map, and mitigate systemic weaknesses across technical, operational, and organizational layers of SoS.

In summary, future work must bridge conceptual models with real-world evidence, ensuring that SoSE for F2F manufacturing is not only theoretically sound but also practically deployable, scalable, and sustainable across industries and regions. Three complementary research streams—the Metasystem concept, Governance, and Systems Pathology—offer critical lenses for diagnosing, guiding, and sustaining performance in interconnected manufacturing ecosystems.

Data availability statement

No supplementary or additional data were generated in this study.

Declaration of generative AI and AI-assisted technologies

The authors did not use generative AI or AI-assisted technologies in the writing of this manuscript.

Acknowledgments

Funding: This work was supported by the National Science Foundation under Grant No. 2119654. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Authors' contributon

Conceptualization, PK; methodology, PK, HT and AH; software, PK, HT and AH; validation, PK, HT and AH; formal analysis, PK and AH; investigation, PK and HT; resources, PK and HT; data curation, PK, and AH; writing—original draft preparation, PK; writing—review and editing, PK, HT and AH; visualization, PK, HT and AH; supervision, PK; project administration, PK and AH; funding acquisition, PK and HT. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Polinpapilinho F. Katina holds the position of Associate Editor for *Advanced Manufacturing* and has not peer reviewed or made any editorial decisions for this paper.

References

[1] Maier MW. Architecting principles for systems-of-systems. *Syst. Eng.* 1999, 1(4):267–284.

[2] US Department of Defense. Systems engineering guide for systems of systems. 2008. Available: https://www.cto.mil/wp-content/uploads/2024/06/DoD-SE-for-SoS-2008.pdf (accessed on 22 January 2026).

[3] Jamshidi M. *System of Systems Engineering: Innovations for the 21st Century*. Hoboken: John Wiley & Sons Inc, 2009.

[4] Katina PF. IoT-based system of systems engineering framework for future F2F manufacturing: Recommendations to improve the integration and governance of future F2F manufacturing systems in a system of systems. Technical Report, University of South Carolina Upstate, 2025.

[5] Anumbe N, Saidy C, Harik R. A primer on the factories of the future. *Sensors* 2022, 22(15):5834.

[6] Jin C, Djurdjanovic D, Ardakani HD, Wang K, Buzza M, *et al.* A comprehensive framework of factory-to-factory dynamic fleet-level prognostics and operation management for geographically distributed assets. In *Proceedings of the 2015 IEEE International Conference on Automation Science and Engineering (CASE)*, Gothenburg, Sweden, August 24–28, 2015, pp. 225–230.

[7] Dahmann JS, Baldwin KJ. Understanding the current state of US Defense systems of systems and the implications for systems engineering. In *Proceedings of the 2008 2nd Annual IEEE Systems Conference*, Montreal, Canada, April 7–10, 2008, pp. 1–7.

[8] Boardman J, Sauser B. System of Systems—the meaning of of. In *Proceedings of the 2006 IEEE/SMC International Conference on System of Systems Engineering*, Los Angeles, USA, April 24–26, 2006, pp. 1–6.

[9] Keating CB. Complex system governance: theory to practice challenges for system of systems engineering. In *Proceedings of the 2015 10th System of Systems Engineering Conference (SoSE)*, May 17–20, 2015, pp. 226–231.

[10] Beer S. *Brain of the Firm: the Managerial Cybernetics of Organization*, 2nd ed. Chichester: Wiley, 1981.

[11] Keating CB, Katina PF. Complex system governance: concept, utility, and challenges. *Syst. Res. Behav. Sci.* 2019, 36(5):687–705.

[12] Nightingale DJ, Rhodes DH. *Architecting the future enterprise*, 1st ed. Cambridge: MIT Press, 2015.

[13] Falagas ME, Pitsouni EI, Malietzis GA, Pappas G. Comparison of PubMed, Scopus, Web of Science, and Google Scholar: strengths and weaknesses. *FASEB J.* 2008, 22(2):338–342.

[14] Tao F, Qi Q, Liu A, Kusiak A. Data-driven smart manufacturing. *J. Manuf. Syst.* 2018, 48:157–169.

[15] Herrera-Vidal G, Coronado-Hernández JR, Maheut J. Complexity management challenges in the industry 4.0 era: a systematic review in production systems. *Results Eng.* 2025, 26:105329.

[16] Weyer S, Schmitt M, Ohmer M, Gorecky D. Towards Industry 4.0—Standardization as the crucial challenge for highly modular, multi-vendor production systems. *IFAC-PapersOnLine* 2015, 48(3):579–584.

[17] Speicher TL, Defranco JF, Stricker CD, Kumara S. Integrating digital twins into small to medium sized manufacturers: a roadmap for engineering internships. *Int. J. Eng. Educ.* 2025, 41(2):432–452.

[18] Boppana VR. Industry 4.0: revolutionizing the future of manufacturing and automation. *SSRN Electronic Journal* 2025.
[19] Ryalat M, Almtireen N, Elmoaqet H, Almohammedi M. The integration of two smarts in the era of Industry 4.0: smart factory and smart city. In *Proceedings of 2024 IEEE Smart Cities Futures Summit (SCFC)*, Marrakech, Morocco, May 29–31, 2024, pp. 9–12.
[20] Dabic-Miletic S. Advanced technologies in smart Factories: a cornerstone of Industry 4.0. *J. Ind. Intell.* 2023, 1(3):148–157.
[21] Khan M, Wu X, Xu X, Dou W. Big data challenges and opportunities in the hype of Industry 4.0. In *Proceedings of 2017 IEEE International Conference on Communications (ICC)*, Paris, France, May 21–25, 2017, pp. 1–6.
[22] Ali S, Qaisar S, Saeed H, Farhan Khan M, Naeem M, *et al*. Network challenges for cyber physical systems with tiny wireless devices: a case study on reliable pipeline condition monitoring. *Sensors* 2015, 15(4):7172–7205.
[23] Alur R. *Principles of Cyber-Physical Systems*, 1st ed. Cambridge: MIT Press, 2015.
[24] Javaid M, Haleem A, Singh RP, Suman R. An integrated outlook of Cyber-Physical Systems for Industry 4.0: topical practices, architecture, and applications. *Green Technol. Sustainability* 2022, 1(1):100001.
[25] Zhong RY, Xu X, Klotz E, Newman ST. Intelligent manufacturing in the context of Industry 4.0: a review. *Engineering* 2017, 3(5):616–630.
[26] Monostori L, Kádár B, Bauernhansl T, Kondoh S, Kumara S, *et al.* Cyber-physical systems in manufacturing. *CIRP Ann.* 2016, 65(2):621–641.
[27] Monostori L. Cyber-physical production systems: roots, expectations and R&D challenges. *Procedia CIRP* 2014, 17:9–13.
[28] Mennenga M, Siemon L, Rudolf S. A system of systems approach to support the sustainable integration of factories into urban areas. *Procedia CIRP* 2023, 116:708–713.
[29] Ramakurthi VB, Manupati VK, Varela L, Putnik G. Leveraging blockchain to support collaborative distributed manufacturing scheduling. *Sustainability* 2023, 15(4):3283.
[30] Lederer B, Walker J, van der Winden E. Climate change and three models of governance to deal with it: polycentricity, experimentalist, and the viable system model. *Syst. Pract. Action Res.* 2025, 38(3):21.
[31] Perez Rios J. The viable system model and the taxonomy of organizational pathologies in the age of artificial intelligence (AI). *Systems* 2025, 13(9):749.
[32] Padovano A, Ivanov D. Towards resilient and viable supply chains: a multidimensional model and empirical analysis. *Int. J. Prod. Res. 2025*, 63(17):6252–6290.
[33] Lowe D, Espinosa A, Yearworth M. Constitutive rules for guiding the use of the viable system model: reflections on practice. *Eur. J. Oper. Res.* 2020, 287(3):1014–1035.
[34] Leng J, Xie J, Li R, Zhou X, Gu X, *et al*. Resilient manufacturing: a review of disruptions, assessment, and pathways. *J. Manuf. Syst.* 2025, 79:563–583.
[35] KPMG International. Resilience amid complexity: quantifying disruption to help drive agility and sustainable growth. 2024. Available: https://kpmg.com/xx/en/our-insights/risk-and-regulation/resilience-amid-complexity.html? (accessed on 22 January 2026).

[36] De Marchi M, Friedrich F, Riedl M, Zadek H, Rauch E. Development of a resilience assessment model for manufacturing enterprises. *Sustainability* 2023, 15(24):16947.
[37] Caputo A, Donati L, Salini P. Estimating resilience of manufacturing plants to physical disruptions: model and application. *Int. J. Prod. Econ.* 2023, 266:109037.
[38] Uday P, Marais K. Designing resilient systems-of-systems: a survey of metrics, methods, and challenges. *Syst. Eng.* 2015, 18(5):491–510.
[39] Gu X, Jin X, Ni J, Koren Y. Manufacturing system design for resilience. *Procedia CIRP* 2015, 36:135–140.
[40] Bruneau M, Reinhorn A. Overview of the resilience concept. In *Proceedings of the 8th US National Conference on Earthquake Engineering*, San Francisco, USA, April 18–22, 2006.
[41] Bruneau M, Chang SE, Eguchi RT, Lee GC, O'Rourke TD, *et al.* A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra* 2003, 19(4):733–752.
[42] Haimes YY. On the definition of resilience in systems. *Risk Anal.* 2009, 29(4):498–501.
[43] Haime YY, Crowther K, Horowit BM. Homeland security preparedness: balancing protection with resilience in emergent systems. *Syst. Eng.* 2008, 11(4):287–308.
[44] Holling CS. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* 1973, 4:1–23.
[45] Deffuant G, Gilbert N. Viability and resilience of complex systems. In *Understanding complex systems*, 1st edition. Berlin: Springer International Publishing, 2011.
[46] Bhamra R, Dani S, Burnard K. Resilience: the concept, a literature review and future directions. *Int. J. Prod. Res.* 2011, 49(18):5375–5393.
[47] Sofic A, Rakic S, Pezzotta G, Markoski B, Arioli V, *et al.* Smart and resilient transformation of manufacturing firms. *Processes* 2022, 10(12):2674.
[48] El-Halwagi MM, Sengupta D, Pistikopoulos EN, Sammon J, Eljack F, *et al.* Disaster-resilient design of manufacturing facilities through process integration: principal strategies, perspectives, and research challenges. *Front. Sustainability* 2020, 1:595961.
[49] Ayyub BM. Systems resilience for multihazard environments: definition, metrics, and valuation for decision making. *Risk Anal.* 2013, 34(2):340–355.
[50] Duchek S. Organizational resilience: a capability-based conceptualization. *Bus. Res.* 2019, 13(1):215–246.
[51] Molenda P, Groneberg H, Schötz S, Döpper F. Resilience balanced scorecard: measuring resilience of manufacturing companies at multiple levels. *Procedia CIRP* 2023, 120:189–194.
[52] Moradlou H, Reefke H, Skipworth H, Roscoe S. Geopolitical disruptions and the manufacturing location decision in multinational company supply chains: a Delphi study on Brexit. *Int. J. Oper. Prod. Manage.* 2021, 41(2):102–130.
[53] Fowler DS, Epiphaniou G, Higgins MD, Maple C. Aspects of resilience for smart manufacturing systems. *Strategic Change* 2023, 32(6):183–193.
[54] Lee B, Preston F, Green G. Preparing for high-impact, low-probability events: lessons from Eyjafjallajökull (A Chatham House Report). 2012. Available: https://www.chathamhouse.org/sites/default/files/public/Research/Energy%2C%20Environment%20and%20Development/r0112_highimpact.pdf (accessed on 22 January 2026).
[55] Lee J, Siahpour S, Jia X, Brow P. Introduction to resilient manufacturing systems. *Manuf. Lett.* 2022, 32:24–27.

[56] Mukherjee A, Glatt M, Mustafa W, Kloft M, Aurich JC. Designing resilient manufacturing systems using cross domain application of machine learning resilience. *Procedia CIR* 2022, 115:83–88.
[57] Pescaroli G, McMillan L, Gordon M, Aydin N, Comes T, *et al*. Definitions and taxonomy for High Impact Low Probability (HILP) and outlier events. *Int. J. Disaster Risk Reduct.* 2025, 127:105504.
[58] Thoma K. Resilience-by-Design: a strategy for the technology issues of the future. 2014. Available: https://en.acatech.de/publication/resilien-tech-resilience-by-design-a-strategy-for-the-technology-issues-of-the-future/ (accessed on 22 January 2026).
[59] Thoma K, Scharte, Hiller D, Leismann T. Resilience engineering as part of security research: definitions, concepts and science approaches. *Eur. J. Secur. Res.* 2016, 1(1):3–19.
[60] Durach CF, Repasky T, Wiengarten F. Patterns in firms' inventories and flexibility levels after a low-probability, high-impact disruption event: empirical evidence from the Great East Japan Earthquake. *Prod. Oper. Manage.* 2022, 32(6):1705–1723.
[61] Sperstad IB, Kjølle GH, Gjerde O. A comprehensive framework for vulnerability analysis of extraordinary events in power systems. *Reliab. Eng. Syst. Saf.* 2019, 196:106788.
[62] Sperstad IB, Kjølle G, Noru EØ. Accounting for uncertainties due to high-impact low-probability events in power system development. *Electr. Power Syst. Res.* 2021, 193:107015.
[63] Torresan S, Maraschini M, Ferrario DM, Casagrande S, Ghaffarian S, *et al*. High-impact low-probability events and systemic resilience: a network-based methodology and its application to the metropolitan city of venice. In *Proceedings of EGU General Assembly 2025*, Vienna, Austria, April 27–May 2, 2025.
[64] Mosayebi M, Fath M, Hedayati MK, Ivanov D. Time-to-Adapt (TTA). *Int. J. Prod. Econ.* 2024, 278:109432.
[65] Masten AS. Resilience in developing systems: the promise of integrated approaches. *Eur. J. Dev. Psychol.* 2016, 13(3):297–312.
[66] Beer S. The viable system model: its provenance, development, methodology and pathology. *J. Oper. Res. Soc.* 1984, 35(1):7–25.
[67] Keating CB, Bradley JM. Complex system governance reference model. *Int. J. Syst. Syst. Eng.* 2015, 6(1,2):33–52.
[68] Keating CB, Katina PF, Pyne JC. System of systems engineering: a literature review and research frontiers. In *Proceedings of the American Society for Engineering Management 2024 International Annual Conference*, Virginia Beach, USA, November 6–9, 2024, pp. 1–10.
[69] ISO/IEC/IEEE 21841:2019: Systems and software engineering—taxonomy of systems of systems. 2019. Available: https://www.iso.org/standard/71957.html (accessed on 2 February 2026).
[70] Keating CB, Rogers R, Unal R, Dryer D, Sousa-Poza AA, *et al.* System of systems engineering. *Eng. Manage. J.* 2003, 15(3):35–44.
[71] Tolk A, Diallo S, Turnitsa C. Applying the levels of conceptual interoperability model in support of integratability, interoperability, and composability for system-of-systems engineering. *J. Syst. Cybern. Inf.* 2007, 5(5):65–74.
[72] Collins ST, Yassine AA, Borgatti SP. Evaluating product development systems using network analysis. *Syst. Eng.* 2009, 12(1):55–68.
[73] Scholz S, Mueller T, Plasch M, Limbeck H, Adamietz R, *et al.* A modular flexible scalable and reconfigurable system for manufacturing of microsystems based on additive manufacturing and e-printing. *Rob. Comput. Integr. Manuf.* 2016, 40:14–23.

[74] Yassine AA, Mostafa O, Browning TR. Scheduling multiple, resource-constrained, iterative, product development projects with genetic algorithms. *Comput. Ind. Eng.* 2017, 107:39–56.

[75] Beer S. *The heart of the enterprise*, 1st ed. New York: John Wiley & Sons, 1979.

[76] Boardman J, Sauser B. *Systems thinking: Coping with 21st century problems*, 1st ed. Boca Raton: CRC Press, 2008.

[77] Keating CB, Katina PF, Chesterman CW, Pyne JC. *Complex system governance: theory and practice*, 1st ed. Cham: Springer International Publishing, 2022.

[78] Katina PF, Keating CB, Zio E, Masera M, Gheorghe AV. Governance of smart energy systems. In *Handbook of Smart Energy Systems*, 1st ed. Cham: Springer International Publishing, 2021. pp. 123–145.

[79] Katina PF. Emerging systems theory–based pathologies for governance of complex systems. *Int. J. Syst. Syst. Eng.* 2015, 6(1,2):144–159.

[80] Katina PF. Systems theory as a foundation for discovery of pathologies for complex system problem formulation. In *Applications of Systems Thinking and Soft Operations Research in Managing Complexity*, 1st ed. Geneva: Springer International Publishing, 2016. pp. 227–267.

[81] Katina PF. System acquisition pathology: a comprehensive characterisation of system failure modes and effects. *IJCIS* 2020, 16(3):255–292.

[82] Katina PF. Metasystem pathologies in complex system governance. In *Complex System Governance: Theory and Practice*, 1st ed. Cham: Springer International Publishing, 2022. pp. 241–282.