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Self-X-based secure human-cyber-physical system (SSHCPS) for autonomous manufacturing in the era of industry 5.0

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ABSTRACT

The transition from Industry 4.0 to Industry 5.0 marks a paradigm shift from technology-driven automation toward secure, resilient, and human-centric manufacturing. While Industry 4.0 enhanced efficiency through cyber-physical systems (CPS), the Internet of Things (IoT), and artificial intelligence (AI), it often overlooks human involvement and introduces heightened cybersecurity risks. Industry 5.0 seeks to overcome these limitations by emphasizing sustainability, resilience, and human-centricity through collaboration between humans and intelligent systems. As a step toward maturing the Industry 5.0 paradigm, we propose the Self-X-based secure human-cyber-physical system (SSHCPS) as a new conceptual framework for autonomous manufacturing. This study introduces an original architecture that integrates Self-X capabilities, human-in-the-loop (HITL) interaction, and cybersecurity (CS). The architecture is structured into four interlinked modules: HITL, Digital Twin, Physical Twin, and CS. As the foundation of this architecture, we categorized the Self-X terms from the literature, merged them into 23 Self-X principles, redefined them, and mapped them into the core values of Industry 5.0 and the SSHCPS modules. Furthermore, we demonstrate the applicability of SSHCPS through potential applications such as lightless and de-urbanized factories, humanoid-enabled SMEs, and the aerospace industry, while also identifying key technical challenges and future direction. This study establishes SSHCPS as a forward-looking foundation for secure, efficient, and human-centered autonomous manufacturing systems in the Industry 5.0 era.

1. Introduction

The manufacturing industry has undergone successive transformations, with each industrial revolution introducing new paradigms and technologies. Industry 4.0 marked a leap by embedding automation, digitalization, and interconnectivity through the Internet of Things (IoT), artificial intelligence (AI), and big data analytics [1,2]. These advances enabled smart factories where machines autonomously managed tasks, optimized production, and anticipated maintenance needs, greatly enhancing efficiency and productivity [3]. At the same time, Industry 4.0 revealed critical challenges, such as cybersecurity (CS) risks and the marginalization of human expertise in increasingly automated environments [4]. Industry 5.0 responds to these shortcomings by emphasizing human-centricity, sustainability, and resilience, ensuring that human creativity and judgment remain central while advanced systems support and enhance overall performance [5].

Despite progress in autonomous manufacturing, a significant research gap remains in integrating Self-X technologies, human-in-the-loop (HITL) principles, and CS into a unified framework. Current approaches often overemphasize automation while sidelining the human element. This has resulted in systems that lack flexibility in complex scenarios requiring human judgment. CS considerations have often been reactive, and this leaves systems vulnerable to evolving threats [6,7]. This fragmented perspective does not reflect the interconnected demands of Industry 5.0, where autonomy, collaboration, and resilience must be achieved simultaneously.

To address this gap, we introduce the Self-X-based secure human-cyber-physical system (SSHCPS), a conceptual paradigm designed for autonomous manufacturing in the Industry 5.0 era. This study does not aim to provide a comprehensive survey of the field but instead proposes

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a novel architecture grounded in existing literature. SSHCPS integrates Self-X capabilities [8], with cyber-physical systems (CPS) [9], HITL principles [10], and CS measures [11]. Together, these enable systems to adapt to dynamic conditions, recover from disruptions, and optimize performance while maintaining human oversight in a secure environment. This holistic approach aligns with Industry 5.0′s vision of secure, efficient, and human-centric manufacturing systems that balance technological autonomy with human collaboration.

The novelty of SSHCPS lies in bridging domains that are typically treated in isolation and in reframing them through the lens of Industry 5.0. By redefining Self-X principles and embedding them within an integrated framework, the study not only advances theoretical clarity but also offers pathways toward practical realization in manufacturing systems. This conceptualization provides a foundation for designing secure, resilient, and human-centric autonomy, positioning SSHCPS as a reference point for future research and industrial adoption.

The paper is structured into eight sections to explore SSHCPS and its implications systematically. Section 2 reviews Industry 5.0, HITL, Self-X concepts, and cybersecurity; Section 3 outlines the approach and elaborates on the contributions of the study. Section 4 reviews the Self-X terms used in the literature, revisits them, and refines 23 Self-X principles for clarity and relevance. Section 5 maps Self-X principles to SSHCPS and Industry 5.0 and elaborates on the proposed framework. Section 6 examines applications with potential case scenarios, Section 7 discusses implementation challenges and future directions, and Section 8 summarizes the research.

2. Background and related works

This section provides a foundation by exploring Industry 5.0′s emphasis on HITL approaches, the role of autonomy and Self-X concepts in modern manufacturing, the integration of CPS as a technical backbone, and the critical importance of security in interconnected production environments.

2.1. Industry 5.0 and human-in-the-loop

Industry 5.0 represents a paradigm shift from the technology-driven automation of Industry 4.0 to a more balanced, human-centric approach that integrates advanced systems with human oversight, prioritizing sustainability and resilience alongside efficiency [12]. Emerging in response to Industry 4.0′s limitations, such as its tendency to minimize human roles and overlook societal impacts, Industry 5.0 considers manufacturing as a collaborative ecosystem where intelligent machines enhance, rather than replace, human capabilities [13]. This shift emphasizes the need for systems that adapt to human needs, support worker well-being, and align with environmental goals, such as reducing waste in production processes like additive manufacturing [14]. The HITL concept is central to this vision, ensuring that automation remains flexible and responsive to human judgment in complex, unpredictable scenarios [5].

The HITL approach integrates human expertise into automated systems, leveraging the precision of machines and the contextual awareness of humans [15]. HITL allows operators to monitor and intervene in manufacturing processes, such as HITL robot learning [16]. This collaboration is particularly vital in Industry 5.0, where ethical considerations and adaptability are paramount; for instance, human oversight can prevent AI-driven errors in quality control or address unforeseen disruptions like supply chain delays [3]. As discussed by Bhattacharya et al. [17], human decision-makers will continue to play a crucial role in many industries for more complicated automation tasks requiring the mass manufacture of highly customized products. In addition, the importance of recognizing the cognitive workload of human operators has become a matter of interest to researchers [18].

This human-centric focus in Industry 5.0 directly informs the design of SSHCPS, which seeks to balance advanced automation with meaningful human involvement. Unlike Industry 4.0, which focuses on minimizing human roles, Industry 5.0 requires systems to be transparent and interpretable, enabling workers to understand and influence automated decisions, as Nahavandi argues in his exploration of human–machine collaboration [4]. For example, in a scenario where a production line adjusts to a new material, HITL ensures that engineers can validate the system's response, maintaining safety and quality [19]. Recently, a novel multi-robot collaborative manufacturing system with HITL control by leveraging cutting-edge augmented reality (AR) and digital twin (DT) techniques has also been proposed to address the issue of teleoperation and coordination of multiple industrial robots with human insight [20].

2.2. Autonomous manufacturing and Self-X concept

Autonomous manufacturing has evolved as the backbone of modern industry, aiming to create production systems that operate with minimal human intervention by leveraging intelligent automation and adaptive technologies [21]. This concept gained attention with Industry 4.0, where advancements in robotics, AI, and IoT enabled factories to self-regulate tasks like assembly or material handling [22]. However, true autonomy requires systems to go beyond pre-programmed routines, adapting dynamically to variables such as demand fluctuations or resource availability, capabilities that the Self-X concept can address. It is rooted in autonomic computing, and equips systems with capabilities that lay the groundwork for modern manufacturing [8].

The Self-X concept encompasses a suite of autonomous capabilities that enable manufacturing systems to manage themselves intelligently and resiliently [23]. For instance, Zhang et al. highlight how self-optimizing systems in semiconductor production adjust process parameters in real-time to maximize yield, reducing waste and enhancing efficiency [24]. Similarly, self-healing mechanisms allow machines to detect and repair faults without halting production [25]. In the context of Industry 5.0, these Self-X capabilities support sustainability by optimizing resource use and resilience by ensuring continuous operation. SSHCPS integrates the Self-X concept to enhance autonomous manufacturing, aligning it with Industry 5.0 key aspects of human-centricity and resilience. While traditional autonomous systems focus on efficiency, the proposed framework extends this by embedding self-awareness and self-explaining features, ensuring that machines can communicate their actions to human operators. By synthesizing Self-X with human-in-the-loop principles, SSHCPS creates a manufacturing framework that is not only autonomous and adaptive but also transparent and secure, addressing the multifaceted demands of modern industry.

2.3. Cyber-physical systems in manufacturing

CPS forms the technological backbone of smart manufacturing, integrating physical machinery with computational models to enable real-time control and monitoring across production environments [11,26]. Introduced as a key enabler of Industry 4.0, CPS uses sensor-actuator networks to connect observable manufacturing elements with digital systems, facilitating data-driven automation in processes such as automotive assembly or aerospace fabrication [27]. The seamless interplay between physical and digital realms has revolutionized manufacturing by bridging the gap between hardware and software.

Despite their strengths, CPS implementations in manufacturing face challenges that Industry 5.0 seeks to address, particularly in resilience and human integration. While CPS excels at automation, its reliance on interconnected networks increases vulnerability to disruptions, such as power failures or cyberattacks, which can cascade across an entire factory, as Lee et al. [28] mentioned in their analysis of Industry 4.0 architectures. Moreover, traditional CPS designs often lack mechanisms for meaningful human interaction, limiting their adaptability in scenarios requiring nuanced judgment. Industry 5.0′s emphasis on resilience and human-centricity thus demands CPS enhancements that incorporate adaptability and collaboration, areas where SSHCPS intervenes with a Self-X-based approach.

SSHCPS builds on CPS by embedding Self-X capabilities and cybersecurity, creating a more robust and human-integrated framework for autonomous manufacturing. For instance, while CPS enables real-time data exchange, it adds self-adaptation to dynamically adjust to environmental shifts and self-healing to recover from faults without external input. Additionally, by integrating human-in-the-loop principles, it ensures that CPS-driven systems remain accessible to operators, allowing manual overrides or validations in critical situations. This synthesis positions SSHCPS as an evolution of CPS, tailored to Industry 5.0′s needs for secure, resilient, and collaborative production systems.

2.4. Cybersecurity in manufacturing

Security has become a paramount concern in modern manufacturing as systems grow increasingly interconnected, exposing them to a spectrum of threats that can disrupt operations and compromise sensitive data [29]. The rise of Industry 4.0, with its reliance on IoT and cloud-based platforms, introduced vulnerabilities such as unauthorized access to production networks, as evidenced by high-profile incidents in the automotive and pharmaceutical sectors [30]. Wu et al. emphasize that these threats not only halt production but also risk intellectual property theft, underscoring the need for robust security measures in smart factories [31]. As manufacturing evolves into Industry 5.0, where resilience is a core pillar, addressing these risks becomes even more critical to ensure uninterrupted and trustworthy operations.

Traditional security approaches, such as firewalls and encryption, are insufficient against the sophisticated threats facing modern manufacturing, necessitating proactive and adaptive defenses [31]. For example, a cyberattack targeting a DT could manipulate simulation data, leading to defective products, a scenario Lee et al. warn about in CPS architectures [32]. Industry 5.0 amplifies this challenge by integrating human operators into digital systems, requiring security frameworks that protect both machine and human interactions without impeding collaboration [33]. Self-X principles, such as self-protection and self-security, offer a promising solution that enables systems to autonomously detect and neutralize threats while maintaining operational continuity. This is a capability that the proposed SSHCPS architecture leverages to enhance resilience.

SSHCPS addresses security in modern manufacturing by embedding Self-X-based cybersecurity into its framework, aligning with Industry 5.0′s resilient and human-centric goals. Unlike conventional systems, SSHCPS incorporates self-protecting mechanisms that actively monitor for anomalies and self-security features that encrypt data flows between physical and digital twins, as suggested by cybersecurity research in smart manufacturing [34]. Furthermore, by integrating HITL, SSHCPS ensures that human operators can respond to security alerts with contextual understanding, such as authorizing a system reset after a detected breach, enhancing trust and adaptability. This comprehensive approach positions SSHCPS as a secure foundation for autonomous manufacturing, safeguarding against evolving threats while supporting Industry 5.0′s vision of sustainable, collaborative production.

3. Research methodology and contributions

3.1. Methodology

Publications in English from the SCOPUS, Google Scholar, and ScienceDirect databases were monitored. The following search strings were used: (“smart manufacturing” OR “industry 5.0” OR “industry 4.0” OR “human in the loop” OR “operator 5.0” OR “human”) AND (“self-x” OR “autonomous manufacturing” OR “machine learning” OR “artificial intelligence”). Initially, papers were screened based on their titles and abstracts. Discussions with co-authors and domain-specific experts further refined the selection process. This research includes peer-reviewed journal articles, conference papers, and white papers. The overall process, including database selection, keyword filtering, and expert validation, is summarized in Fig. 1, which provides a step-by-step visualization of the research methodology used in this study. To further analyze the research landscape, we performed a bibliometric analysis of relevant keywords. Fig. 2 illustrates the overlay visualization of keyword occurrences across the Scopus database, showing temporal evolution and clustering of terms. This visualization highlights the prominence of concepts such as artificial intelligence, smart manufacturing, and machine learning, and helps contextualize how these themes relate to the SSHCPS paradigm.

3.2. Contributions

The aims of this study can be categorized as:

- *To Develop a Comprehensive Framework for Industry 5.0 Manufacturing:* The study aims to propose and define the SSHCPS as an integrated framework that combines Self-X capabilities, HITL principles, and robust cybersecurity measures, tailored specifically for autonomous manufacturing in the Industry 5.0 paradigm. This framework seeks to align with Industry 5.0′s goals of human-centricity, sustainability, and resilience.
- *To Address the Research Gap in Integrating Autonomy, Human Collaboration, and Security:* The study intends to bridge the identified gap in existing literature, where autonomous manufacturing systems often lack a cohesive integration of Self-X technologies, human oversight, and proactive cybersecurity. It aims to provide a unified solution that balances these elements to meet modern industrial needs.
- *To Refine and Apply Self-X Principles:* A key aim is to systematically review, refine, and map Self-X capabilities to the SSHCPS framework and Industry 5.0 objectives. This involves clarifying their roles and ensuring their practical applicability in enhancing system autonomy, adaptability, and security.
- *To Demonstrate Practical Relevance and Identify Challenges:* The study aims to demonstrate the real-world applicability of SSHCPS through potential case scenarios (e.g., aerospace manufacturing), highlighting how it optimizes processes, ensures security, and maintains human involvement. Additionally, it aims to identify technical

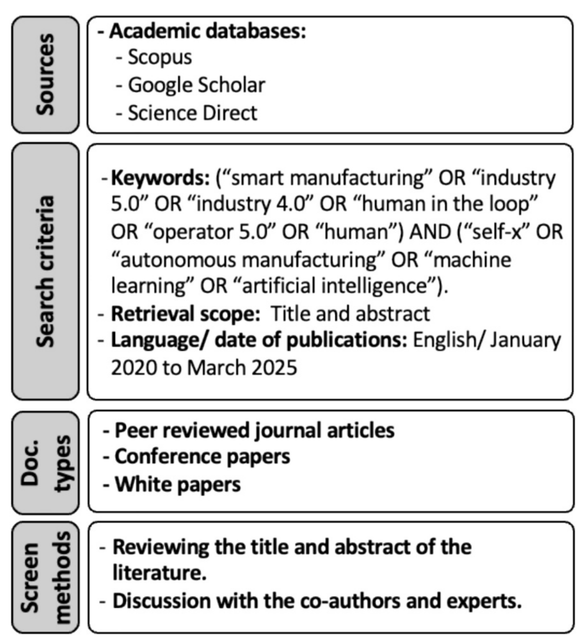

Fig. 1. Summary of research methodology.

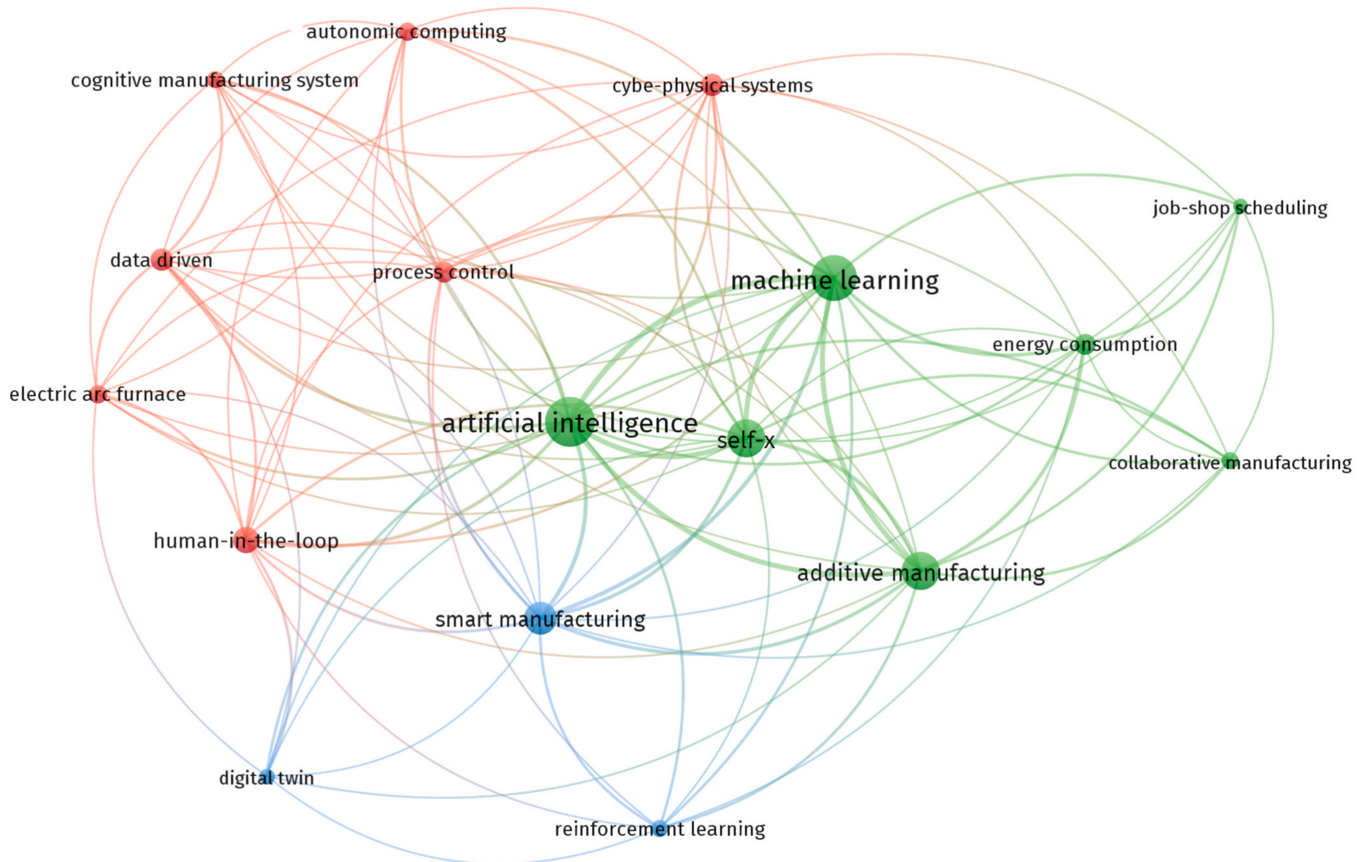

Fig. 2. Overlay visualization of the keyword occurrence from the Scopus database generated by VOSviewer.

challenges (e.g., scalability, real-time data processing) to guide future research and implementation efforts.

- *To Advance Human-Centric and Secure Autonomous Manufacturing:* Ultimately, the study aims to set a new benchmark for manufacturing systems by advancing the development of autonomous, secure, and human-centric solutions. It intends to contribute to the evolution of Industry 5.0 by providing a framework that enhances efficiency, resilience, and trust in industrial automation.

4. Self-X characterization

The Self-X is a foundational aspect of SSHCPS in autonomous manufacturing, encompassing a wide range of autonomous capabilities that enable intelligent manufacturing systems to operate, adapt, and secure themselves with minimal human intervention.

4.1. Review of Self-X terms

Self-X capabilities are fundamental to the evolution of autonomous manufacturing, aligning with the principles of Industry 5.0. These capabilities enable manufacturing systems to function with efficient human intervention by embedding intelligence, adaptability, and resilience within their operational framework. By integrating Self-X properties, systems can autonomously monitor their own performance, optimize operations, detect and mitigate failures, and enhance security against cyber and physical threats. These features enhance efficiency and productivity, contributing to the overall robustness and sustainability of autonomous manufacturing environments. In the context of Industry 5.0, where human-centricity, resilience, and sustainability are emphasized, Self-X properties serve as key enablers of intelligent decision-making. For example, self-monitoring and self-diagnosing functions allow systems to proactively identify inefficiencies or faults, while self-healing and self-repair capabilities ensure continuous operation with minimal downtime. Additionally, self-protection, self-defending, and self-security functions are critical for safeguarding industrial systems against evolving cyber threats and ensuring uninterrupted production. To provide a comprehensive overview, Table 1 presents 48 Self-X terms relevant to autonomous manufacturing systems and their descriptions. This compilation highlights the diverse functionalities contributing to system autonomy, intelligence, and security, offering a foundation for further research and development.

4.2. A revisit to Self-X terms

The concept of Self-X plays a vital role in enabling autonomy and adaptability. These principles represent a set of attributes that empower a system to independently manage its functions, optimize its performance, and respond to environmental or internal changes. Integrating these principles into autonomous manufacturing systems makes it possible to develop systems capable of creating a more resilient and efficient manufacturing environment. The following table presents 23 key Self-X principles that are foundational to the development of the SSHCPS paradigm in the era of Industry 5.0. These principles highlight how systems can function with minimal human intervention, ensuring improved productivity, adaptability, and robustness. It should be noted that this categorization represents one iteration of a broader synthesis effort, derived through discussions among the co-authors, and is intended primarily to illustrate a possible pathway for structuring Self-X concepts across the SSHCPS modules rather than to prescribe a fixed or exhaustive taxonomy.

The Self-X principles encompass a wide range of capabilities, including the ability to sense and interpret internal and external conditions, optimize performance, protect against threats, and ensure self-sustainability. These principles also facilitate the continuous

Table 1
The Self-X terms from the literature.

Self-X terms	Description	Ref
Self-governance	The capacity for manufacturing systems to independently organize, control, and optimize their operations without centralized oversight.	[35]
Self-directedness	The ability to independently initiate, prioritize, and pursue its own operational goals without requiring explicit instructions from a human operator or centralized controller.	[36]
Self-determination	It is the ability to independently make decisions, set its own goals, and control its actions without external influence or interference. It emphasizes the autonomy in choosing its course of action based on its own perception, reasoning, and internal objectives, rather than being dictated by predefined programming or external commands.	[37]
Self-motivation	Refers to the capability to generate its own internal goals, incentives, or drive to initiate and sustain actions without relying on external triggers, instructions, or predefined directives from a human operator or designer.	[38]
Self-management	Self-management is the capability of a system to autonomously oversee and regulate its own operations, resources, and functions without external intervention, with the goal of maintaining performance, achieving predefined objectives, and reducing the burden of management tasks on human operators.	[23]
Self-maintenance	The ability to perform tasks necessary to keep its operational condition. This means that the system can independently monitor its own state, perform routine checks, and make adjustments.	[39]
Self-sustaining	Sustains its own operations without requiring external assistance. Such a system handles its own energy, materials, or other resources necessary for operation, and adjusts to environmental shifts or internal variations to maintain functionality.	[40]
Self-regulating	The ability of a system, organism, or entity to independently monitor and adjust its own processes, behaviors, or conditions to maintain stability, achieve specific goals, or adapt to changing environments without external intervention.	[8]
Self-containedness	It operates as a complete, independent entity with clearly defined boundaries, goals, and capabilities, requiring minimal or no external intervention to fulfill its intended purpose.	[41]
Self-reliant	Being independent and able to rely on oneself for needs, decisions, and problem-solving without depending on others. It involves resourcefulness and the capacity to manage challenges independently.	[42]
Self-monitoring	to continuously observe and assess its own internal state, performance, and operational conditions without external assistance. This capability involves the use of sensors, algorithms, or diagnostic tools to track system parameters, such as resource levels, functionality, or potential faults, and detect changes or anomalies in real time.	[8]
Self-diagnosis/ diagnosing	independently identify, analyze, and evaluate issues, faults, or anomalies within its own operations or components without requiring external intervention. This process involves the system using its internal sensors, data processing, and diagnostic algorithms to detect problems and determine their nature or cause.	[43]
Self-testing	Self-testing refers to the capability of an autonomous system to independently evaluate its own functionality, performance, or integrity by executing internal tests or checks without requiring external tools or human intervention.	[44]
Self-inspection/ inspecting	The system examines and evaluates its own components, structure, or operational state to ensure proper functioning, detects potential issues, or verifies compliance with expected standards, without requiring external intervention.	[45]
Self-assessment	Ability to independently evaluate its own performance, capabilities, or operational state against predefined criteria or goals, using internal data and analytical processes, without requiring external input or intervention.	[8]
Self-analysis	The capability of an autonomous system to independently examine and interpret its own operational data or behaviors to derive insights about its performance or state.	[41]
Self-optimization	Self-optimization includes analyzing the current situation, determining objectives, and adapting system behavior.	[46]
Self-tuning	It is a system's ability to improve itself regarding certain goals and is considered a synonym for self-optimization.	[47]
Self-balancing	Self-balancing ensures maximum utilization of resources to meet system requirements and requires continuous monitoring of available resources and configurations.	[48]
Self-improve/ improving	enhance its own performance, functionality, or efficiency over time by learning from experience, adapting its processes, or optimizing its behavior, without requiring external intervention. This process involves the system identifying areas for enhancement	[40]
Self-evolve/ evolving	It develops, adapts, or refines its own functionality, structure, or behavior over time based on experience, environmental interactions, or internal analysis, without external programming or intervention.	[49]
Self-calibration	The capability of an autonomous system to autonomously adjust or fine-tune its own sensors, parameters, or operational settings to maintain accuracy, precision, or optimal performance without external intervention.	[50]
Self-sufficient	Self-sufficiency in smart manufacturing refers to the ability of manufacturing systems to operate autonomously, adapting to changing environments and optimizing processes without human intervention. This concept is characterized by decentralized, networked compositions of autonomous systems inspired by biological organisms	[51]
Self-organizing/ organization	To rearrange or adapt its own structure to achieve a global goal based on local actions. A self-organizing system offers adaptability by modifying its own structure.	[52]
Self-assembly	Self-assembly in smart manufacturing refers to the autonomous organization of components into patterns or structures without human intervention. It bridges the gap between nanoscale arrangement and macroscale fabrication, offering opportunities for new printable materials, improved properties, and eco-sustainability.	[53,54]
Self-synchronization	Self-synchronization in smart manufacturing refers to the autonomous coordination and adaptation of manufacturing processes without human intervention.	[36]
Self-reconfiguration/ reconfiguring	Refers to the ability of systems to autonomously adapt and optimize their operations in response to changing conditions or requirements. This concept is	[55]

(continued on next page)

Table 1 (*continued*)

Self-X terms	Description	Ref
	central to next-generation manufacturing systems, enabling improved responsiveness and efficiency.	
Self-adapting/ adopting	Self-adapting/adopting in smart manufacturing refers to the ability of systems to autonomously modify their behavior in response to changing circumstances. This concept involves decentralized, distributed networks of autonomous components inspired by biological systems	[51]
Self-protecting/ protection	Refers to the ability of systems to autonomously detect and mitigate security threats at runtime. This concept is part of the broader vision of smart manufacturing, which aims to create decentralized, networked systems of autonomous entities inspired by biological organisms	[56]
Self-defending	Refers to a system's capability to detect, prevent, and respond to cybersecurity threats, operational anomalies, and physical disruptions without direct human intervention.	[57]
Self-security	Refers to a system's ability to autonomously detect, prevent, and mitigate security threats across cyber, physical, and human dimensions.	[58]
Self-configuration/ configuring	Refers to the ability of manufacturing systems to autonomously configure and optimize themselves without human intervention. This capability is crucial for achieving high levels of automation, flexibility, and efficiency in production processes.	[57]
Self-immunity	Refers to the system's ability to autonomously detect, diagnose, and respond to anomalies or disturbances, much like the biological immune system. This concept is inspired by biological systems and aims to enhance the resilience and adaptability of manufacturing processes.	[58]
Self-explaining/ explanation	Self-explaining systems help in comprehending the behavior of complex technical systems, which can often appear non-deterministic. This is particularly useful for debugging, diagnosing failures, and optimizing system operations	[59,60]
Self-representation/ representing	Refers to the ability of manufacturing systems, components, or processes to perceive, interpret, and respond to their environment and operational status without human intervention. This concept is integral to achieving the goals of smart manufacturing, which include increased efficiency, adaptability, and sustainability.	[61]
Self-expression/ expressing	Refers to the ability of manufacturing systems, components, and processes to autonomously perceive, decide, and act based on real-time data and contextual information. This concept is integral to the autonomous and intelligent nature of smart manufacturing systems.	[62]
Self-description/ descriptive	Refers to the capability of devices and systems to describe their offered services and the information they exchange. This capability is crucial for achieving integration and interoperability in complex and dynamic industrial environments	[63]
Self-awareness	Refers to the capability of manufacturing systems, machines, and components to perceive, understand, and respond to their own state and the environment in real-time.	[64]
Self-perception	Refers to the ability of machines, work-in-progress (WIP), and other physical resources on the shop floor to autonomously perceive their environment and internal states. This capability is a fundamental aspect of creating intelligent and adaptive manufacturing systems.	[61]
Self-repair/ repairing	Self-repairing is similar to self-healing, but includes adding new materials or changing existing ones, whereas self-healing requires rehabilitation of components	[65]
Self-heal/ healing	Capability to identify errors or faulty components, diagnose the issue, and implement corrective actions.	[66]
Self-stabilizing	It is the ability to detect and correct deviations, maintaining or returning to a stable operational state without external intervention, ensuring consistent manufacturing outcomes despite disruptions or variability.	[67]
Self-recovery	Self-recovery is synonymous with self-healing, describing a system's ability to detect and correct errors or faulty components, and to reach a safe state after a fault.	[8]
Self-similarity	It refers to the property where the system's structure, behavior, or processes exhibit similar patterns or characteristics across different levels of its organization. This means that the way individual components or subsystems operate mirrors the operation of larger groups or the system as a whole.	[68]
Self-administered / administration	Refers to the capability of manufacturing systems to autonomously manage and optimize their operations without human intervention. This concept is integral to the vision of Industry 4.0, where manufacturing systems are designed to be intelligent, adaptive, and capable of self-organization, self-optimization, and self-healing.	[69]
Self-strengthening	refers to the ability of manufacturing systems to autonomously improve and optimize their operations through advanced technologies and intelligent systems. This concept is integral to the vision of Industry 4.0, where manufacturing processes are enhanced by self-organizing, self-optimizing, and self-healing capabilities.	[70]
Self-destruction/ destructing	This could be interpreted as a system's ability to autonomously identify and isolate faulty components or processes to prevent further damage or security breaches. This involves:	[71]
Self-replication/ replicating	refers to the ability of a system or machine to produce copies of itself autonomously. In smart manufacturing, this concept is particularly relevant due to the increasing need for flexible, adaptive, and efficient production systems.	[69]

improvement of systems by allowing them to learn from experience and adapt to changing circumstances. By applying these Self-X principles, autonomous systems can significantly enhance their own functionality while also ensuring security and stability in dynamic manufacturing environments. Table 2 provides a detailed breakdown of these principles, outlining their associated merged terms and offering redefinitions to better clarify their role in an autonomous system.

The relative prominence of certain Self-X principles across the reviewed literature reflects clear technological and algorithmic trends rather than arbitrary selection. For instance, the widespread discussion of self-optimizing, self-adapting, and self-healing principles aligns with advances in data-driven control, reinforcement learning, and robotics, which have enabled systems to dynamically tune parameters, predict failures, and recover from disturbances. Likewise, self-monitoring and self-diagnosis capabilities have become central because of the growing use of sensor fusion and model-based reasoning within digital twin and robotic applications. In contrast, domains such as human-centric decision support and cybersecurity show limited empirical realization of

Table 2
A revisit to Self-X terms to achieve Self-X principles.

Self-X principles	Merged Self-X terms
Self-awareness	–
Self-perception	Self-expression
Self-explaining	Self-description, Self-representation
Self-optimizing	Self-balancing
Self-adapting	Self-reconfiguration
Self-synchronization	Self-organizing
Self-configuration	Self-calibration
Self-maintenance	Self-repairing, Self-healing
Self-assembly	Self-replication
Self-protecting	Self-defending
Self-security	Self-immunity, Self-destructing
Self-diagnosis	Self-testing,
Self-tuning	Self-motivation
Self-improving	Self-strengthening
Self-description	–
Self-representation	–
Self-monitoring	Self-inspecting
Self-analysis	Self-assessment
Self-reliant	Self-containedness
Self-healing	Self-repairing, Self-stabilizing, Self-recovery
Self-sustaining	Self-sufficient
Self-governance	Self-directedness, Self-determination
Self-evolving	–

self-explaining and self-security functions, revealing an imbalance in current research maturity across the Self-X spectrum. Recognizing these asymmetries helps identify where future investigations should concentrate, specifically on extending the algorithmic intelligence achieved in robotic and automation contexts toward explainable, secure, and human-interpretable operations within broader cyber-physical ecosystems.

5. Self-X-based secure human-cyber-physical system

This section introduces the concept of the SSHCPS, which combines the principles of autonomy, adaptability, and security in the context of Industry 5.0. SSHCPS is designed to enhance the integration of human, cyber, and physical systems, ensuring a balanced collaboration between intelligent machines and human operators while maintaining system security. By incorporating Self-X principles, SSHCPS offers a framework enabling autonomous systems to manage their functions and interactions with minimal external intervention. This section explores the conceptual framework, mapping the Self-X principles to the various components that make up a secure, resilient, and adaptive system. We have identified four modules for realizing the SSHCPS concept in autonomous manufacturing, namely HITL, DT, Physical Twin (PT), and CS, which will be discussed in detail in Section 5.2. This approach can pave the way for safer and more efficient manufacturing environments in the age of Industry 5.0.

5.1. Mapping Self-X principles to SSHCPS and industry 5.0

As discussed earlier, the proposed framework consists of four interlinked modules: HITL, DT, PT, and CS. The rationale for this modular division is grounded in established CPS and HCPS frameworks [72,73], which consistently identify the integration of human oversight, digital representations, physical assets, and secure communication as essential components for resilient autonomy. HITL ensures that human expertise is not marginalized but embedded in decision-making, a principle aligned with Industry 5.0′s human-centricity [5]. DT enables predictive analytics and continuous optimization, providing adaptability and efficiency [74–76]. PT represents the execution layer where autonomous operations are physically realized, ensuring sustainability and robustness. Finally, CS forms the protective layer, which is increasingly recognized as a foundational, not auxiliary, dimension of modern CPS [77].

The mapping of 23 refined Self-X principles to these four modules provides the theoretical foundation for SSHCPS. Each principle is positioned not arbitrarily but according to its functional role in enabling autonomy, adaptability, and resilience. For example, self-awareness and self-perception are mapped to HITL, since they allow transparent human–machine collaboration. Self-optimizing, self-adapting, and self-synchronization are central to DT, ensuring continuous improvement and synchronization between digital and physical entities. PT aligns with principles like self-maintenance, self-sustaining, and self-assembly, which reinforce physical autonomy and resource efficiency. CS incorporates self-protecting, self-security, and self-healing, directly addressing the vulnerabilities of interconnected environments.

To connect SSHCPS to the overarching goals of Industry 5.0, these 23 principles are also mapped to its three core values, human-centricity, sustainability, and resilience, ensuring that the framework not only enhances autonomy but also aligns with societal and industrial priorities. Table 3 illustrates this mapping along with the redefinition of the Self-X principles, while Fig. 3 visualizes how the principles converge into the modular framework. Based on the authors' discussion, three key Self-X principles, self-sustaining, self-governance, and self-evolving, are identified as common among the modules of the proposed framework.

Recent progress in robotic technologies illustrates how Self-X first matures within the Physical Twin module before influencing other layers of the SSHCPS framework. Adaptive path planning, self-calibration, and self-maintenance routines developed in robotics exemplify practical implementations of self-optimizing and self-healing behaviors. These mechanisms are now informing Digital Twin research through self-diagnosis and self-tuning capabilities that allow virtual models to mirror and refine real-world performance. Similarly, their principles can extend to Human-in-the-Loop operations by introducing self-explaining and self-awareness features that make automated reasoning transparent and traceable for human operators. This cross-domain progression, from robotic actuation to digital representation and human collaboration, demonstrates how algorithmic advances in one component accelerate the overall convergence of Self-X capabilities across the SSHCPS.

5.2. Conceptual framework for SSHCPS

The conceptual framework integrates four interconnected modules: HITL, DT, PT, and CS. It is worth noting that the combination of DT and PT can be considered as the CPS. These modules work together to enhance efficiency, adaptability, and security in autonomous manufacturing environments. The HITL module ensures human oversight, fostering trust, safety, and informed decision-making. The DT module leverages real-time data acquisition, predictive analytics, and simulations to optimize manufacturing processes and enhance system intelligence. The PT module focuses on automation, energy efficiency, and self-sustaining operations, ensuring the physical infrastructure can function with minimal intervention. Meanwhile, the CS module plays a critical role in safeguarding the system from cyber threats through self-protection, secure communication, and intrusion detection.

5.2.1. Human-in-the-loop

The HITL module serves as a critical bridge between human intelligence and autonomous manufacturing systems, ensuring that automation remains adaptable, explainable, and aligned with human decision-making. While AI and automation enhance efficiency, they often lack contextual awareness and the ability to handle complex, unpredictable scenarios [78]. By integrating human supervision into the decision-making loop, HITL enables real-time monitoring, intervention, and optimization of manufacturing processes. This interaction ensures that human expertise guides automation where needed, enhancing system performance while maintaining flexibility. HITL also mitigates risks associated with fully autonomous systems, such as unintended errors, ethical concerns, and operational uncertainties, by allowing humans to

Table 3
Mapping the Self-X principle to SSHCPS and Industry 5.0.

Self-X principles	SSHCPS				Industry 5.0			Re-definition
	HITL	Digital Twin	Physical Twin	Cybersecurity	Human Centricity	Sustainability	Resilience	
Self-awareness	×				×			Essential for human operators to interact with intelligent systems.
Self-perception	×				×			Enables HITL to recognize and interpret contextual information.
Self-explaining	×				×			Supports transparency and human understanding in system decisions.
Self-optimizing		×					×	Enhances system efficiency through adaptive performance tuning.
Self-adapting		×					×	Enables real-time adjustment to changing operational conditions.
Self-synchronization		×					×	Facilitates coordinated operations in digital twin environments.
Self-configuration			×					Ensures autonomous system setup and integration in physical twins.
Self-maintenance			×			×		Enables predictive maintenance and longevity in physical assets.
Self-assembly			×				×	Supports autonomous system construction and adaptation.
Self-protecting				×			×	Strengthens system security by preventing cyber threats.
Self-security				×			×	Ensures secure communication and data protection.
Self-diagnosis				×			×	Facilitates real-time detection of faults and anomalies.
Self-tuning	×	×					×	Optimizes HITL and DT systems for improved adaptability.
Self-improving	×	×					×	Enhances learning and efficiency over time.
Self-description	×		×			×		Provides transparency and contextual representation.
Self-representation	×		×		×			Enables digital and physical models to represent system states.
Self-monitoring		×		×		×	×	Ensures real-time status tracking across all modules.
Self-analysis		×		×		×	×	Supports decision-making based on system data insights.
Self-reliant			×	×			×	Strengthens autonomy and operational independence.
Self-healing			×	×		×		Facilitates recovery from failures and disruptions.
Self-sustaining	×	×	×	×	×	×	×	Ensures system longevity, adaptability, and efficient resource use.
Self-governance	×	×	×	×	×	×	×	Enables autonomous decision-making and management.
Self-evolving	×	×	×	×	×	×	×	Ensures continuous improvement and adaptation in SSHCPS.

oversee and validate critical decisions [79].

Beyond enabling human oversight, the HITL module fosters collaborative intelligence, where human operators and intelligent systems work together to achieve higher levels of efficiency and adaptability. This collaboration enhances system reliability by allowing human intuition to complement machine learning-driven predictions and automated control mechanisms. Additionally, it promotes user trust and acceptance of automation by giving workers the ability to understand, influence, and refine machine behavior. As a result, HITL not only improves manufacturing productivity but also empowers human workers by making automation more intuitive and responsive to their expertise. The integration of immersive technologies and foundation models, including but not limited to large language models (LLM) [80], vision language models (VLM) [81], and vision language action models (VLA) [82], further strengthens human–machine collaboration, allowing for enhanced situational awareness and intuitive interaction with digital representations of manufacturing processes.

A crucial enabler of HITL is its Self-X capabilities, which provide the system with self-awareness, self-perception, and self-explaining functionalities. Self-awareness allows the system to continuously assess its operational state, detect anomalies, and ensure optimal performance, reducing reliance on external monitoring. Self-perception enhances the system's ability to recognize and interpret human inputs, making interactions more intuitive and effective. Meanwhile, self-explaining capabilities provide clear, interpretable reasoning behind automated decisions, ensuring that operators understand and trust system actions. These capabilities transform HITL from a basic supervisory mechanism into an intelligent, human-centric automation framework that enhances efficiency, safety, and transparency in autonomous manufacturing. By embedding these capabilities, HITL ensures that the future of manufacturing remains not only automated but also human-driven, balancing machine precision with human judgment.

5.2.2. Digital twin

The DT module plays a fundamental role by providing a virtual replica of physical manufacturing processes, assets, and environments. This digital counterpart enables real-time data acquisition and processing, allowing for continuous synchronization between the physical and digital worlds. By leveraging predictive analytics and simulation capabilities, DT empowers manufacturers to conduct extensive shop-floor management and control analyses [83], optimize operations, detect inefficiencies, and address potential failures. Through real-time mirroring of the PT, DT not only enhances decision-making but also minimizes risks, reduces downtime, and improves overall system

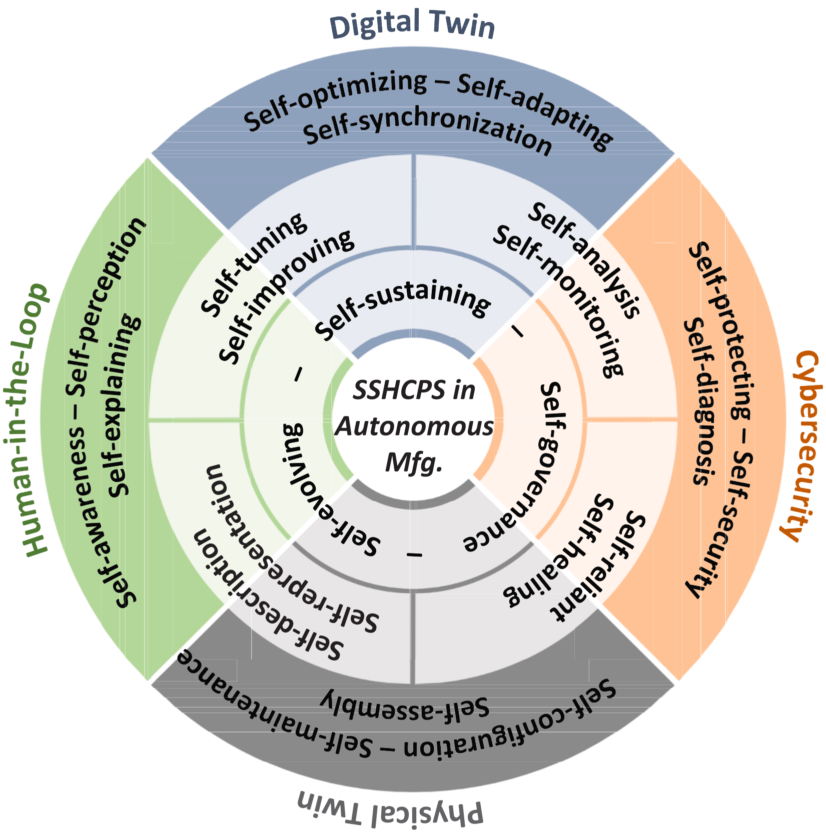

Fig. 3. Mapping Self-X principle to SSHCPS framework.

resilience [84]. In autonomous manufacturing, where precision and adaptability are paramount, DT ensures that all operational variables are monitored, analyzed, and fine-tuned dynamically, leading to more robust and efficient production systems [85].

One of the most transformative aspects of DT in SSHCPS is its ability to support autonomous optimization and adaptation. The integration of Self-X capabilities, such as self-optimizing, self-synchronization, and self-adapting, allows the digital model to continuously refine its parameters, adjust workflows, and synchronize data streams with minimal human intervention. Self-optimizing DT leverages advanced algorithms to enhance performance by dynamically adjusting system parameters based on real-time insights. Self-synchronization ensures seamless coordination between digital and physical elements, reducing latency and improving responsiveness to changes. Meanwhile, self-adapting DT enables the system to evolve over time, adjusting to fluctuations in production demands, environmental conditions, or unforeseen disruptions. These capabilities collectively enhance the agility and resilience of autonomous manufacturing, ensuring that processes remain efficient, responsive, and continuously improving without requiring constant manual recalibration.

Moreover, DT significantly strengthens human–machine collaboration by offering an interactive, data-driven decision support system. The integration of LLMs with DT in the context of smart manufacturing and Industry 5.0 has also been studied by the community [86]. It provides engineers, operators, and decision-makers with a transparent, high-fidelity representation of the manufacturing environment, enabling them to monitor, analyze, and intervene when necessary [87]. The Self-X capabilities embedded in DT facilitate explainability, ensuring that system actions and optimizations are interpretable and justifiable. Additionally, by integrating DT with immersive technologies such as AR and virtual reality (VR), human operators can engage with manufacturing systems in a more intuitive and interactive manner. This enhances situational awareness and enables proactive problem-solving and training simulations, allowing workers to anticipate and mitigate potential failures before they occur. As autonomous manufacturing evolves, DT will remain a cornerstone technology, driving efficiency, adaptability, and security while maintaining a crucial human-in-the-loop presence to oversee and refine automated processes.

5.2.3. Physical twin

The PT module in SSHCPS for autonomous manufacturing represents the tangible, operational counterpart of the DT and serves as the foundation for all manufacturing activities. It comprises smart robotic systems, energy-efficient operations, and sensor-actuator networks that work in coordination to execute precise manufacturing tasks. PT interacts directly with materials, tools, and the surrounding environment, translating digital insights into real-world actions [88]. By integrating intelligent automation and advanced control mechanisms, the PT ensures that manufacturing processes remain efficient, accurate, and adaptable [89]. The seamless interaction between the PT and DT enables real-time feedback loops, ensuring that adjustments made in the virtual model are instantly reflected in the physical domain. This interconnectivity is crucial in autonomous manufacturing, where precision, responsiveness, and self-sufficiency determine the system's overall efficiency and reliability.

A key feature of the PT is its ability to operate with a high degree of autonomy through Self-X capabilities, including self-sustaining, self-maintenance, and self-assembly. The self-sustaining nature of the PT ensures that it can autonomously manage resources such as power, lubrication, and cooling, optimizing energy efficiency and minimizing waste. Self-maintenance allows the system to diagnose wear and tear, schedule preventive maintenance, and even conduct minor repairs without human intervention, significantly reducing downtime and operational costs. Meanwhile, self-assembly capabilities enable robotic systems to autonomously configure or reconfigure their components based on production requirements, ensuring adaptability to different tasks and product variations. These Self-X capabilities contribute to the resilience and longevity of the physical twin, making it a robust and self-reliant component in autonomous manufacturing environments.

Beyond automation and self-sufficiency, the PT plays a critical role in ensuring system adaptability and security. Equipped with an extensive network of sensors, actuators, and embedded AI systems, the PT can dynamically respond to changing production conditions, detect anomalies, and react to potential threats in real-time. This adaptability allows manufacturing systems to operate in unpredictable environments while maintaining efficiency and safety. Additionally, the PT enhances human–machine collaboration by providing real-time sensory feedback, allowing human operators to oversee and intervene when necessary. Advanced robotic platforms integrated with the PT can work alongside human workers in shared workspaces, leveraging collaborative intelligence to enhance productivity and safety. By continuously evolving and refining its operational strategies, the PT ensures that autonomous manufacturing systems remain secure, efficient, and future-proofed against emerging challenges.

5.2.4. Cybersecurity

The Cybersecurity (CS) module within the proposed framework plays a vital role in safeguarding the integrity, confidentiality, and availability of crucial interconnected components. As depicted in Fig. 4, this module seamlessly integrates with the HITL, DT, and PT modules, functioning as a defense and coordination layer that supports secure, resilient, and adaptive operations. Rather than being an additional feature, the CS module is an intrinsic architectural layer designed to protect against cyber-physical threats, facilitate secure data exchanges, and uphold system integrity throughout both digital and physical environments. Here, CS is not merely reactive measures; it embodies a proactive stance, harnessing autonomous detection, response, and recovery capabilities that resonate with the broader goals of Industry 5.0: prioritizing human-centricity, sustainability, and resilience.

In addition, CS is treated not as an auxiliary safeguard but as a co-equal architectural module because it directly sustains the resilience and trustworthiness of human-cyber-physical interactions. While the Human-in-the-Loop, Digital Twin, and Physical Twin constitute the canonical structure of HCPS, their effective operation depends on continuous protection of data integrity, process reliability, and human trust. Positioning security at the same hierarchical level reflects its systemic interdependence with the other modules; any compromise in cyber integrity can propagate across digital and physical layers and undermine human oversight. This treatment is also consistent with recent perspectives in Industry 5.0 and HCPS research, which identify security and resilience as foundational attributes rather than supporting features [11,73]. Therefore, elevating “Secure” to an independent module does not seek numerical symmetry but acknowledges its role as an essential condition for autonomy, adaptability, and sustainability within the SSHCPS framework.

The CS module integrates several critical Self-X principles, specifically, self-protecting, self-security, self-diagnosis, and self-healing, to fortify the system against internal and external threats. Self-protecting mechanisms enable the system to continuously monitor for anomalies, unauthorized access, and behavioral deviations through AI-driven threat detection. Self-security ensures that all data communications across HITL, DT, and PT layers are encrypted, authenticated, and tamper-proof, preserving trust in digital interactions. Self-diagnosis provides real-time assessment of system vulnerabilities, enabling autonomous evaluation and the isolation of compromised components. Self-healing capabilities allow the system to restore secure operational states after a breach or failure, minimizing downtime and preserving continuity. This suite of Self-X functions positions the CS module as a dynamic enabler of operational resilience [90]. Beyond technical fortification, the CS module supports human-in-the-loop oversight, making cybersecurity transparent and actionable. Through self-explaining functionalities, the system can generate interpretable logs, alerts, and

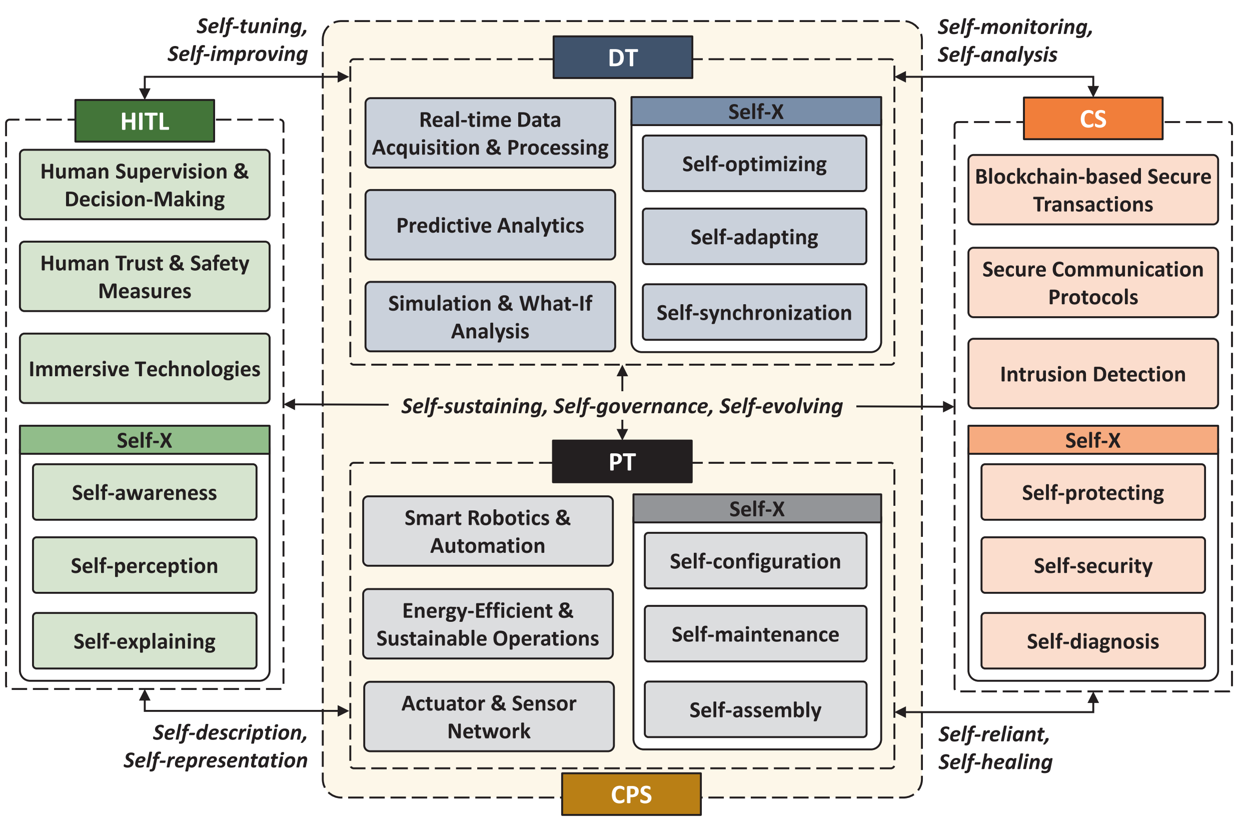

Fig. 4. Conceptual Framework for SSHCPS in autonomous manufacturing.

rationales for automated decisions, ensuring that operators are informed and can intervene when necessary. In tandem with the DT, this enhances situational awareness and empowers human actors to oversee security protocols effectively, fostering trust and collaboration [91]. Additionally, the CS module supports contextual and real-time decision-making, allowing for strategic human responses to dynamic cyber-physical threats without disrupting operations.

Ultimately, the CS module enables SSHCPS to move beyond conventional security approaches by embedding intelligence, adaptability, and collaboration into its very foundation. Its integration ensures that autonomous manufacturing systems are not only optimized and adaptive but also resilient and secure by design. As Industry 5.0 continues to emphasize interconnectedness and human–machine collaboration, the CS module provides the essential infrastructure to safeguard innovation without compromising operational integrity.

6. Potential applications

The implementation of SSHCPS presents transformative possibilities for advancing autonomous manufacturing. Rooted in Industry 5.0 principles, SSHCPS enables systems to go beyond automation by integrating self-management, human oversight, real-time decision-making, and robust cybersecurity. To illustrate its practical relevance, this section explores three distinct application scenarios where our framework can deliver measurable improvements in sustainability, resiliency, and human-centricity.

Each subsection highlights a context where the interplay of the modules unlocks new operational capabilities. From enabling autonomous operations in remote environments to enhancing agility in small and medium-sized enterprises (SMEs) through humanoid robots. These applications demonstrate not only the technical feasibility but also the strategic value of adopting SSHCPS in diverse manufacturing environments. The subsections are supported by comparative analyses and conceptual figures that position SSHCPS in relation to both Industry 4.0 and 5.0 implementations, highlighting its distinct advantages in real-world use cases.

6.1. Lightless and de-urbanized factory

The vision of a lightless and de-urbanized factory represents a shift in the smart factories [92], emphasizing fully autonomous operations in remote or off-grid environments. In such factories, human presence is minimal or intermittent, and intelligent CPS equipped with advanced Self-X capabilities operate in lightless environments, enabled by the absence of human-dependent infrastructure. This vision aligns seamlessly with the principles of the SSHCPS framework, where autonomous systems can self-monitor, self-adapt, self-diagnose, and self-maintain with minimal external support.

In a lightless factory, lighting, HVAC, and other human-centric infrastructure are no longer necessary, resulting in significant energy savings and carbon footprint reduction. The Self-sustaining and Self-maintenance capabilities of the PT become critical, enabling machines and equipment to autonomously manage energy consumption, perform diagnostics, and execute preventative maintenance routines without manual intervention. These features enhance operational continuity even in isolated environments. The DT module enables real-time simulation, monitoring, and remote optimization of processes, which is especially crucial when factories are situated in rural or hard-to-reach locations. The DT's self-optimizing and self-adapting features ensure that processes can be autonomously calibrated in response to changes in material availability, environmental conditions, or demand fluctuations. By leveraging edge computing and AI-driven analytics, these systems can remain responsive and efficient without relying on constant human input.

Cybersecurity in a de-urbanized factory takes on even greater importance. As these operations may depend heavily on remote connections, the Cybersecurity module's self-protecting, self-security, and self-diagnosis functionalities are indispensable. They enable the system to detect and counter cyber threats autonomously, ensure secure data transmission, and maintain trust in decentralized operations. The HITL module remains vital in strategic oversight, exception handling, and decision validation. Remote human operators may intervene only when necessary, supported by self-explaining and self-awareness features that provide transparency and contextual information to facilitate rapid understanding and action.

Table 4 performs a comparison between distributed manufacturing [93,94], dark Factory, light-out manufacturing [95,96], and lightless and de-urbanized manufacturing in the context of SSHCPS. Overall, the lightless and de-urbanized factory scenario demonstrates the practical realization of the framework. It embodies the principles of resilience, sustainability, and autonomy, and redefines manufacturing for a future where intelligent systems are not just tools but trusted, self-directed collaborators, capable of functioning independently and sustainably across various environmental and infrastructural contexts. Fig. 5 demonstrates how lightless and de-urbanized factories can be realized through SSHCPS and what features they will have.

6.2. Humanoid-enabled SMEs

SMEs often struggle to implement automation due to cost, complexity, and fluctuating production demands [97]. General-purpose humanoid robots offer a practical solution by providing adaptability, human compatibility, and the ability to integrate into existing infrastructure with minimal changes [98]. A key advantage of these robots is their general-purpose functionality, enabled by human-like mobility and dexterity. This allows them to perform a wide range of tasks such as assembly, inspection, material handling, and maintenance [99]. Humanoid robots can consolidate diverse manufacturing roles into one platform, improving agility and energy efficiency [100]. In the SSHCPS framework, humanoid robots play a core role in the PT module. With Self-X capabilities like self-maintenance, self-configuration, and self-adaptation, they monitor their own condition, adjust to task variations, and maintain performance with minimal oversight. Their ability to work in human-designed spaces makes them ideal for SMEs with limited floor space or highly customized operations.

Connected to the DT module, these robots receive real-time feedback to improve performance and reduce errors. Their actions can be simulated, monitored, and optimized continuously, enhancing process stability. The HITL module enables intuitive human interaction. Self-awareness and self-explaining functions help robots communicate their reasoning and respond to operator guidance. This boosts user trust and makes human-robot collaboration more effective. Security is addressed through the CS module. Self-protecting and self-security features let robots detect threats, prevent unauthorized access, and ensure safe data exchange, which is crucial in digitally connected environments. Integrating humanoid robots within SSHCPS empowers SMEs to access flexible, secure, and scalable automation. This supports Industry 5.0 goals while making advanced manufacturing accessible to smaller players. Table 5 presents a comparative analysis of Industry 4.0 and 5.0, focusing on Humanoid Robots for SMEs within the context of SSHCPS. In addition, Fig. 6 shows the humanoid-enabled SME concept.

6.3. Aerospace Industry

The aerospace sector is among the most technologically advanced and safety–critical industries, where errors can have far-reaching consequences. Traditional aerospace manufacturing has relied heavily on human expertise, with Industry 4.0 introducing advanced automation and digitalization to improve efficiency [105]. However, these developments often emphasized automation at the expense of human oversight and introduced new vulnerabilities through complex cyber-physical integrations [106]. The SSHCPS paradigm addresses these

Table 4
Comparison between distributed manufacturing, dark Factory, light-out manufacturing, and lightless and de-urbanized Manufacturing.

Aspect	Distributed Manufacturing [93,94]	Dark Factory, Light-out Manufacturing [95,96]	Lightless and De-urbanized Manufacturing (via SSHCPS)
Sustain—ability	– Reduces transport emissions via local production	– Saves energy – Eliminating lighting and HVAC – Self-sustaining	– Optimized for low energy use – Self-sustaining – Ideal for off-grid zones
Resiliency	– High resilience – Geographical dispersion – Local autonomy – Rapid response to disruptions.	– High resilience – Self-reliant – Functions in isolated environments	– High resilience – Self-reliant – Functions in isolated environments – Shorter recovery by human intervention
Human-Centricity	– Promotes local employment – Moderate human intervention – Varying standards	– Designed for full automation – Low human intervention	– Designed for full automation – Strategic human oversight via HITL – Self-explaining systems

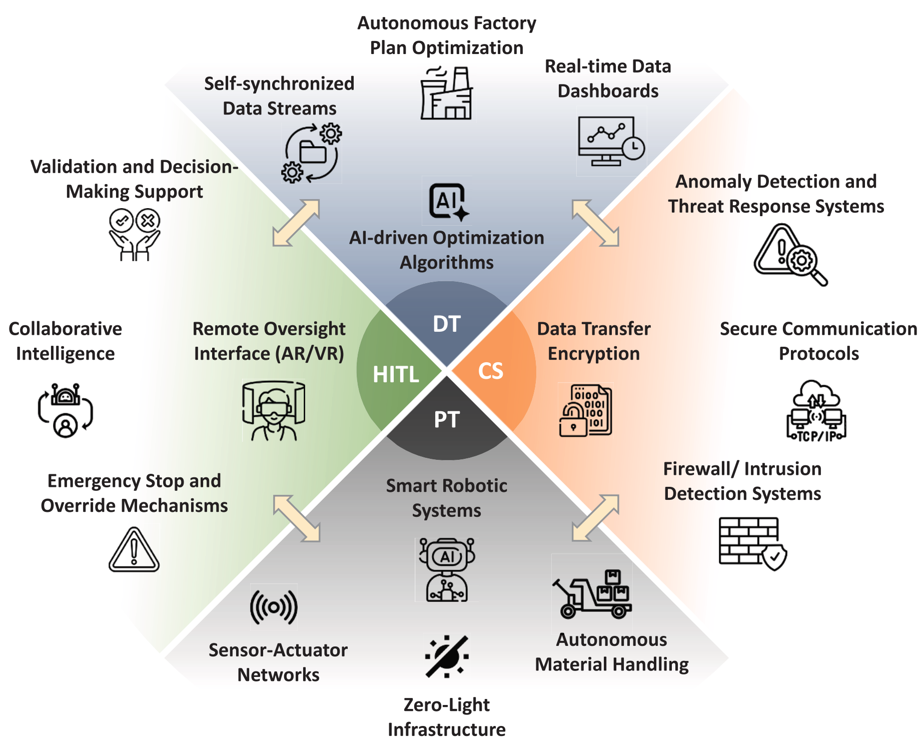

Fig. 5. Lightless and De-urbanized Factory realized through SSHCPS.

Table 5
Comparison between Industry 4.0 and 5.0 with Humanoid Robots for SMEs (via SSHCPS).

Aspect	Industry 4.0 for SMEs [101,102]	Industry 5.0 for SMEs [22,103,104]	Humanoid Robots for SMEs (via SSHCPS)
Sustain—ability	– Improves efficiency through automation – Enables waste reduction via predictive maintenance	– Focuses on sustainable production – Encourages energy-efficient and eco-conscious designs	– Reduces the need for new infrastructure by adapting to human environments – Humanoids perform multiple tasks, lowering energy and material redundancy – Initial investment may be high for SMEs
Resiliency	– Real-time data improves fault detection – Automation enhances process consistency – Vulnerable to centralized failures and cyberattacks	– Emphasizes flexible, adaptive, and human-guided systems	– Self-X-enabled humanoids can self-diagnose and adapt in SME settings – Remote HITL allows continuity during local disruptions
Human-Centricity	– Enhances operator safety/ productivity – Supports some collaborative automation – Often replaces human decision-making and skills	– Places humans at the core of design – Encourages transparent, explainable systems	– Humanoids operate in human spaces without major layout changes – HITL design enables real-time collaboration and learning by doing

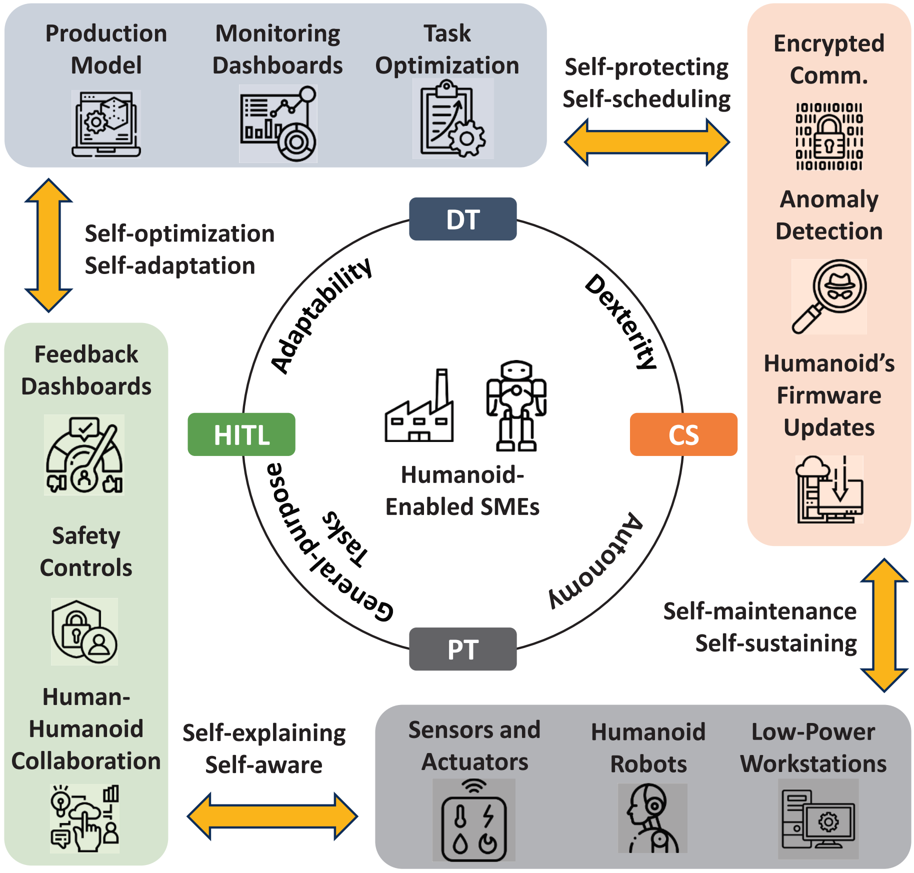

Fig. 6. Humanoid-enabled SMEs through SSHCPS.

limitations by harmonizing Self-X capabilities, HITL oversight, and proactive cybersecurity within a secure and adaptable manufacturing ecosystem. In doing so, it provides aerospace manufacturing with an architecture that not only enhances precision and efficiency but also ensures safety, compliance, and resilience in the face of disruptions.

Each module contributes to advancing aerospace manufacturing. The HITL module enables engineers and operators to remain integral to production processes, ensuring that human judgment is available to validate simulations, address unforeseen anomalies, or approve mission-critical decisions. The DT module provides high-fidelity, real-time simulations of processes such as composite material layup, turbine blade fabrication, or assembly of avionics systems. Coupled with Self-X features like self-optimizing and self-adapting, DTs ensure that processes are continuously fine-tuned to maintain quality and reduce waste. The PT module focuses on execution with embedded self-maintenance and self-sustaining features, enabling precision machining, robotic assembly, and automated inspection systems to operate reliably while minimizing downtime and resource consumption.

Cybersecurity plays an equally vital role in aerospace manufacturing under SSHCPS. Intellectual property protection, flight-critical system integrity, and secure supply chain interactions demand resilience against cyber threats. The CS module incorporates Self-X capabilities such as self-protecting, self-security, and self-diagnosis to safeguard sensitive digital assets and maintain operational trust. For instance, the CS module ensures that a DT of an aircraft engine cannot be tampered with during design iterations, while self-healing features allow systems to recover from attacks with minimal disruption. Importantly, HITL oversight provides an additional safety net, allowing aerospace

Table 6
Comparison between conventional aerospace manufacturing, Industry 4.0 aerospace, and SSHCPS-enabled aerospace.

Aspect	Conventional Aerospace Industry [107]	Industry 4.0/5.0-based Aerospace [105,106]	SSHCPS on top of Industry 5.0 Aerospace
Sustain −ability	– High material waste in manual/legacy processes- Limited real-time optimization	– Improved efficiency via automation and digital twins – Energy-intensive operations and complex infrastructure	– Self-sustaining PT reduces energy/ resource use – DT-driven optimization lowers material waste – Alignment with sustainability goals
Resiliency	– Relies heavily on human expertise – Vulnerable to human error and downtime	– Automated systems improve consistency – Cyber-physical vulnerabilities can cascade disruptions	– Self-healing and self-diagnosis minimize failures – Secure, adaptive systems maintain continuity – Faster recovery from disruptions
Human-Centricity	– Human expertise is central, but labor-intensive – Limited digital support tools	– Reduced human role as automation dominates – Lower transparency in automated decision-making	– HITL ensures human oversight in critical tasks – Self-explaining DT improves transparency – Balanced collaboration between humans and machines

engineers to monitor security alerts, interpret system explanations, and intervene where necessary. This balanced integration ensures that even in highly automated environments, humans remain the final safeguard for mission-critical processes.

Table 6 compares SSHCPS with earlier eras of aerospace manufacturing, conventional methods, and Industry 4.0 approaches, across the key Industry 5.0 dimensions of sustainability, resiliency, and human-centricity. The comparison highlights how the proposed framework represents a paradigm shift, extending beyond efficiency-driven automation toward a secure, adaptive, and human-centered model tailored to the unique demands of aerospace.

7. Technical challenges and actionable solutions

The implementation of an SSHCPS in the Industry 5.0 era presents several technical challenges that must be addressed to ensure scalability, resilience, and sustainability. In this section, we revisit these challenges and propose actionable solutions that align with the goals of Industry 5.0.

- *Real-time Data Processing and Latency:* SSHCPS depends on seamless real-time data exchange between humans, digital twins, and physical systems. Processing vast amounts of sensor and interaction data with minimal delay remains a major challenge. To address this, edge computing can be integrated to reduce latency by processing data closer to its source, while 5G-enabled communication networks enhance bandwidth and responsiveness. Self-optimizing and adaptive data-streaming algorithms can dynamically balance loads to ensure consistent performance. These measures enable HITL operators to engage effectively without delay, enhancing both resiliency and human-centricity.
- *Cybersecurity Vulnerabilities:* As SSHCPS integrates IoT, AI, and digital twins, it becomes a prime target for cyberattacks such as ransomware or model manipulation. Conventional defenses are insufficient for such threats. Proactive measures include adopting blockchain-based frameworks for tamper-proof data sharing, implementing AI-driven self-healing to autonomously isolate and recover compromised nodes, and embedding self-protecting and self-diagnosis mechanisms at runtime. These ensure that cybersecurity evolves from a reactive safeguard to an adaptive, self-reinforcing capability, aligned with Industry 5.0′s goals of trustworthiness and resilience.
- *Scalability and Interoperability:* Manufacturing environments vary widely, and deploying SSHCPS across SMEs and large enterprises requires adaptable and interoperable solutions. Standardized communication protocols such as OPC UA and ISO/IEC frameworks can provide the backbone for interoperability. Embedding self-configuration and self-synchronization allows SSHCPS to integrate new machines, sensors, or digital twins without extensive manual reprogramming. These strategies strengthen scalability while ensuring that even SMEs can adopt SSHCPS, reinforcing Industry 5.0′s inclusivity and human-centricity.
- *Trust and Ethical Considerations:* AI-driven decision-making in SSHCPS raises issues of trust, accountability, and fairness. To address these, explainable AI (XAI) can be embedded into HITL interfaces, ensuring that automated actions are interpretable and auditable. From a broader perspective, it can be enhanced by Generative AI (GenAI), which is behind the artificial intelligence-generated content (AIGC) [108], through adaptive decision support, self-explaining system outputs, and generative simulations that strengthen human-in-the-loop collaboration and resilience. On the other hand, ethical AI governance frameworks should define standards for fairness and accountability, while self-explaining mechanisms ensure that operators understand the rationale behind system behaviors. This transparency builds confidence among users, aligning SSHCPS with Industry 5.0′s emphasis on human-centricity and responsible innovation. More recently, federated learning-empowered smart manufacturing and product lifecycle management [109] has also become a topic of interest among researchers, which can be complemented by the proposed SSHCPS paradigm.
- *Human-Machine Collaboration:* Seamless collaboration between humans and intelligent systems is crucial but challenging due to variations in human cognition, skills, and adaptability. Actionable solutions include the integration of multimodal interfaces, such as AR, VR, haptic feedback, and natural language processing, to enhance intuitiveness and inclusivity. Embedding self-tuning and self-improving feedback loops allows systems to adapt interfaces to user behavior, making collaboration smoother and more personalized. These measures ensure that humans remain empowered and engaged, reinforcing Industry 5.0′s vision of augmenting rather than replacing human capabilities.
- *Energy and Resource Efficiency:* The computational intensity of SSHCPS poses sustainability challenges. High-performance AI models and large-scale data processing consume substantial energy. Solutions include the development of lightweight AI models, green computing strategies, and optimized resource scheduling to minimize energy consumption. Integration with renewable energy systems and embedding self-sustaining PT mechanisms further reduces the environmental footprint. These strategies align with Industry 5.0′s sustainability imperative, ensuring that efficiency gains are balanced with ecological responsibility.
- *Emerging AI Paradigms for Industry 5.0:* Beyond addressing immediate technical challenges, the future of SSHCPS lies in adopting value-oriented AI paradigms tailored to Industry 5.0 [110]. Physics-informed machine learning (PIML) can embed domain knowledge into AI models, reducing data requirements and enhancing interpretability. Federated learning allows distributed systems to collaboratively train models while preserving data privacy, a crucial factor in interconnected ecosystems. Diffusion model-driven design [111] can support generative and adaptive manufacturing processes, enabling rapid prototyping and mass customization. Finally, human-centric AI frameworks ensure that autonomy complements, rather than overrides, human expertise. Incorporating these paradigms strengthens SSHCPS's alignment with Industry 5.0′s pillars of human-centricity, resilience, and sustainability.

Table 7 provides a structured overview of the major technical challenges encountered in implementing SSHCPS, the corresponding actionable solutions proposed in this study, and their alignment with the three core values of Industry 5.0: human-centricity, sustainability, and resiliency. By consolidating these aspects, the table not only highlights how SSHCPS can overcome current limitations but also demonstrates its potential to serve as a practical and future-oriented paradigm for autonomous manufacturing.

8. Summary and outlook

8.1. Summary

In this paper, we introduced the SSHCPS as a comprehensive framework designed to advance autonomous manufacturing in the era of Industry 5.0. Through a review of 48 Self-X terms, distilled into 23 key principles, and a meticulous mapping to the modules and Industry 5.0 essentials, this research offers a detailed analysis of how autonomous systems can be enhanced with human-centric and security-focused features. The framework integrates advanced Self-X capabilities, such as self-awareness, self-optimization, and self-protection, with HITL principles and robust cybersecurity measures. This creates a manufacturing system that is not only autonomous but also secure, resilient, and aligned with human needs. The framework is structured around four interconnected modules:

Table 7
Technical challenges in SSHCPS and actionable solutions aligned with Industry 5.0 values.

Challenge	Actionable Solutions	Alignment with Industry 5.0 Values
Real-time Data Processing & Latency	Edge computing, 5G-enabled communication, adaptive streaming, and self-optimizing algorithms	Resiliency: continuous operation under load Human-centricity: seamless HITL interaction
Cybersecurity Vulnerabilities	Blockchain frameworks; AI-driven self-healing, embedded self-protecting, and self-diagnosis	Resiliency: proactive defense Sustainability: avoids costly disruptions Human-centricity: trust in secure operations
Scalability & Interoperability	Standardized communication protocols, self-configuration, self-synchronization	Resiliency: adaptable across contexts Human-centricity: enables SME participation
Trust and Ethical Issues	XAI, GenAI, ethical governance frameworks, self-explaining interfaces	Human-centricity: accountability and transparency Resiliency: builds confidence in AI systems
Human-Machine Collaboration	Multimodal interfaces (AR/VR, NLP, haptics), self-tuning, and self-improving feedback	Human-centricity: inclusive interaction Sustainability: supports long-term adoption
Energy and Resource Efficiency	Lightweight AI models, renewable integration, optimized scheduling, and self-sustaining PT	Sustainability: reduced environmental impact Resiliency: stable energy-aware operations
Emerging AI Paradigms	Physics-informed ML, federated learning, diffusion model-driven design, human-centric AI	Human-centricity: interpretable and collaborative AI Resiliency: distributed, adaptive learning Sustainability: efficient resource use

- *Human-in-the-Loop (HITL):* Ensures meaningful human oversight through self-awareness and self-explaining features.
- *Digital Twin (DT):* Leverages self-optimizing and self-adapting capabilities for real-time process enhancement.
- *Physical Twin (PT):* Focuses on self-maintenance and self-sustaining operations.
- *Cybersecurity (CS):* Employs self-protecting and self-security mechanisms to safeguard against cyber threats.

Building on the foundations of Industry 4.0 and 5.0, SSHCPS addresses the shortcomings of fully automated systems by reintroducing human expertise via HITL, ensuring flexibility and trust in automation. The incorporation of Self-X principles enables the system to dynamically adapt to changing conditions, optimize performance, and protect itself from emerging threats. Furthermore, it provides a structured approach to embedding cybersecurity within autonomous manufacturing, a critical yet often neglected aspect of traditional smart systems, ensuring operational continuity amidst cyber-physical risks. The paper also explores potential case scenarios, such as its application in aerospace manufacturing, demonstrating SSHCPS's ability to optimize processes, maintain security, and facilitate human intervention. However, implementing the proposed framework presents technical challenges, including real-time data processing, cybersecurity vulnerabilities, scalability, trust in AI-driven decisions, effective human–machine collaboration, and energy efficiency. These challenges highlight areas for future research and development.

Beyond proposing the SSHCPS framework, this study identifies several converging trends that are shaping the future of autonomous and human-centric manufacturing. The literature reveals a growing shift from reactive automation toward self-protecting, self-healing, and self-optimizing architectures that combine adaptive intelligence with human oversight. The analysis also highlights cybersecurity as an underexplored yet essential dimension influencing each module differently: within the Human-in-the-Loop layer, it ensures trust and interpretability of machine actions; in the Digital Twin, it preserves the integrity and privacy of virtual representations; and in the Physical Twin, it secures operational continuity and fault isolation. These differentiated effects demonstrate that security is not an auxiliary function but a driver of resilience. Looking ahead, progress will depend on empirical validation of Self-X behaviors, interoperable standards linking DT-PT ecosystems, and robust human–machine trust metrics. Addressing these directions will transform SSHCPS from a conceptual foundation into a deployable pathway for secure and sustainable Industry 5.0 manufacturing. In conclusion, SSHCPS marks a significant leap forward in autonomous manufacturing. It offers a secure, efficient, and human-centric solution that aligns with Industry 5.0′s vision of human-centricity, sustainability, and resilience. By harmonizing autonomy, security, and human collaboration, SSHCPS establishes a new benchmark for the future of intelligent and resilient industrial automation.

8.2. Outlook

Although SSHCPS consolidates key elements for autonomous manufacturing, targeted studies are required to translate the concept into practice. First, controlled testbeds and pilot lines should be established to quantitatively validate Self-X behaviors across the HITL, Digital Twin, and Physical Twin layers, with repeatable protocols for latency, stability, and recovery. Through this, self-optimizing and self-healing functions can be measured under realistic load and disturbance. Second, interoperability studies are needed to operationalize integration with existing CPS, focusing on implementation profiles based on current industrial communication standards and lifecycle data continuity between DT and PT, and reporting the migration steps, costs, and risks for SMEs and large plants. Third, human-in-the-loop evaluation protocols should be designed to assess decision quality, transparency, and operator workload during routine operation and abnormal events, comparing alternative interface designs and levels of automation, and documenting how these choices affect resilience and throughput. Fourth, cyber-resilience exercises using a manufacturing-oriented cyber-range should test self-protecting and self-security mechanisms with clear metrics for detection time, containment, and safe recovery. Fifth, energy-aware operation studies should examine scheduling and control strategies that maintain SSHCPS performance while reducing computational and facility energy use, reporting trade-offs between responsiveness, accuracy, and resource consumption. Finally, multi-site longitudinal pilots should synthesize these aspects, demonstrating scalability across different products and shop-floor configurations and documenting the conditions under which secure, resilient, and human-centric operation is sustained. Addressing these directions will move SSHCPS from conceptual architecture to validated deployment within the evolving Industry 5.0 landscape.

CRediT authorship contribution statement

Mahdi Sadeqi Bajestani: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Changjong Kim:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Kyung-Chang Lee:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Duck Bong Kim:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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