A LEARNING FACTORY FOR INDUSTRY 4.0 BASED ON CYBER-PHYSICAL SYSTEM TECHNOLOGY

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Abstract. *Industry 4.0 represents the new stage in the organization and control of the industrial value chain; its basis is represented by Cyber-Physical Systems (CPS) that use intensively automation, bridge the physical and digital world through Industrial IoT, are controlled with distributed intelligence by smart products driving the production steps in closed-loop data models and controls, and operate in business models integrated in the cloud universal manufacturing space. With reference to the manufacturing models of the 4th industrial revolution, the foundational technologies and standards integrated in the reference architectural model of Industry 4.0 (RAMI 4.0) from the perspective of production, digital, AI and cyber technologies are analysed. The paper describes a learning factory developed for Industry 4.0 based on an industrial manufacturing cell controlled by a CPS and a 42-week program with hands-on training and master course teaching.*

Abstract. *Industria 4.0 reprezintă noua etapă în organizarea și controlul lanțului valoric industrial; baza sa este reprezentată de sistemele ciber-fizice (CPS) care utilizează intens automatizarea, fac legătura între lumea fizică și cea digitală prin IoT industrial, sunt controlate cu inteligență distribuită de produse inteligente care conduc etapele de producție în modele și controale de date cu buclă închisă și operează în modele de afaceri integrate în spațiul de producție universal în cloud. Cu referire la modelele de producție ale celei de-a 4-a revoluții industriale, sunt analizate tehnologiile și standardele fundamentale integrate în modelul arhitectural de referință al Industriei 4.0 (RAMI 4.0) din perspectiva tehnologiilor de producție, digitale, AI și cibernetice. Lucrarea descrie o fabrică de învățare dezvoltată pentru Industria 4.0 bazată pe o celulă de producție industrială controlată de un CPS și un program de 42 de săptămâni cu instruire practică și predare a cursurilor de masterat.*

Keywords: neural networks, *qualia*, information, meaning, cybersemiotic.

DOI 10.56082/annalsarsciinfo.2025.1.48

1. Introduction.

Industry 4.0 represents the vision for the Industry of the Future; the term 'Industry 4.0' defines a methodology to generate the transformation from machine dominant manufacturing to *digital manufacturing* [1]. The digital transformation of manufacturing advocated by Industry 4.0 is asked for by the economic and societal realities of the 21st century: markets are currently demanding customized, high-quality products with frequent changes in their characteristics, in highly variable batches with shorter delivery times, forcing companies to adapt their design, plan-

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ning, supply, production and internal logistics processes in conjunction with reconfigurable resource teams orchestrated in flexible, efficient, agile and reality-aware factories. The service-dominant logic extends manufacturing of product with services offered during their lifecycle.

New production and IC^2T (Information, Communication and Control technologies) are developed to sustain the digitalized production in the global vision of the 4^{th} industrial revolution. Industry 4.0 points to digital production patterns in holistic and adaptive automation system architectures exposing cooperation between plant components and product intelligence [2].

The 2030 Vision for Industry 4.0, formulated in a holistic approach by Platt-form Industrie 4.0 [3], promotes the global design of open digital ecosystems by assuming three strategic fields of action: 1) *Autonomy*: self-determination and free scope for action guarantee competitiveness in digital business models by help of technology development, security and digital infrastructure; 2) *Interoperability*: cooperation in open ecosystems eases plurality and flexibility through regulatory framework (security data handling), standards and integration, AI and distribution of intelligence; 3) *Sustainability*: modern industrial value creation ensuring high standard of living by decent work and education, social inclusion, climate change mitigation and the circular economy.

Industry 4.0 involves the technical integration of Cyber-Physical Systems (CPS) into manufacturing and logistics and the use of the Internet of Things and Services (IoT, IoS) in industrial processes. The shift is to networked manufactur-ing, self-organising adaptive logistics and customer-integrated engineering requi-ring business models that will be mainly implemented by a highly dynamic net-work of businesses rather than by a single company [4]. A key component of the I4.0 vision is the smart factory embedded into inter-company value networks, characterised by end-to-end engineering and automation that encompass both the manufacturing process and the manufactured product, achieving seamless convergence of the digital and physical worlds.

Industry 4.0 makes use of the Industrial Internet of Things (IIoT) and Services framework in which the CPS technology allows virtualized resources, products and orders to interact to achieve production goals. The focus of the I4.0 platform is realizing strongly coupled, smart manufacturing and logistics systems. CPSs pair a physical layer handled by IIoT technologies and a virtual layer handled by cloud computing technologies [5].

This paper proposes a systems engineering-oriented higher education (HE) program devoted to the knowledge and skills needed to put in practice the Industry of the Future (IoF) transformation set up by the 4^{th} industrial revolution. The foundational technologies of Industry 4.0 that transform industrial production, the factory levels and the architecture layers on which they are related in RAMI 4.0 (the Reference Architectural Model Industry 4.0) for product development and production are described in Chapter 2 of the paper; they will be mapped in the courseware of the HE program. Chapter 3 discusses 'related work' in worldwide programs aligned to the paradigm of the fourth educational revolution (also called Education 4.0) that exploits the potential of digital technologies and personalised knowledge and data. The new master program RA4I4.0 with hands-on training in Industry 4.0 technologies, CPS and IoT solution development is introduced in Chapter 4. Conclusions about the economic and technical feasibility of the educational program and specific partnership with industry needed are formulated in Chapter 5.

2. Foundational technologies and standards integrated in the Reference Architectural Model Industry 4.0

The digital transformation of manufacturing promoted by Industry 4.0 is driven by nine foundational technology advances. Some of them are already used in manufacturing, although not in a generalised way; with Industry 4.0, they basically transform production interconnecting separated, locally optimized shop floor units (machines, cells) in fully integrated, globally optimized, agile and reality-aware production flows:

- *Additive manufacturing*: a new key enabling production technology, component of the Direct Digital Manufacturing (DDM) concept that includes novel 3D printing, digital shape reconstruction and modelling technologies (the need for tooling and setup is reduced by producing parts directly based on digital models).
- *Autonomous robots*: in the IoF perspective, industrial robots, automated guided vehicles (AGV) and autonomous mobile robots (AMR), already used in the last years, will become more autonomous and collaborative. They will be able to interact with one another and learn from humans to be more dexterous (e.g., by emulating manipulative gestures of expert workers).
- *Augmented reality*: AR-based systems will be used in the IoF to provide workers with real-time information to assist and improve work procedures; this is an AI-type technology that will be used for virtual training of human operators (handling emergencies, interacting with machines) and support to decision.
- *Simulation*: will use real-time data to mirror the physical world in an extended digital model, which can include production entities: resources, products, orders, processes, and humans. The *Digital Twin* (DT) is an AI-based technology that embodies this extended model of digital 3D shape representation, operating mode, execution context, history of behaviour, time evolution and status. DT-

based simulation is used for resource health monitoring, anomaly detection, predicting unexpected events, and optimizing production systems.

- *Industrial Internet of Things*: with the Industrial Internet of Things (IIoT) production entities (resources, products and execution orders of product instances) and the environment will be pervasively instrumented with embedded computing and interconnected using standard technologies (e.g., broadband Internet, wireless). IIoT architectures use *edge computing* technologies (edge gateway, aggregation node, next unit of computing) to process shop floor data downstream cloud services and upstream IoT services at the edge of the physical network, and *fog computing* decentralized infrastructure in which data, computation results, storage and applications enable short-term analytics and ad-hoc decision making [6].
- *Big Data and Analytics*: the integration of increasingly smart devices, products and control software caused an explosion in data points available at shop floor level. In the Industry 4.0 context, smart sensors will pervasively instrument resources, products, processes and orders as ‘plug-and-produce’ modules [7], while IoT hardware aggregation nodes and middleware align data streams in normalized time intervals and transfer data in the cloud MES for analysis.
- *Cloud*: the IT model of Cloud Computing (CC) is extended in IoF perspective to services that orchestrate factory resources and their automatic controls through operational technologies. This dual Cloud Control and Computing (CCoC) model is the real time partition of the CMfg enterprise model mapped on its technical layer, and which: i) transposes pools of factory resources (robots, machines, controllers) into on-demand product making services; ii) may involve on-demand network access to a shared pool of configurable high performance computing resources - servers, storage, applications that can be rapidly provisioned and released as services to global MES workloads with minimal management [8, 9]. Global MES workloads virtualized in the cloud call for real time shop floor (big) data streaming.
- *Cybersecurity*: in the context of multi-tenant shop floors where multiple and sometimes competing organisations share the same manufacturing facility, security requirements at plant level and throughout the MES and ERP components become very important, as physical security is no longer enough. Likewise, with the decentralization of control, there is an increased need for secure, reliable communications, identity and access management of resources and users, authentication and encryption of intelligent, moving products.
- *Horizontal and vertical system integration*: IoF businesses will establish global networks that incorporate their logistics, production and warehousing systems. Enterprise integration means that manufacturing systems are vertically networked with business processes within factories (for agility and responsiveness to the increasing knowledge intensity and complexity of negotiations), and

horizontally connected to dispersed value networks (supply, design and engineering, production, logistics for delivery, after-sales services) managed in real time [10, 25].

The actors in the manufacturing value chain (suppliers, producers, vendors, service providers) must work with governments to adapt education to create a skilled workforce as they embrace these advanced technologies of Industry 4.0 integrated in implementing frameworks (Figure 1). The implementing framework for Industry 4.0 is represented by Cyber-Physical Systems that comprise smart embedded resources, products, warehousing systems and production facilities created by virtualizing the physical plant components, interact and collaborate to accomplish global goals, and feature end-to-end IC^{2}T integration on all enterprise layers. Industry 4.0 involves the use of the IIoT to create networks that integrate shop floor devices equipped with sensing, identification, processing and communication capabilities [11]; it uses industrial wireless networks and the Internet, and embeds Web services.

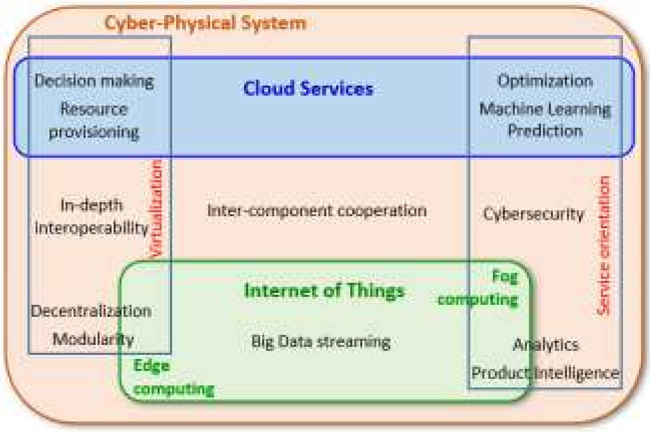

Figure 2. Industry 4.0 framework integrating the technology advances

The manufacturing CPS framework in Industry 4.0 perspective is characterized by pervasive instrumenting of plant devices, automation with distributed intelli-gence embedded on strongly coupled information counterparts of generic or ins-tantiated entities – resources, products, orders – that are virtualized with various techniques: multi-agent systems, holarchies, digital twins for individual or collective, local (shop floor) or global (batch, customer order, value chain) workloads. CPS benefit from cloud services in the dual control-computing model for process optimization and reality-aware control. Modelling of control in industrial CPS uses the holonic manufacturing paradigm, service orientation, and in-depth interoperability of intelligent beings that create a software platform on which intelligent decision makers (agents) are the applications.

The RAMI 4.0 - Reference Architecture Model Industry 4.0 is based on a three dimensional map synthetizing the most important aspects of Industry 4.0 about reference architectures, structured deployment frameworks, standards and norms, offering to all participants involved a common understanding of technologies, functionalities, networking and interactions, and perspectives of I4.0 framework development [12].

RAMI 4.0 defines a service-oriented architecture where application components provide services to the other components through a communication protocol over a network; it represents in a 3D frame all essential aspects of Industry 4.0 [23]. RAMI 4.0 combines all elements and IT components in a layer and life cycle model (Figure 2):

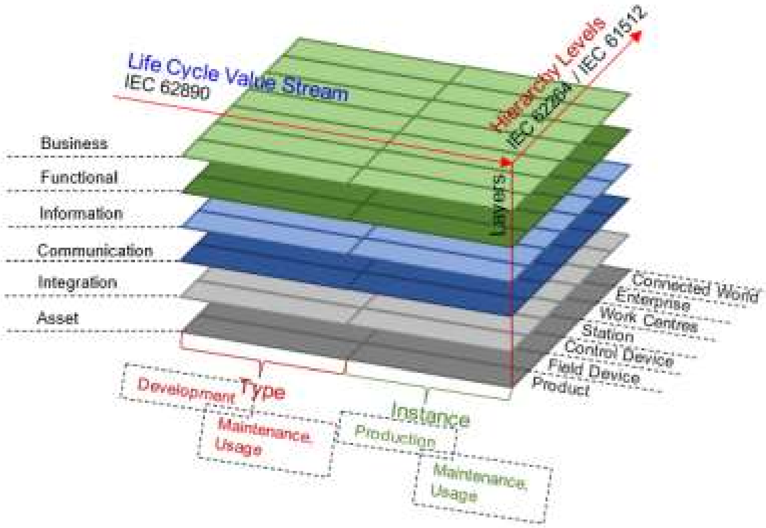

Figure 2. RAMI 4.0, the Reference Architecture Model Industry 4.0 (adapted from [13])

- The *Hierarchy Levels* axis: on the right horizontal axis are hierarchy levels from the standard IEC 62264, based on ANSI/ISA95 for *Enterprise information and control systems*. These hierarchy levels represent functionality locations within factories. To represent the I4.0 environment, the ISA95 functionalities are expanded to include manufacturing outcome labelled "Product," and the connection to the Internet of Things and Services labelled "Connected World".
- The *Life Cycle Value Stream* axis: represents the life cycle of facilities (factory) and products, based on IEC 62890, *Life-cycle management for systems and products* used in process measurement, control, and automation. Furthermore, a distinction is made between "types" and "instances". A "type" becomes an "instance" when design and prototyping have been completed and the actual

product is being manufactured, or when the execution of an ordered product has been instantiated (i.e., operations scheduled and allocated on machines).
- The *Layers* axis: the six layers on the vertical axis define the structure of the information-based (virtual) representation of I4.0 components (e.g., machine, robot, control) *properties structured layer by layer*. The layers symbolise various perspectives: data maps, functional descriptions, communication modes, vertical integration, hardware assets. This corresponds to IT and system theory where complex projects are split up into clusters of controllable parts.

The special characteristic of the RAMI4.0 the life cycle value stream combined with a hierarchically structured approach to define I4.0 components. The model highlights the interaction between: (A1) horizontal integration through value networks; (A2) vertical integration within a factory; (A3) life cycle management, end-to-end engineering; (A4) humans orchestrating the value stream.

3. Key skills and formation programs for Industry 4.0

The 21st century skills involve competencies related to learning and innovation, digital literacy as well as career and life. Examining key skills for Industry 4.0, experts consider two main approaches that educational systems may take towards I4.0 [14, 15]:

- Educating *followers*: people having the right skill set for reacting to changes in their working environment, adapting their performance, and learning to cope with the technological development.
- Educating *change makers*: in addition to people who are highly knowledgeable of I4.0 technologies, specialists are needed who can make informed decisions related to usability, reality awareness, safety, sustainability, and ethics.

Operating CPSs stresses the value of human interactions. As digitalisation, robotics, AI, networking and the industrial internet are freeing people from routine labour, human abilities for idea sharing and critical thinking are called for. I4.0 is still evolving, which limits the understanding of the skills needed to work in I4.0 manufacturing. Yet, forerunning companies are looking to upskill their current workforce and to recruit employees with the right skill sets.

The paradigm shift in manufacturing accounts for social and market changes combined with technological advancements (integration of virtual and physical world; creating value by data insights; automation; human-machine collaboration) that bring added value in products, business models, processes, and human work.

The EU project 'Universities of the Future' grounds the reference framework for Industry 4.0 skills on *working life skills* (WLS) that are defined as knowledge, skills or attitudes needed to perform a job successfully [16]. WLS refer to both I4.0 (discipline)-specific competencies and knowledge and transferable skills (may be ap-plied in many different professional contexts). Table 1 shows the *discipline-specific competencies* and knowledge related to Industry 4.0, as a result of literature analysis; in addition, *transferable skills* include problem-solving skills, personal (soft) skills, systems thinking, commercial knowledge, and technological literacy [21, 22, 23, 24].

With Industry 4.0, it has become imperative for educational organizations to move towards a new revolution: Education 4.0 (E4.0) - a vision of the future of education that exploits the potential of digital technologies, personalized data, and the opportunities offered by this connected world to foster lifelong learning. Education 4.0 is about integrating the technological advances of Industry 4.0 for educational purpose [17]. In addition to considering the requirements of Education 4.0, the University 4.0 model has been defined to provide autonomous management of learning processes based on the integration of the physical and digital worlds to improve and adapt learning [20]. The concept of the 4th university revolution aims at applying the Industry 4.0 paradigm in universities to foster the automation, adaptation, and personalization of learning processes, contributing thus to the transition to Education 4.0

Table 1. Taxonomy of discipline-specific competencies and knowledge for Industry 4.0

Discipline-specific competencies and knowledge for Industry 4.0	
Technical and Engineering competencies	Data science and big data analytics; Human-machine interface; Digital-to-physical transfer technologies (3D printing, shape reconstruction); Simulation and virtual plant modelling; Data communication and networks; System automation; AI; Robotics; Programming; Product and process quality control; Real-time logistics and supply chain optimization
Business and Management competencies	Technology awareness; Change management and strategies; Organizational structures and knowledge; Managers' roles; Tech-enabled processes: forecasting and planning metrics
Design and innovation competencies	Understanding the impact of technology; Human-robot interaction and user interfaces; Tech-enabled product and service design; Tech-enabled ergonomic solutions and user experience

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Industry 4.0, as global digital manufacturing initiative, is seen as a technology driven strategic advance for economy which, at the moment, brings some challenges: the need to integrate legacy systems, the high cost of business cases, and the shortage of qualified personnel. These problems are perceived by SME manufacturers as difficulties for digitalisation. A low cost, tactical approach at country level is represented by the 3-year research project 'Digital Manufacturing on a Shoestring' funded in the UK by the Engineering and Physical Science Research Council [18]. The scope of this initiative is twofold: developing individual digital solutions for which the total cost of deployment is kept low and applying the approach in a large number of companies and labs, i.e., outreach, engagement and dissemination towards Industry 4.0. The Shoestring program has five stages: 1) *Digital requirement assessment*: identifying specific digital needs of SMEs to identify solution priorities; 2) *Solutions development*: defining standardised 'building blocks' that can be reused and plugged together to form a solution; 3) *Prototyping / Pilot testing* of the developed technologies and methods in partner SMEs; 4) *Incremental integration*: integrating solutions incrementally with existing legacy manufacturing facilities; 5) *Engagement and dissemination*: outreach of low cost digital solutions through informal development settings, application in production companies.

Such initiatives raise the awareness and skills' level for the participation of companies and personnel in Industry 4.0 developments.

4. The FMCell learning factory for Industry 4.0 training and research

This section presents the FMCell Learning Factory created in the Department of Automation and Industrial Informatics of the University Politehnica of Bucharest as a reality-conform manufacturing environment for education of change makers, hands-on training and research in Industry 4.0 key technologies, smart control solutions and Cyber-Physical Production Systems. The infrastructure is a pilot manufacturing cell integrated with a private cloud platform set up in partnership with industry - producers and integrators of high tech automation, robotics, vision, cloud and software: East Electric (main partner, https://www.eastelectric.ro/), Cognex, Omron Adept Technology, ABB, Rockwell Automation and IBM.

This complex Industry 4.0 learning environment is based on the authentical replica of an industrial production system with manufacturing value chain components, and on the integration of newest industry trends with academic content, physical infrastructure and engineering practices. The FMCell learning factory is defined by:

- Real industrial *activities and processes* that are automatically performed on multiple workstations, use material components to manufacture *products* that travel between storages and machines, are handled, packed and palletized for distribution by robots.
- A 600 m^2 location with *shop floor layout* and reconfigurable *resource team* (CNC machines, industrial robots) that can be reengineered using modularity and pluggability, supporting thus the plug & produce metaphor, hardware and software control reconfigurability in the *value chain* from both technical and organizational viewpoint.
- A set of types of *physical products* that are manufactured differently, from open shop to fixed precedencies mode (e.g., pneumatic cylinders, carburettors, tool boxes, etc.)
- A *didactic model* including a 42-week systems engineering-oriented master program (Robotics and Automation for I4.0) with 8h formal teaching, 8h hands-on training in the pilot cell, and 12h case study and application development (team work for skills growth) per week; 12h-week individual research project for innovation in IoT, CPS.

Figure 3 left shows the layout and structure of the industrial manufacturing cell with four robotized workstations: two part processing stations with (3+1)-axis CNC Concept Mill 105 milling machines from EMCO tended by 6-d.o.f. vertical articulated robots Viper s650 from Omron Adept, and two part assembly stations with 4-d.o.f. SCARA robots Cobra s600 from Omron Adept interconnected by a closed-loop transport system with access branches - a twin-track conveyor belt from Bosch-Rexroth controlled by four IndraLogic PLCs with 512I/256E lines, Ethernet, Profibus, and RS 232 communication. The workstations have local storages for material components; in case of storage depletion, missing parts are retrieved by a 4-d.o.f. SCARA robot Cobra s850 from a dual-spare part feeding ASRS in a strategy established by the information extracted from images collected by two 2D video cameras. These parts travel on pallets on the conveyor to the depleted storage where they are handled by the station robot. The operations on products are executed at the assigned workstations; products are placed on pallet carriers by robots and move on the conveyor from one station to the next. There is a 6^{th} workstation where empty pallets are introduced pallets with final products are moved out from/to a pallet buffer cabinet tended by a 4-d.o.f. Cartezian Python robot from Omron Adept.

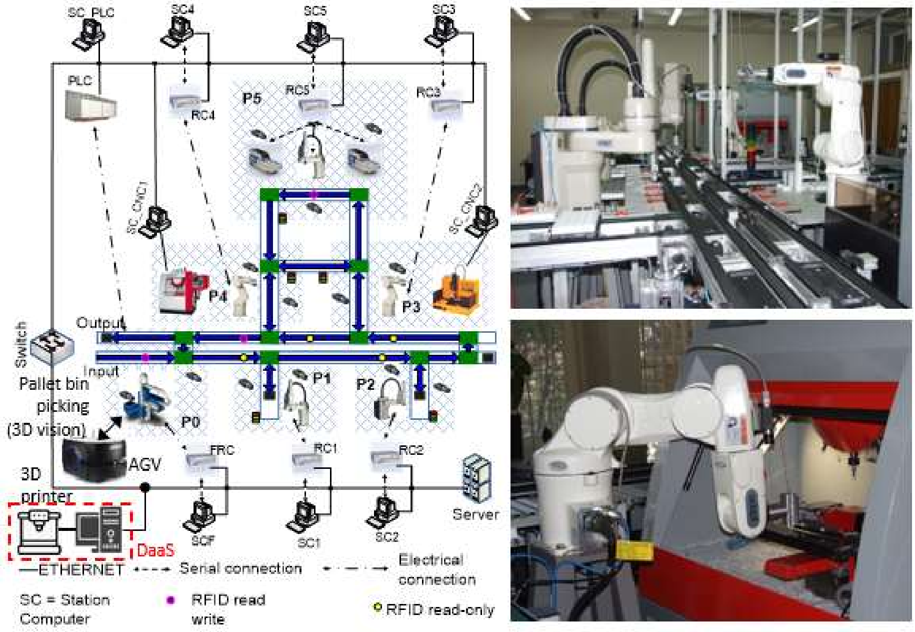

Figure 3. Pilot manufacturing cell (the factory): layout (left); global view, machine tending (right)

The quality control of shape geometry, surface state and component alignment is done by machine vision measurements from 2D and 3D video cameras. Each industrial robot is equipped with stationary, down looking and mobile, arm-mounted cameras.

Groups of resources have similar capabilities (e.g., CNC machines, industrial robots), so certain operations on products can be allocated to any of them; this feature is exploited in product planning for global batch production optimization. The material/product flow can connect any two workstations via the closed-loop conveyor, for both job shop and flow shop production processes. Empty pallets are brought in bins by an Omron LD-type AGV with laser and sonar; 3D vision Cognex is used for bin picking.

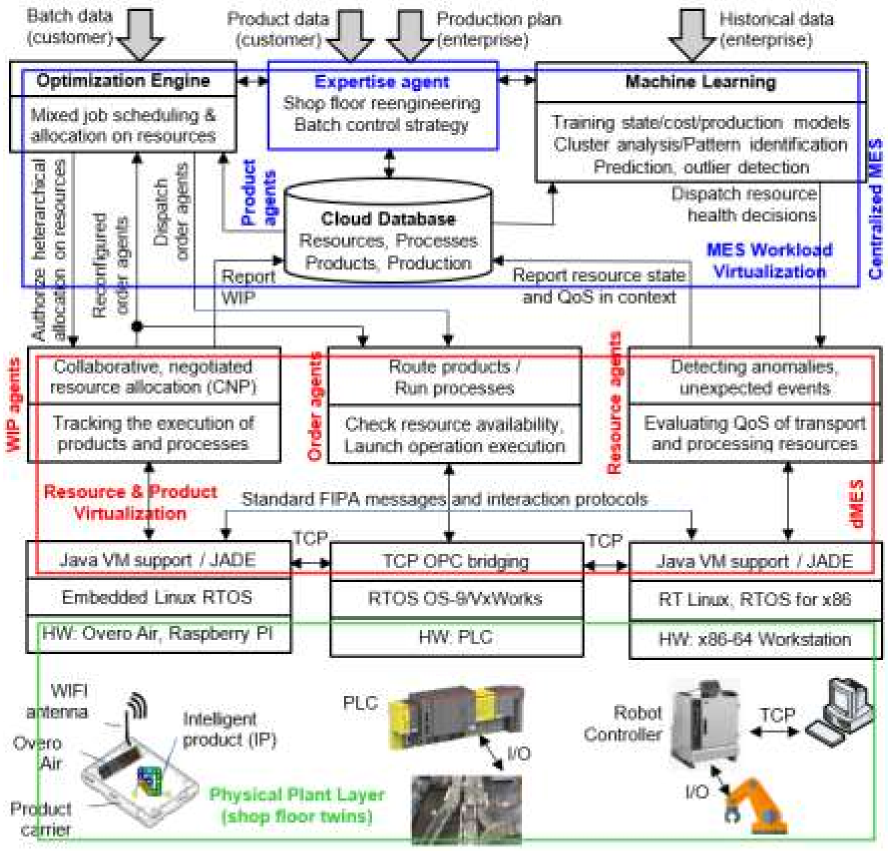

Figure 4. Virtualization of the factory entities (products, resources) and MES in CPS layers

Intelligence is embedded on products during their execution lifecycle through Intelligent Embedded Devices (IED) - OMAP3503 Overo computer-on-module, processor ARM Cortex A8 - placed on product carriers (pallet carriers). IEDs host Work in Process (WIP) agents that maintain the dynamic image of product execution orders optimized in the cloud and transferred to the cell's product routing PLC. The communication between shop floor entities uses Ethernet (cell workstations host resource images, cell PLC dispatches optimized product execution orders), Bluetooth and 802.11b/g Wi-Fi (IEDs track product execution) LANs. Product locating: RFID tags on carriers read by belt sensors.

The private cloud computing and service infrastructure is based on IBM CloudBurst 2.1 platform with 460 preconfigured virtual machines, 4GB RAM, 60GB of HDD; server management node IBM x3550 M3 dual-socket Intel Xeon 5620 2.4 GHz 4-core processors; 13 cloud compute nodes IBM BladeCenter H, 29 TB System Storage; blade operating system VMware vSphere 4.1 enterprise ed., IBM system director, network control, active energy and security manager. Customers have access via cloud to order products.

A cyber-physical system has been developed to transform the pilot manufacturing cell in a smart factory; products and resources are virtualized, networked and can communicate in a smart control system with distributed, semi-heterarchical architecture (Figure 4). The CPS for smart production control operates with distributed intelligence and collaborative decisions of strongly coupled shop floor devices; the modelling approach is the holonic paradigm with agent-based implementing framework. This approach is based on the virtualization of a set of abstract entities: *products* (types in RAMI4.0 lifecycle value stream), *resources* (technology, humans), and *orders* (instances in RAMI4.0 life-cycle value stream) that are modelled by autonomous holons collaborating by means of their information counterparts - *intelligent agents* organized in dynamic clusters [19].

The agents that are virtualizing the generic classes of factory entities instantiate them at production run for two types of *local workloads* - (a) *individual* resource state, behaviour and performance monitoring, respectively tracking product execution; (b) *collaborative* activity (re)scheduling and allocating on resources for products that add up to the factory's capacity of simultaneous execution. *Global* MES workloads are virtualized in the cloud: *optimization* at batch horizon based on insights from aggregated data streams originating from shop floor resources, processes and environment and ML-based prediction of resource usage cost and resource health management for predictive maintenance.

The cyber-physical system available for the pilot manufacturing cell hosts 20 hours per week of hands-on training, case studies, proof-of-concept and demos on I4.0 functionalities, design and implementing solutions. Figure 5 illustrates the courses held in the 42-week Master of Science program RA4I4.0. The courses are related to I4.0 technologies and are grouped in four categories: (green) Industrial robot sensing, control and mobility; (red) Artificial Intelligence in robotics and manufacturing: learning, interaction, image processing; (blue) I4.0 technologies and framework: CPS, IIoT, edge computing, MAS & Cloud; (orange) Applications: I4.0 in manufacturing, logistics & supply chains. Students work out projects from these topics in a 4-stage research program.

Figure 5. Courses on Robotics and Automation for manufacturing in Industry 4.0 framework

Table 2 lists these practical activities and their mapping with I4.0 technologies, RAMI 4.0 layers and RA4I4.0 teaching program.

Table 2. FMCell practical training and mapping with I4.0 technologies and courses

I4.0 hands-on training chapters	**RA support courses**	**I4.0 technology**	**RAMI4.0 layers**
Product lifecycle: 1) **Design**: digital models, group technology, DAAS (design as a service), customer input, virtualization; 2) **Making**: product intelligence, WIP MAS, product-driven automation 3) **Usage**: smartness, servitization, after-sales services	- Mechatronics engineering, DDM Human-machine interaction	Cloud, Simulation (S) H&V system int. (HVI) HVI	Business (B) Communication (C) B, Functional (F)

Value chain: 1) **Activities**: layout design, resource team configuring, production plan., activity scheduling & resource alloc., supply & inventory mngmt., manufacturing coordination & supervision, logistics for product distribution 2) **Processes**: DDM (additive manuf., 3D digital shape reconstruct., adaptive machining), robot services, 2D/3D vision (motion guid., quality ctrl., bin picking), transport (AGV, conveyor) 3) **Asset**: integration (robot, PLC, 3D print, CNC), instrumenting, health monitoring, maintenance, tooling	- Intelligent manuf. systems and value chain integration (IMS) - Robot motion planning and control - Guidance vision for robots and AGVs - IMS	HVI, S Additive manufacturing (AM), Autonomous robots (AuR) AM, AuR	Asset (A), F Integration (It) A, It
IC²T for CPS: 1) **Data collecting**: edge computing, IoT gateways, aggregation nodes, big data streaming, data aggregation 2) **Data transmission**: I/O and web-service communic. protocols, comm. middleware, TCP/OPC, Wi-Fi, fog computing 3) **Data processing**: analytics, optimization, anomaly detection, decisions 4) **AI and AR**: prediction, classification, clustering, pattern recognition, Mach. Learning, model DT	- Embedded systems and IIoT design - IIoT - Big Data streaming and Analytics - Machine learning techniques & applic.	Industrial IoT (IIoT), Big Data Analytics (BDA) IIoT, Cybersecurity (Cy), BDA Cloud S, AR, Cloud	A, It C, If F, B F, If
CPS: 1) **Models**: holarchies, data-driven DT, semi-heterarchical control, MAS, software in-the-loop, SOA, CPS 2) **Layers**: shop-floor control, MES, SC 3) **Cloud**: workload virtualization, VM, containers, cybersecurity, Manuf. Service Bus, Software Defined Networks	- Multi-agent system and programming - CPS models, design - Holonic MES ctrl. - Cloud models and HA services	S, HVI, IIoT Cloud, HVI Cloud, Cy	C, F F, It, If C, B

5. Conclusions

Considered as a part of the 4th industrial revolution, Industry 4.0 is a trend towards automation, digital transformation of processes and controls, integration and interaction of products and factory devices throughout their lifecycles, and new business models with enterprise presence in the cloud. New IC^2T and production technologies are used for these changes: Cyber-Physical Systems, Industrial Internet of Things, Cloud services, Artificial Intelligence and Human-Machine cooperation.

The Learning Factory is an efficient concept for the formation of professionals having Industry 4.0-related competencies, capable to operate cyber-physical production systems and pushing forward the development of key enabling technologies (IC2T) and innovative solutions for the industry of the future.

The paper describes a model of learning factory for Industry 4.0 based on an industrial real manufacturing cell controlled by a CPS that virtualizes individual shop floor devices and global MES workloads in the cloud for cost optimization, reality awareness, agility to product and market changes; this factory facilitates practical training that is driven by the learning content of courses scheduled in the 42-week master program 'Robotics and Automation for Industry 4.0'. This integrated learning factory benefits from the Education 4.0 concept and methods inspired by I4.0 transformations: personalization of learning with flexible, dynamic, individual learning pathways, digital teaching means, knowledge validation by real life examples, research projects offered by industry partners.

Future research consists in extending the learning factory model with an incremental training program on I4.0 technologies for SME personnel combined with the creation of a low-cost solution portfolio for automation and information management in production companies.

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