A Smart Manufacturing Ecosystem for Industry 5.0 using Cloud-based Collaborative Learning at the Edge

Salman Javed*, Saleha Javed, Jan van Deventer, Hamam Mokayed and Jerker Delsing
Dept. of Computer Science, Electrical and Space Engineering, Lulea University of Technology Luleå, Sweden 97187
*salman.javed@ltu.se

NOMS 2023-2023 IEEE/IFIP Network Operations and Management Symposium | 978-1-6654-7716-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/NOMS56928.2023.10154323

***Abstract*—In the modern manufacturing industry, collaborative architectures are growing in popularity. We propose an Industry 5.0 value-driven manufacturing process automation ecosystem in which each edge automation system is based on a local cloud and has a service-oriented architecture. Additionally, we integrate cloud-based collaborative learning (CCL) across building energy management, logistic robot management, production line management, and human worker Aide local clouds to facilitate shared learning and collaborate in generating manufacturing workflows. Consequently, the workflow management system generates the most effective and Industry 5.0-driven workflow recipes. In addition to managing energy for a sustainable climate and executing a cost-effective, optimized, and resilient manufacturing process, this work ensures the well-being of human workers. This work has significant implications for future work, as the ecosystem can be deployed and tested for any industrial use case.**

***Index Terms*—Industry 5.0, Smart Manufacturing Ecosystem, Eclipse Arrowhead Framework, Value-driven Automation, Local Cloud-based Architecture, AI at the Edge, Collaborative Learning**

I. Introduction

INdustry 5.0 (I5.0) promotes value-driven automation for smart manufacturing. In 2021, the European Commission introduced I5.0 based on three core values: Resilience, Sustainability, and Human Centricity / Well-being [1]. In the shop floor use case of a smart factory, the aim of I5.0 is to ensure a cost-effective and value-sensitive execution of manufacturing processes. That is a fully resilient automation without sacrificing the well-being of workers and the environment. In addition, industrial systems and production processes in I5.0 must be able to continuously and dynamically learn, collaborate, and adapt to changing conditions and demands. Recent research in manufacturing automation employs technologies such as the Internet of Things (IoT), Service-oriented Architecture (SoA), Cyber-Physical Systems (CPS), and global cloud-based technologies. Although global cloud solutions are highly scalable, they could introduce security, privacy, and latency issues into production processes [2]. Therefore, I5.0 core value-driven and edge-based solutions that can securely integrate and intelligently and efficiently manage manufacturing processes on the shop floor are still missing [3] [4].

The International Data Corporation (IDC) review report for 2021 indicates that digital transformation will continue to drive IoT adoption, especially during emerging recovery from the pandemic around the world [5]. Most of these adoptions have been implemented in industries to increase remote capabilities, digitize manual processes, and automate business processes. Today, whenever there is a need for efficient process automation, it requires intelligent execution in addition to the digitalization of industrial tasks. Artificial Intelligence is plugged into Industry 5.0 solutions to address these challenges by engineering Machine Learning models as a service within the SOA of CPS [20]. The synergy of the CPS and ML models leads to several additional challenges of how digitalization and automation must be designed to achieve maximum optimization.

To guide this research work, we investigate the following three questions: 1) How to use individual task-based AI at the edge for smartly managing an IoT system of systems at the edge; 2) How to conceptualize the mapping between IoT-based industrial systems, manufacturing processes, and Machine Learning-based collaborative learning methods; 3) How does the smart workflow manager use its CCL-based AI at the edge to dynamically optimize manufacturing workflow recipes.

The primary contribution of this research is to propose a Smart Manufacturing Ecosystem for Industry 5.0 (SMEI5.0) using local cloud-based collaborative learning at the edge. SMEI5.0 employs SoA-based Eclipse Arrowhead local clouds to enable secure integration between different IoT systems and ensure stable, safe and reliable communication. The innovation lies in incorporating collaborative AI at the edge of each industrial system and production process. We propose that each AI at the edge system should be designed to optimize its execution using single or multi-objective optimization. Moreover, we propose using a thread-pooling mechanism to enable parallel executions of optimizations. Ultimately, the ecosystem is empowered to dynamically collaborate to generate and manage the most resilient, sustainable, and human-centric manufacturing workflows on the shop floor in real-time.

The remaining sections are as follows: Section:II describes the related work. Section:III offers specifics on the local cloud-based Arrowhead framework. The SMEI5.0 shop floor use case is explained in Section:IV. Next, Section:V details the concept of Cloud-based Collaborative Learning at the edge. Finally, Section:VI concludes with a summary of the thoughts, and key outstanding topics for further research are discussed in Section:VII.

II. Related Work

Smart, value-driven, and edge-based automated production is an important objective for the next generation of manufacturing in the I5.0 era. Gupta et al. provide a comprehensive review of approaches and challenges for intelligent manufacturing [3]. Maddikunta et al. have argued that the I5.0 core value-driven approach is still missing for next-generation industrial automation [4]. Moreover, the value-sensitive design suggested by Longo et al. for smart factories addresses the possibilities of human-machine symbiosis and does not incorporate IoT-enabled building-machine collaboration to achieve a sustainable climate [6] [7]. In the manufacturing process automation domain, several tools have been presented in recent years. These tools are often referred to as Workflow Management Software (WfMS). WfMS develops and reconfigures workflow recipes, which are instructions and schedules to automate shop-floor processes. Kozma et al. present a workflow choreographer for dynamic reconfiguration of production recipes based on production tasks [8]. The authors have not provided a mechanism for collecting input from independent workstations or how to optimize and regenerate the recipe. Lam et al. and Larrinaga et al. present a decentralized approach that applies the concepts of a local automation cloud at the edge [9] [10]. The authors have not addressed the mechanism for the collaboration of multiple local automation clouds to dynamically generate and reconfigure workflow recipes. Montini et al. and Bettoni et al. discuss the inclusion of worker well-being in production workflow management [11] [12] [13]. They propose using wearables to build Human Digital Twins (HDT). However, the authors have not provided a mechanism for HDT collaboration with other WfMS.

Therefore, current state-of-the-art approaches lack any I5.0 core value-driven mechanism for AI-based collaboration among industrial systems to generate WfMS recipes in manufacturing execution within a smart factory.

III. Arrowhead Local Clouds

The European Arrowhead Project initiated the Eclipse Arrowhead framework that supports the automation and digitalization of the Internet of Things using open-source integration solutions [14]. It is based on service-oriented architecture (SOA) and design concepts such as service abstraction and composability, autonomy, standardization of service contracts, late binding, and loose coupling [15]. The framework provides automation at the edge, built on the concept of automated systems based on self-contained local clouds (LC). These LCs guarantee low lotency, data and system security and privacy, and scalability in intra- and inter-cloud communicatio [16]. A LC at the edge includes three mandatory core systems: Service Registry, Authorization, and Orchestrator and multiple Supporting Systems: Data Manager, Event Handler, Gateway, Gatekeeper etc. All inter-cloud communication occurs through ActiveMQ broker systems, as shown in Figure1. In the framework, the services of the core and supporting systems are specified and their use is required for every implementation. These core systems provide governance and interconnection among services and are the backbone of automation. Then there are application systems defined by users according to their requirements. By registering their individual services with the core systems, these application systems may perform operations.

IV. SMEI5.0 Shop Floor Use Case

In this Section, we present a collaborative SMEI5.0 that is compliant with I5.0 core values: a) Resilience, b) Sustainability,c) Human centricity. The proposed SMEI5.0 consists of fully integrated and collaborative Smart Building Automation and Energy Systems, Smart Logistic Robots, Smart Production Line Systems, Smart Human Workers / Operator Aide Systems, and Smart Workflow Management Systems on the shop floor as shown in Figure 2. Integrating such a diverse set of industrial systems in SMEI5.0 requires extensive AI models and algorithms. We propose grouping industrial IoT and systems that perform similar automation tasks on the shop floor into LC-based edge systems of systems. Every edge system of systems has its own edge AI that is most optimal for its dataset. Then the Smart Manufacturing Workflow Management Systems dynamically generate the production workflow recipes by collaboration among all the various edge AIs of each respective edge system of systems. We have selected the local cloud-based Eclipse Arrowhead framework for implementing a shop floor use case. The distributed local cloud-based architecture of the framework ensures total data privacy, as all data is stored in the local cloud at the edge. The use of the Arrowhead framework to realize the SMEI5.0 shop floor use case makes the ecosystem resilient by design, as the framework already provides service-level authorization, composability, dynamic orchestration, and access control, which are required for a resilient system operation.

A. Smart Building Infrastructure and Energy Management Local Cloud

The purpose of this local cloud is to integrate building automation and HVAC systems within SMEI5.0 on the shop floor and assist WfMS in generating recipes based on worker well-being and reduction of carbon footprint. The Arrowhead framework already supports the integration of building IoT devices, such as Z-Wave thermostat valves and energy plugs, with the framework [17]. This ensures efficient management of energy systems, which can lead to a significant reduction in energy wastage. Additionally, it promotes sustainability by supporting environmental preservation and pursuing zero net emissions.

B. Smart Logistics Management Local Cloud

This local cloud integrates the logistic robots with the rest of the ecosystem on the shop floor. Arrowhead already supports the integration of the Robot Operating System (ROS)

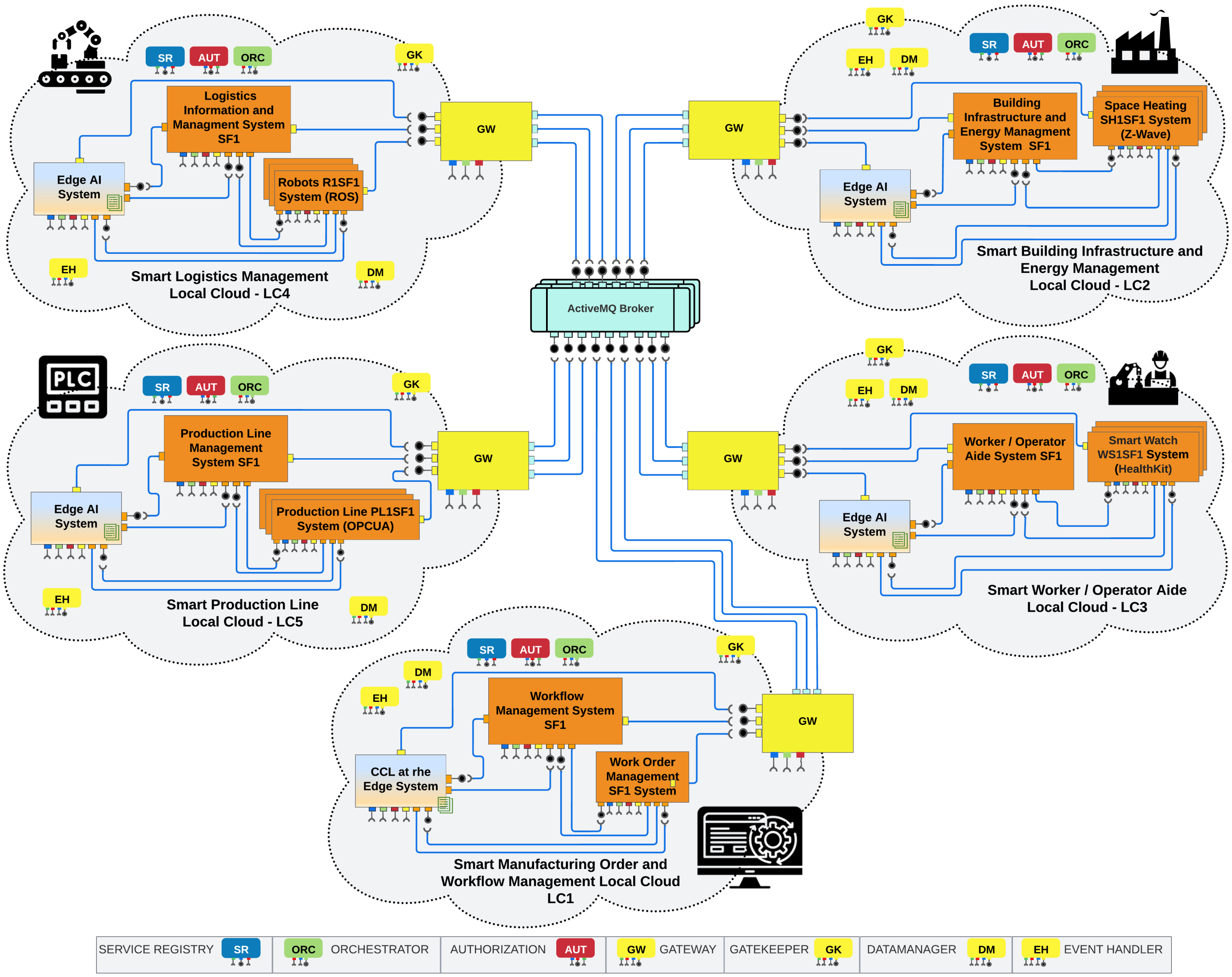

Figure 1. The systems using Eclipse Arrowhead Local Cloud and Application Systems for the demonstration experiment.

with the framework [18]. This ensures efficient planning and management of logistic resources on the shop floor while generating the WfMS production recipes.

C. Smart Worker / Operator Aide Local Cloud

The objective of this local cloud is to ensure the inclusion and collaboration of human worker well-being in SMEI5.0 on the shop floor. We propose integrating smart wearables (smart watches) with the Arrowhead framework to ensure real-time cooperation between workers, energy systems, logistic robots, and WfMS. This can guarantee the well-being of the workers on the shop floor.

D. Smart Production Line Local Cloud

This local cloud integrates production line systems within SMEI5.0 on the shop floor. Arrowhead already supports the integration of industrial production technologies such as OPC UA (Open Platform Communications Unified Architecture) [18]. Using a local cloud ensures real-time operation of the production line without incurring latency issues.

E. Smart Manufacturing Order and Workflow Management Local Cloud

The purpose of this local cloud is to run WfMS and dynamically generate/modify the best-optimized production workflow recipes based on the input from the rest of SMEI5.0 on the shop floor. WfMS receives the work order from the Work Order Management System. It uses the CCL at the Edge explained in SectionV to generate the recipes for each automation task. Then sends recipes to the local cloud for corresponding edge automation.

V. Cloud-based Collaborative Learning (CCL) at the Edge

Our aim in this section is to provide a global discussion of the main issues concerning the synergy of IoT and AI. We synthesize a smart manufacturing ecosystem that is designed to utilize the core features of Artificial Intelligence e.g., decision-making for resource allocation and optimization, early predictions based on data, process automation, and optimizations. We also take it up a notch by incorporating Cloud-Based Collaboration [19] at the edges of this ecosystem.

In this section, we demonstrate the CCL at the edge concept in a step-by-step approach. The complete concept flow chart is illustrated in Figure 2. Each subsection belongs to the domain, and the steps mentioned within are the rationale behind mapping CPS IIoT Tasks onto ML downstream tasks. The functionality of each task of both domains is thoroughly investigated and verified by experts from both domains. The experts provided scientific and conceptual details of their concepts. All experts mutually agreed on keeping two core assets for conceptualizing this mapping:

- DATA
- TASK

A. Investigate IIoT Task(s) as per the Use-Case

First, we investigate the CPS task of each local cloud and study its operations. This gives us information about the functionality of each operation. For the sake of the current focus on the management of the IIoT domain, we only study the use cases that comply with workflow management in the cloud-based architectures. The list of tasks extracted with the focus on workflow management is listed in Table I.

Table I
List of all local clouds and their corresponding tasks

Local Cloud Details		Task w.r.t Management Use-Case
LC 1	Smart Manufacturing Order and Workflow Management	Manufacturing Workflow Recipe Generation
LC 2	Smart Building Infrastructure and Energy Management	Building IoT devices , Energy and HVAC System Automation and Management
LC 3	Smart Worker / Operator Aid	Human Workforce Wearable IoT devices
LC 4	Smart Logistics Management	Logistic Robots Automation and Management
LC 5	Smart Production Line	Production Line Automation and Management

B. IIoT Tasks Mapping onto ML Downstream Task

Next, we start asking trivial questions to find the key players involved in every task. After identifying the IIoT task of that Local Cloud / System, it is important to understand its process description. This gives us all the required knowledge about the dataset that will be used for ML downstream tasks. The procedure we adopted is as follows:

1) Identify in this task what/who:
   a) are the key players involved in the task
   b) will be the input(s) for the system(s)
   c) will be the output(s) from the system(s)
2) List down the plausible formats of input(s) and output(s) information (data) of that local cloud/system that can be.
3) Identify the type of **DATASET** that ML methods will utilize to execute the required task on those data.
4) Next, go back and forth between CPS/IIoT process description and the Dataset used. This gives us the exact downstream task that we need to design.

C. Identify the Objective Functions

Then, we find out the ML downstream task to investigate whether the task can be solved by:

- Single-Objective
- Multi-Objective

A single-objective function corresponds to the single-objective optimization problem. An example scenario is an environmental objective in which the goal is to optimize the heating system within a room so that human comfort is maximized. On the contrary, when more than one objective function contributes to computing the main results, it is a multi-objective optimization problem. An example of such a scenario is the path optimization function, in which the goal must be achieved by computing a path that uses minimum resources, provides maximum coverage of the needed area, and executes surveillance at a minimum distance. Here, three objective functions optimize the main goal; therefore, it is a multi-objective optimization problem.

D. CCL Solution

We designed and tested Cloud-based collaborative learning (CCL) in [19] for wind turbines use-case. CCL enabled shared learning across local clouds based on an unsupervised machine learning approach. In this paper, we further expand the CCL concept and propose it as a solution; of AI at the Edge; for a bigger umbrella of the CPS / IIoT domain. In the current use case, the CCL solution is computed by the CCL system in the Smart Manufacturing Order and Workflow Management Local Cloud 1. The aim of this system is to combine individual optimizations of individual local clouds. Each cloud may have its task and optimization goal, respectively. The CCL system is such an AI at The edge that it should provide collaboration across local clouds. Collaboration can be of various types, but for this paper, we conceptualize it as the output of optimization functions of each local cloud combined with all the rest, and a final optimizer is computed. Based on the said task of the local cloud, this optimizer function suggests which type of learning should be used by the Edge AI System of that cloud. Then, it also should suggest an adequate ML model that is lightweight and can be executed at the edge for solving the task of that local cloud. Lastly, the optimizer or the CCL Solution should suggest trainable/learnable hyper-parameters of individual objective functions. This output of CCL solution is mainly what the smart workflow management system is doing to optimize the entire local-cloud-based ecosystem intelligently. Hence, making it a Smart Manufacturing Ecosystem by incorporating

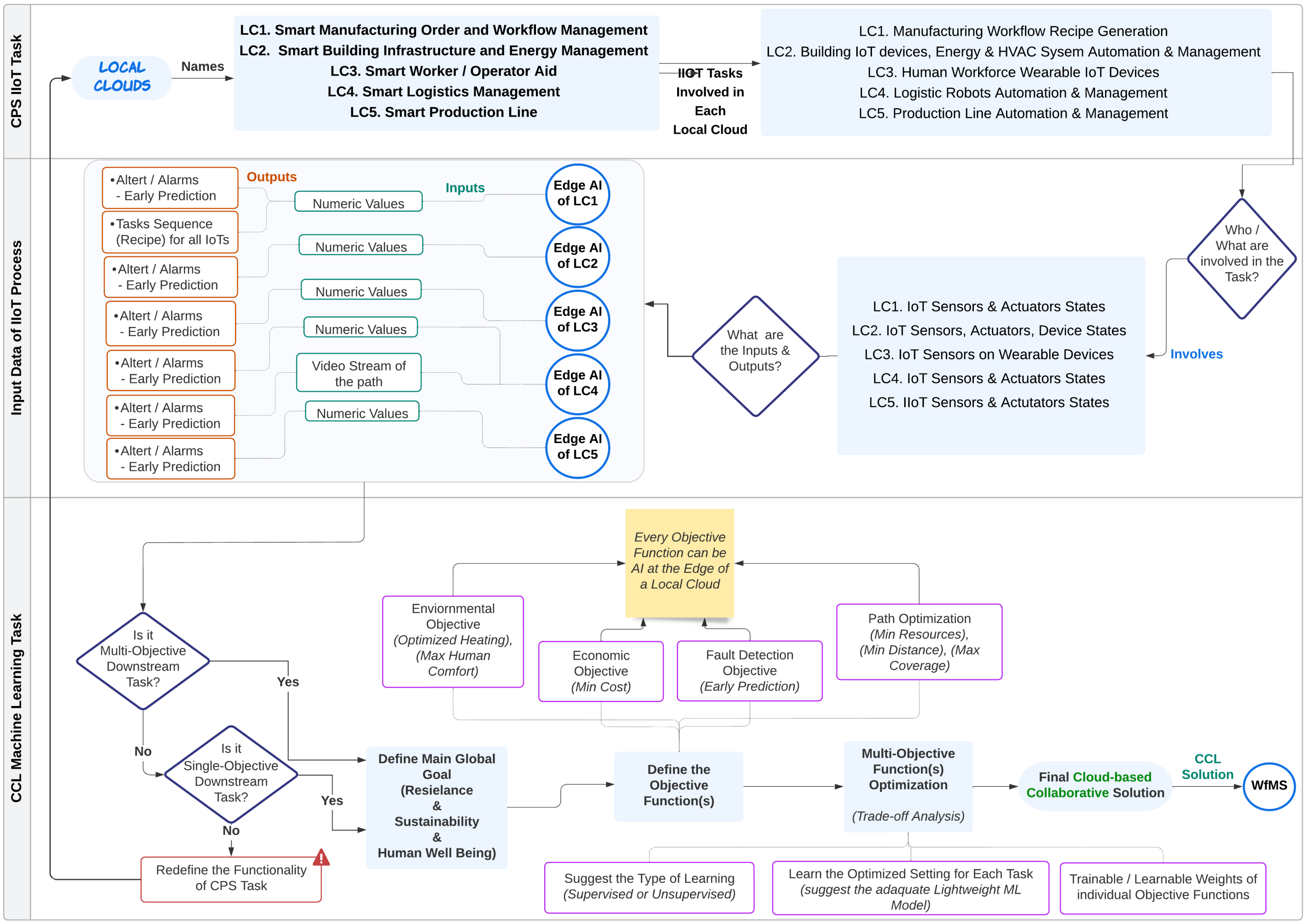

Figure 2. Flowchart demonstrating the transition of data from CPS to ML domain. This conceptualization can be adapted to any industrial use case.

CCL at the Edge. Moreover, this system can also be engineered to combine optimizations of individual local clouds running in parallel via a **thread pooling mechanism** [21].

VI. Conclusion

In this paper, we proposed a value-driven smart manufacturing ecosystem for I5.0. We presented its architecture along with CCL-based manufacturing process automation to ensure its compliance with I5.0 core values of Resilience, Sustainability and Human-centricity. We propose to use Eclipse Arrowhead Local clouds to build automation task-based edge systems of systems. Each local cloud has an Edge AI system for early predictions and management. Then the Smart Manufacturing Workflow Management System dynamically generates the production workflow recipes based on the early predictions from individual Edge AIs. Hence, smart building energy systems, logistic robots, production line systems, and Human worker aide systems participate in generating the most optimized workflow recipes. We engineered a process flow of how IIoT local-clouds-based models can be mapped onto ML models. We designed the step-by-step process flow that maps the transition of data used in any IIoT task to the dataset to be utilized for any ML model. Hence, this collaboration among all the diverse Edge AIs helps the manufacturing execution system to keep the system alive, good for workers' well-being, and sustainable for society. The CCL system adheres to Industry 5.0 core values in three stages:

A. Stage One: Resilience

Resilience refers to **Always Keep The System Live**. By incorporating **early prediction** ML models, we can monitor if any IoT asset is going to fault or fail, and then it can be replaced beforehand. Secondly, the **optimization** models should compute and suggest what/who should replace what/who. Hence, the ecosystem does not face any failures.

B. Stage Two: Sustainability

Sustainability complies to **Energy Efficient** principle. It promotes the efficient management of energy and HVAC systems to reduce energy waste and carbon footprint. That can further ensure the reduction in manufacturing costs.

C. Stage Three: Human Centricity

Industry 5.0 visualized industrial automation by keeping humans in the loop. Our proposed ecosystem is designed on the principle of **Digitalization for the Betterment of Humans**. The CCL system optimization has the **Enviornment Objective function** that is designed for ensuring maximum human comfort. It should predict or detect if the health of any worker can get affected by the environment, and an alarm must be triggered. Then that worker can be given a break or necessary care.

VII. Future Work

As part of future work, we will implement and test different AI optimization approaches on an industrial use case. We want to see which ones are lightweight and can be implemented at the Edge. Then, We will test the thread pooling concept [21] using services within Arrowhead local cloud. We also want to thoroughly explore multi-objective optimization for such ecosystems and test existing SOTA for the industrial use case [22]. We will implement shared learning and collaboration among the shop floors so that the building management system of shop floor 1 learns from the building management system of shop floor 2 using Arrowhead secure intercloud communication. Next, we plan to deploy decision-making and learning designed for CCL system that can combine optimizations of the different LCs of that industrial use case. Lastly, we want to investigate what more benefits this ecosystem can offer to society and humans.

VIII. Ethical Concerns

Humans are part of the ecosystem but we carefully curate the proposed solution so that it does not conflict with data privacy concerns. Moreover, each automation process is designed so that it can be used mainly for the betterment of society and humans.

Acknowledgement

The authors would like to thank the European Commission and Arrowhead Tools project (ECSEL JU grant agreement No. 826452) for funding.

References

[1] M. Breque, L. De Nul, and A. Petridis, “Industry 5.0: Towards a sustainable, human-centric and resilient European industry,” Luxembourg, LU: European Commission, Directorate-General for Research and Innovation, 2021.

[2] H. Derhamy, J. Eliasson and J. Delsing, “IoT Interoperability—On-Demand and Low Latency Transparent Multiprotocol Translator,” in IEEE Internet of Things Journal, vol. 4, no. 5, pp. 1754-1763, Oct. 2017.

[3] P. Gupta, C. Krishna, R. Rajesh, et al. “Industrial internet of things in intelligent manufacturing: a review, approaches, opportunities, open challenges, and future directions,” Int J Interact Des Manuf 2022.

[4] P. Maddikunta, Q. Pham, B. Prabadevi, et al. “Industry 5.0: A survey on enabling technologies and potential applications,” Int J Interact Des Manuf 2022.

[5] Market Report, “IDC’s Worldwide IoT Platforms and Analytics Taxonomy, 2021” Kate Merrick https://www.reportlinker.com/p05916278/IDC-s-Worldwide-IoT-Platforms-and-Analytics-Taxonomy.html

[6] F. Longo, A. Padovano, S. Umbrello, “Value-Oriented and Ethical Technology Engineering in Industry 5.0: A Human-Centric Perspective for the Design of the Factory of the Future.” Applied Sciences. 2020

[7] D. Minoli, K. Sohraby, and B. Occhiogrosso, “IoT Considerations, Requirements, and Architectures for Smart Buildings – Energy Optimization and Next Generation Building Management Systems,” IEEE Internet of Things Journal, vol. PP, pp. 1–1, 01 2017.

[8] D. Kozma, P. Varga and F. Larrinaga, “Dynamic Multilevel Workflow Management Concept for Industrial IoT Systems,” in IEEE Transactions on Automation Science and Engineering, vol. 18, no. 3, pp. 1354-1366, July 2021, doi: 10.1109/TASE.2020.3004313.

[9] A. N. Lam, O. Haugen and J. Delsing, “Dynamical Orchestration and Configuration Services in Industrial IoT Systems: An Autonomic Approach,” in IEEE Open Journal of the Industrial Electronics Society, vol. 3, pp. 128-145, 2022, doi: 10.1109/OJIES.2022.3149093.

[10] F. Larrinaga, W. Ochoa, A. Perez, J. Cuenca, J. Legaristi and M. Illarramendi, “Node-RED Workflow Manager for Edge Service Orchestration,” NOMS 2022-2022 IEEE/IFIP Network Operations and Management Symposium, Budapest, Hungary, 2022, pp. 1-6, doi: 10.1109/NOMS54207.2022.9789940.

[11] E. Montini, N. Bonomi, F. Daniele, A. Bettoni, P. Pedrazzoli, E. Carpanzano, and P. Rocco, “The human-digital twin in the manufacturing industry: Current perspectives and a glimpse of future,” in Trusted Artificial Intelligence in Manufacturing: A Review of the Emerging Wave of Ethical and Human Centric AI Technologies for Smart Production,J. Soldatos and D. Kyriazis, Eds. Now Publishers, 2021, ch. 7.

[12] E. Montini, A. Bettoni, M. Ciavotta, E. Carpanzano, and P. Pedrazzoli, “A meta-model for modular composition of tailored human digital twins in production,” Procedia CIRP, vol. 104, pp. 689–695, 2021.

[13] A. Bettoni, E. Montini, M. Righi, V. Villani, R. Tsvetanov, S. Borgia, C. Secchi, and E. Carpanzano, “Mutualistic and adaptive human-machine collaboration based on machine learning in an injection moulding manufacturing line,” Procedia CIRP, vol. 93, pp. 395–400, 2020, 53rd CIRP Conference on Manufacturing Systems 2020.

[14] “Arrowhead Framework.” Accessed on: Dec. 02, 2022 [Online]. Available: https://arrowhead.eu/

[15] Delsing, J. Eliasson, M. Albano, P. Varga, L. Ferreira, H. Derhamy,C. Hegedus, P. P. Pereira, and O. Carlsson, “Arrowhead Framework coresystems and services,” in IoT Automation: Arrowhead Framework. CRCPress, 2017, ch. 4.

[16] J. Delsing, “Local Cloud Internet of Things Automation: Technology and Business Model Features of Distributed Internet of Things Automation Solutions,” in IEEE Industrial Electronics Magazine, vol. 11, no. 4, pp. 8-21, Dec. 2017

[17] S. Javed, C. Paniagua, S. Patil, J. van Deventer and J. Delsing, “Smart Adapter System Architecture for Seamless and Scalable Integration of Industry and Smart Home IoT,” IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium, 2022

[18] A. Tripathy, J. van Deventer, C. Paniagua and J. Delsing, “Interoperability Between ROS and OPC UA: A Local Cloud-Based Approach,” 2022 IEEE 5th International Conference on Industrial Cyber-Physical Systems (ICPS), Coventry, United Kingdom, 2022

[19] S. Javed, S. Javed, J. van Deventer, F. Sandin, J. Delsing, M. Liwicki, and S. Martin del Campo Barraza, “Cloud-based Collaborative Learning (ccl) for the Automated Condition Monitoring of Wind Farms,” in 5th IEEE International Conference on Industrial Cyber-Physical Systems (ICPS), 2022.

[20] S. Javed, “Towards Digitization and Machine learning Automation for Cyber-Physical System of Systems. Diss. Luleå University of Technology, 2022.

[21] H. Mokayed et al. “On Restricted Computational Systems, Real-time Multi-tracking and Object Recognition Tasks are Possible.” 2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). IEEE, 2022.

[22] Javed, Saleha, and Kashif Zafar. ”Player profiling and quality assessment of dynamic car racing tracks using entertainment quantifier technique.” Computational Intelligence 34.4 (2018): 1046-1071.