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The human-centric Industry 5.0 collaboration architecture

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A R T I C L E I N F O

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I5arc - Industry 5.0 collaboration architecture

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A B S T R A C T

While the primary focus of Industry 4.0 revolves around extensive digitalization, Industry 5.0, on the other hand, seeks to integrate innovative technologies with human actors, signifying an approach that is more value-driven than technology-centric. The key objectives of the Industry 5.0 paradigm, which were not central to Industry 4.0, underscore that production should not only be digitalized but also resilient, sustainable, and human-centric. This paper is focusing on the human-centric pillar of Industry 5.0. The proposed methodology addresses the need for a human-AI collaborative process design and innovation approach to support the development and deployment of advanced AI-driven co-creation and collaboration tools. The method aims to solve the problem of integrating various innovative agents (human, AI, IoT, robot) in a plant-level collaboration process through a generic semantic definition, utilizing a time event-driven process. It also encourages the development of AI techniques for human-in-the-loop optimization, incorporating cross-checking with alternative feedback loop models. Benefits of this methodology include the Industry 5.0 collaboration architecture (I5arc), which provides new adaptable, generic frameworks, concepts, and methodologies for modern knowledge creation and sharing to enhance plant collaboration processes.

- The I5arc aims to investigate and establish a truly integrated human-AI collaboration model, equipped with methods and tools for human-AI driven co-creation.
- Provide a framework for the co-execution of processes and activities, with humans remaining empowered and in control.
- The framework primarily targets human-AI collaboration processes and activities in industrial plants, with potential applicability to other societal contexts.

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Resource availability:	Ontology-based analysis of manufacturing processes: https://github.com/abonyilab/wire_harness_assembly

Method details

Introduction

The importance of increasing productivity while not removing human workers from the shopfloor creates challenges for the production enterprises and the developers of industrial information systems. Additionally, the horizontal and vertical integration of systems requires more efficient data processing in Industry 4.0 applications.

The European manufacturing industry’s key challenge is improving its productivity and resilience to possible external market turbulence and resource availability. The ongoing Industry 4.0 digitalization technologies create a fair technical condition to cope with this challenge. However, the recent digitalization impact studies indicate that developing manufacturing plants with sophisticated, in many cases, not interoperable technical systems alone will not fully address this challenge, as resulted in human-centric Industry 5.0 focus [1]. Despite the digitalization and automation focus, humans (e.g., operators, technicians) will remain as a fundamental resource for competitiveness of the manufacturers, especially for activities requiring flexibility, customization, and uniqueness [2]. Humans will have fewer physical tasks in the highly automated and digitalized factories of the future, but more decision making and problem-solving tasks [3] in the context of increasingly complex, socio-cyber-physical manufacturing system [4].

The Industry 5.0 collaboration architecture (I5arc) supports the development and implementation of human-AI collaborative process design and innovation methodology to support the design and implementation of next-generation AI-driven co-creation and collaboration tools. From this motivation, the scope of the I5arc specified as:

- Collaboration knowledge: required for efficient and resilient plant operational process (e.g., supervision, quality control, maintenance, remote assistance).
- Research: new generic, sector-independent Industry 5.0 collaboration concepts and architectures.
- IT services: management of knowledge structures (based on the Semantic web) and user-controlled creation and use of knowledge.
- Business: improving plant productivity and resilience by better multi-agent collaboration.
- Human control: the capability to customize the generic collaboration platforms and processes, with user-friendly communication, and reliable and explainable AI (Artificial Intelligence) knowledge services.
- Availability: I5arc services accessible from standard desktop and mobile wearables (e.g., smart glasses). Plant specific user-friendly Communication Language (PCL) for all collaboration agents.

The research gap is the development of a comprehensive methodology that enables effective human-AI collaboration, incorporating diverse innovative agents in plant-level processes. This includes creating adaptable frameworks, tools, and techniques that facilitate human-AI co-creation and co-execution while ensuring humans remain empowered and in control. Additionally, the methodology should be applicable to various societal contexts beyond industrial plants, extending its potential impact and relevance.

The I5arc identified five topics, that constitute the conceptual and technological challenges to be overcome:

√ AI-Human co-creation of ontology-based Plant Knowledge Base (PKB) structure.
√ Co-creation and execution of multi-agent resilient and innovative collaboration processes.
√ Explainable and trustworthy AI services for empowering users.
√ Immersive learning services for Human-AI collaboration.
√ Sustainable I5arc Innovation Methodology.

Background

This Section summarizes the background, the problem statement, the need of the industry, and the development goals of the human-centric collaboration architecture topic. First describes the needs of industry stakeholders, then presents the main goals of the Industry 5.0 collaboration architecture. Finally the semantic web-based approach of collaboration support is introduced.

The common needs of the manufacturers

The manufacturing industries must face rapid technological transformation, mass customization, and the need for advanced manufacturing. Robots must be coupled with the human mind and a strong necessity to increase productivity [2]. This problem is addressed by digitalizing human-centric plant-level collaboration activities (e.g., production unit set-up, work safety, maintenance, repairs, etc.). The common need in this domain can be summarized as follows:

(a) The collaboration activities are planned or recorded in unstructured formats [5]. Although there are simple data entry (check-list) apps on the market, the industry acceptance could be higher for several reasons: special working conditions (as free hands requiring smart glasses [6]or flexibility in the process change. These apps are mainly capable of 1:1 Human-machine interactions only.
(b) However, the core problem is the need for more approaches and solutions for the coordination and digitalization of collaboration activities of several actors [7] in real-time. Humans, IoT Machine, AI services in the future working together in a process e.g., in major production line repairs.
(c) Limited availability of user-friendly practices for structuring and reusing collected process data by other participants (e.g., plant technologists) and AI services. Furthermore, there is a clear professional user interest to act not only as an operator but as a knowledge co-creator of digital service structures and be able to access and contribute to the company's knowledge base directly from their workplace.

Aims of the Industry 5.0 collaboration architecture

The Industry 5.0 collaboration architecture (I5arc) aims to solve the question: how does the quality of collaboration in terms of technical tools, knowledge services, and the social environment provided for participants affect manufacturing process quality and operational sustainability? The main aims are the followings:

1. Availability of digital content of the collaboration processes (planned, performed, and evaluated) as part of the plant's digital twin.
2. The latest technologies are integrated into the process: wearables for in-line digitalization of user interactions [8], VR/AR, and extended reality visualization services.
3. The extent of creation and reuse of new knowledge produced by reliable AI services, alongside the whole collaboration process.
4. Availability of comprehensive methods for user-controlled creation and instant innovation of plant-specific collaboration platforms.
5. Social management of the new digital collaborating culture. Inclusion of all relevant stakeholders of the plant - from top management to frontline workers - into controlled creation and access to knowledge about the collaboration processes. Services for on-demand learning and remote work services improve plant human resources' work-life balance.

The human-centric collaboration supported by the semantic web methodologies

The Semantic Web stands for an extension of the World Wide Web with standards aiming to make the internet data machine-readable. It involves publishing in languages specifically designed for data, such as Extensible Markup Language (XML), Resource Description Framework (RDF) and Web Ontology Language (OWL). An ontology can be determined as a graph-based data model that manages how entities (individuals) are grouped into categories (classes) and which appear on the most fundamental level. Additionally, ontologies can describe real-world phenomena and their relationships among each other in a machine-readable way by using formal elements, such as instances, rules, relationships and axioms [9]. A knowledge graph is a highly flexible non-SQL database representing data as "knowledge" through a graph-like structure of nodes and edges. The nodes that refer to the knowledge are often defined in an ontology, the concepts that describe the domain. They can be traversed semantically using domain knowledge.

An ontology-based development framework is visualized in Fig. 1, where the three main steps are data collection, ontology modeling, and the so-called advanced manufacturing analytics [10]. Semantic technologies can be combined not only with manufacturing-related analytic tools, but with industrial standards and specific Industry 5.0 technologies, which can facilitate the creation of a human-centered knowledge graph [11]. Industry 5.0 will be an "Age of Augmentation" or the human-machine symbiosis [8]. However, humans must be well-aware of the decision they are making and why. Humans must establish confidence in the automatically derived predictions and suggested decisions within smart factories [12]. The Operator 4.0 concept [13] is the lead framework of human-centered solutions. Also, a common interface for Operator 4.0 applications as an architecture of a human-digital twin is proposed [14], and the enabling technologies of Operator 4.0 [13] are compared with the Industry 4.0 solutions. Furthermore, brownfield digitalization smart retrofitting solutions can be aided by integrating the Operator 4.0 concept with IoT and further Industry 4.0 solution [15].

Additional emerging graph-based modeling and analysis method relays on hypergraphs, which is a generalization of a graph, where an edge (also known as a hyperedge) can connect more than two vertices. Hypergraph-based representation and analysis can be applied to identify the indirect interactions in a complex system or data structure [16] or can support the human-centric approach

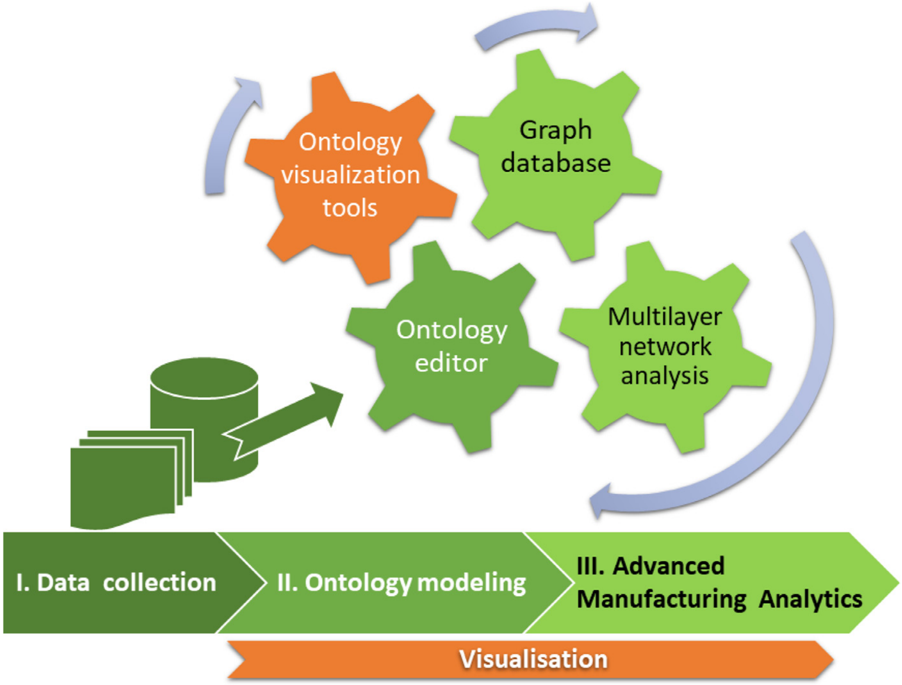

Fig. 1. Ontology-based development framework for manufacturing process analysis [10].

as described in connection with the so-called Intelligent collaborative manufacturing space [17] as well. It can be concluded, that graph or hypergraph-based semantic networks as ontologies or knowledge graphs has a high potential to facilitate data integration and contextualization in Industry 4.0 and 5.0 environments.

Several semantic web methodologies and systems are studied and tested [10,18], suitable to implement the semantic framework for a manufacturing plant: PoolParty [19], Oxford Semantics, and Ontotext. The aim is to find the ideal operational platform that provides the best user interface for creating and updating plant taxonomy and ontology. The semantic web standards have analysed, which are available for manufacturing execution systems (MES) [20]. Their disadvantages include needing more detailed collaboration, location and time concepts, and relationships.

Method details - The I5arc framework

This section introduces the I5arc approach for human-AI collaboration, starting with the main methodology, the I5arc Process Innovation Cycle. First, the Human-AI empowerment approach, then the event-driven workflow concept is presented. The proposed I5arc framework introduces a new culture for plant-level multi-agent collaborations involving the support of AI agents, where human is a center point in these processes. Therefore, the key challenge is the Human-AI acceptance of this type of collaboration. The approach aims to introduce tangible, reliable economic, technical and social benefits.

The I5arc Innovation Cycle Methodology (ICM) presented in Fig. 2 represents the integrated objective of the project and establishes a framework for co-design and execution of human-AI collaborative processes functioning and adapting towards common goals, combining the best of human and AI roles, knowledge, and abilities, as well as incorporating the societal requirements. Therefore, the proposed framework addresses six improvement opportunity domains highlighting the key results, namely: *1.* Evaluate and plan the process, *2.* Design process in PCL (Plant Collaboration Language), *3.* Consider societal aspects, *4.* Implement the process, *5.* Create digital knowledge in PCL and *6.* analyze process knowledge. The participating agents of the I5arc Process Innovation Cycle are also visualized in Fig. 2, such as Plant knowledge worker, AI agent service, Frontline worker, Collaborative robot and IoT device. Additionally, the internal tasks of the six domains are also listed in Fig. 2.

Furthermore, the I5arc framework defines the following new research concepts in RDF notations:

1. Collaboration participant: Definition of collaboration scope of the participant. Multi-agent participant classes (Human, IoT machine, Robot, AI service).
2. Participant actual tasks overview: An overview of collaboration tasks where the participant must or can participate.
3. Active participation: Participation in a task of a manufacturing process (work order). An agent can participate in several work order tasks.
4. Recommended participation: Recommended by a participant's supervisor or by Recommendation of AI services.

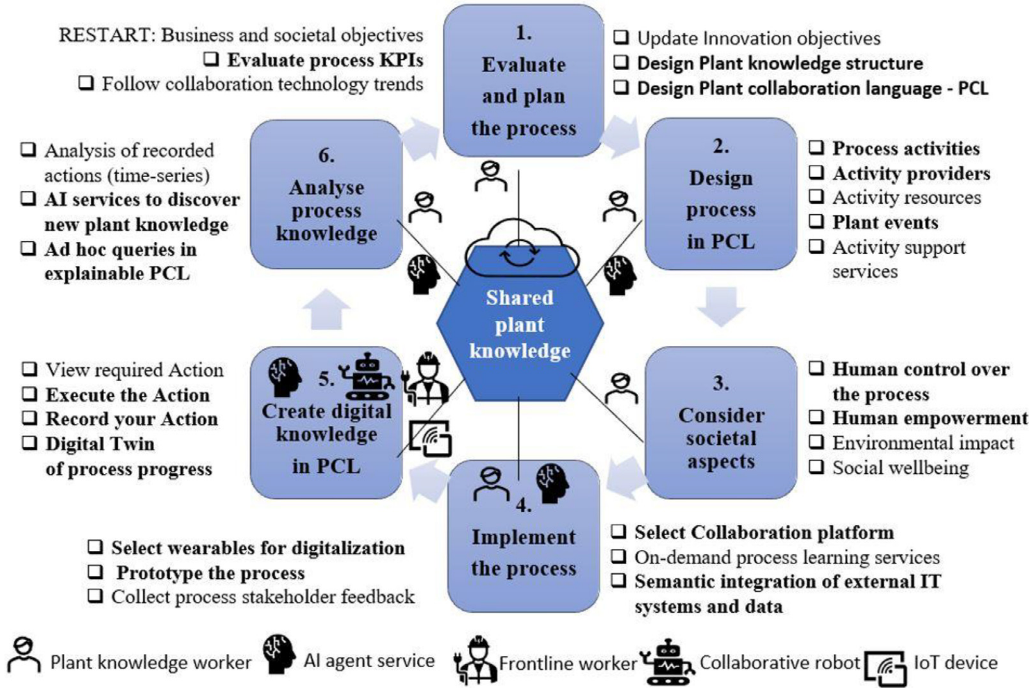

Fig. 2. The methodology of the I5arc Process Innovation Cycle, that creates the Shared plant knowledge with the combination of the six elements.

5. Plant events: Relevant plant operational events structured by process domains. Event attributes are name, value, time of setting, and plant location relevant to the event. The event can be single or composed of Boolean expressions.
6. Collaboration process: Defines the standard collaboration activity structure in the plant. Collaboration platforms and plant operational domains can structure it. Execution of concurrent workflows (work orders) is synchronized by plant events, as outlined in Fig. 2. The process can involve several concurrent workflow instances.
7. Collaboration platform: Technical, operational environment providing certain collaboration support services. (e.g., AR, VR, 3D Models) available to agents.
8. Plant operational assets: Plant asset register by locations and asset classes (machines, infrastructure, systems). The ISA-95 standard for Production model taxonomy and Plant resources is also recommended for implement.
9. Plant resources: Structured by agent, raw material, energy, tools, consumables, and services classes, and their instances.
10. Plant knowledge base (PKB): Contains formal machine-readable definitions, relationships, and instances of the *1–9.* concept. Human-centric interaction with PKB in a user-definable metalanguage.

The human-AI empowerment approach

The introduction of credible human empowerment for any new work culture requires:

- Humans with access to up-to-date tacit knowledge perform their work with high quality and satisfaction.
- AI, which services, must use the same tacit knowledge to create new and trustworthy knowledge for humans.

The cornerstone of the solution is the plant's digital memory, a consistent and common source of any activity for Humans and AI services. Therefore, the implementation of the Plant Knowledge Base (PKB) concept is key to addressing the needs and ambitions of this framework. The technical measures are summarized in Fig. 3, where the three main categories are the *Common Plant Knowledge Base (PKB)*, the *Plant collaboration Language (PCL) with user services* and the *On-line visualization services (Explainable AI)*. The relevant factors for empowerment are listed for each group on Fig. 3.

The common technical measures should be dedicated to each stakeholder group participating in the collaboration processes:

- Company managers (improved productivity and resilience).
- Plant specialists (improved governance and analytics on the process).
- Frontline workers (online support for work execution and workplace learning).
- Citizen groups (access of less qualified workforce to qualified jobs).

The implementation approach and the collaboration levels (platforms) can be adjusted to the company culture and digital maturity of the plant human resources by support services as:

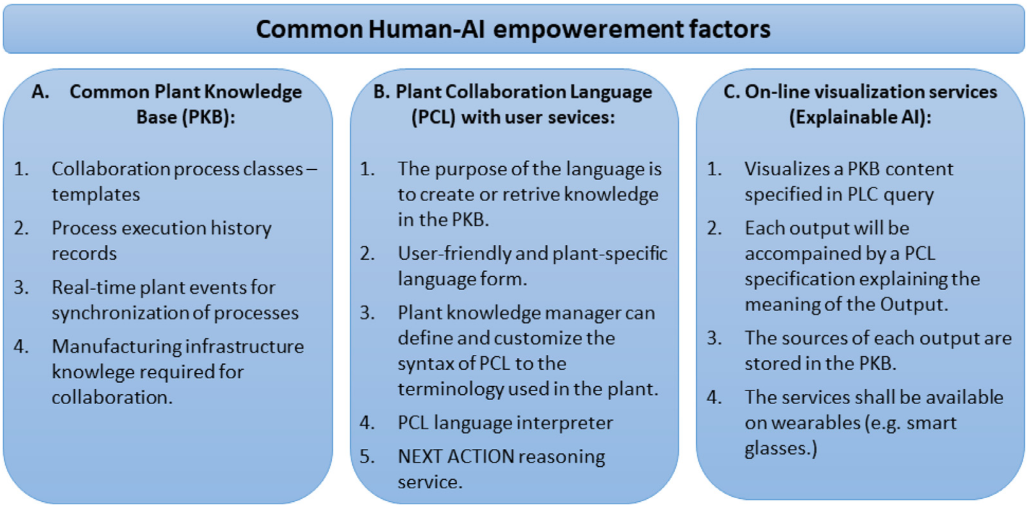

Fig. 3. Human-AI empowerment factors in three categories: Common Plant Knowledge Base, Plant Collaboration Language and On-line visualization services.

- Providing tacit and AI-generated plant knowledge *via* user-friendly communication language and visualization services.
- Real-time learning-on-demand of collaboration tasks of human participants adjusted to their role.
- Remote and extended reality collaboration services improve the work-life balance of the plant's human resources.
- Access of less qualified workers to more skilled jobs.

The event-driven workflow concept

An important feature of the approach is the generalized definition of the participant (*1.*). The most frequent scenario in many high-tech industrial plants, the bilateral Human – AI relationship is analysed and optimized in a multi-agent collaboration efficiency context. The concepts are centered around. The primary activity concept of the collaboration process (*6.*) - the I5arc event-driven workflow concept is demonstrated in Fig. 4. This innovative concept enables time and location-sensitive control of the execution of each elementary workflow action. Additionally, the interaction of PKB with collaboration scenarios (multi-agent workflows) is also outlined in Fig. 4. A *workflow* depends on the *Collaboration process*, the *Requester resource* and the *Provider resource*. Sub-steps and instructions are the building elements of a complex workflow. The results of instructions trigger the different events in Fig. 4. Additionally, the instructions are enabled by certain events only. The *steps* (group of actions) are related to a physical location (as machines or components) of the plant.

Thanks to the presented workflow, the I5arc framework enables to embed of the vital priority (human AI empowerment) into the broader perspectives of the manufacturing plant level collaboration needs as:

- Multi-agent real-life scenarios where Human agents have increased control roles.
- Creation of a solid and focused research foundation for this broader approach, resulting in increased empowerment of the introduction and use of AI in manufacturing.

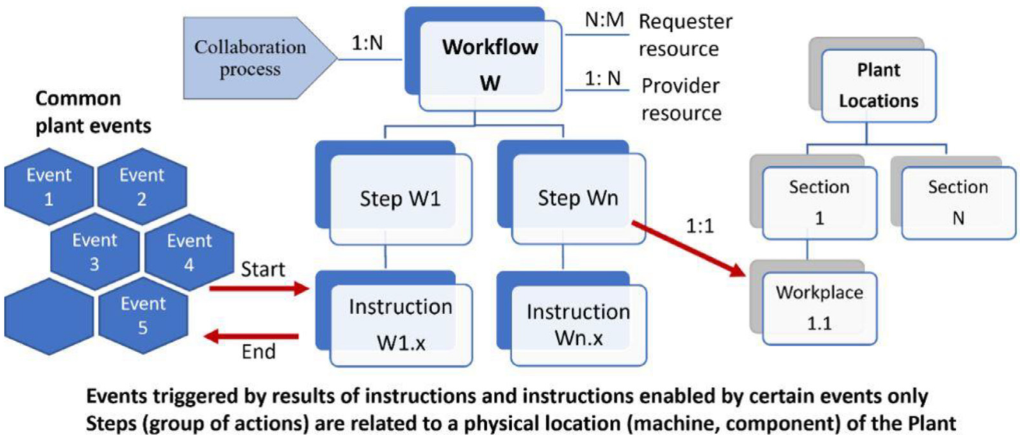

Fig. 4. The methodology of event-driven workflow concepts, which aims to support human-AI collaboration.

- Common communication language (PCL – Plant Collaboration Language) among all agents always *via* the PKB interaction services.

Advantages and disadvantages of the proposed framework

Based on the previous discussions of the methodology, this subsection aims to summarize the potential advantages and disadvantages of the human-centric Industry 5.0 collaboration architecture.

The potential advantages of adopting the presented human-centric approach are numerous and could have significant impacts on productivity, efficiency, and innovation, including the followings:

- Improved collaboration: The human-centric approach promotes cooperation and collaboration between humans and machines, fostering a more efficient, resilient, and innovative work environment.
- User-oriented design: AI-driven co-creation of PKB ontology accommodates user needs, work culture, and plant terminology, leading to more intuitive and easy-to-use tools.
- Enhanced decision-making: The ability to incorporate human input in real-time, event-driven processes can lead to more informed decision-making, thereby improving the overall efficiency and productivity.
- Flexibility: This approach allows for the participation of multiple innovative agents, providing the flexibility to adapt to different situations and requirements.
- Continuous innovation: The model encourages ongoing innovation, with an ontology-controlled PKB IT service portfolio that supports the evolution of collaboration processes.

However, as with any transformative change, there are also potential challenges and disadvantages to consider, which may include:

- Technological complexity: The integration of various innovative agents such as AI, IoT, and robots might present technical challenges related to interoperability, data privacy and security.
- Need for training and adaptation: Implementing a new system that heavily involves human-AI collaboration could necessitate significant training for workers to adapt to the new system, and there might be resistance to change.
- Financial implications: The implementation and maintenance of such a sophisticated and technologically advanced system could be costly, particularly for smaller businesses, potentially limiting its accessibility.
- Risk of technological redundancy: Given the pace of technological advancements, there is a risk that elements of the system may become outdated, requiring continuous updates and adaptations.

It is crucial to thoroughly evaluate these potential advantages and disadvantages when considering the implementation of a human-centric Industry 5.0 collaboration architecture in real-life applications.

Conclusions

Industry 5.0 research advancements are advised to promote cooperation between humans and machines, including the AI-aided joint creation of PKB ontology that supports user-oriented design and regulation of the ontology, adapted to the specific needs, work culture, and terminology of the plant. Moreover, a universal semantic description of plant-level collaborative processes is necessary, allowing multiple innovative agents (e.g., humans, AI, IoT, robots) to participate in real-time, event-driven processes. The creation of artificial intelligence techniques is also essential for human-in-the-loop optimization, cross-referenced with alternative feedback loop models. It is vital to incorporate all individual objectives into a comprehensive innovation lifecycle for shopfloor-level manufacturing collaboration processes, taking into account both technological innovation and societal factors. Additionally, the innovation of each collaborative process is sustained by a coherent ontology-controlled PKB IT service portfolio, which provides online access and customization of the methodology for plant innovation users.

The proposed approach primarily focuses and explores the Human-AI collaboration processes in industrial contexts. The six presented domains also represent the current and potential industrial needs in the Human-AI driven co-design and co-execution of manufacturing plant-level collaboration processes. These processes involve typical collaboration human-centric activities such as production facility testing, workplace material logistics, regular maintenance, repairs, work safety audits, quality control, etc. The definition of the Human-AI driven plant-level collaboration process include the following aspects:

- Set of actions aiming to achieve a plant operational objective (e.g., weekly preventive maintenance of all water supply units of the plant, setup/repair of a machine line requiring coordinated participation of several actors, etc.).
- Each action shall be executed by the provider role defined in the workflow definition (qualified person or technical agent).
- The actual execution workflow of Actions depends on the actual plant events.
- Actions of a collaboration process can be executed in multiple locations (workplaces) of the plant.

The I5arc Innovation Cycle methodology, supported by AI services, facilitates the creation of new jobs as well, for example, plant knowledge engineer, plant robot engineer, and plant data analyst. In addition, it enables more personalized human access to plant knowledge and improve work safety and work-life balance by enabling remote plant work.

Ethics statements

NA.

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.

CRediT authorship contribution statement

Attila Tóth: Conceptualization, Methodology, Writing – original draft. **László Nagy:** Writing – original draft. **Roderick Kennedy:** Conceptualization, Methodology. **Belej Bohuš:** Conceptualization, Methodology. **János Abonyi:** Writing – review & editing, Supervision. **Tamás Ruppert:** Conceptualization, Methodology, Writing – review & editing, Supervision.

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