Critical Infrastructure for Industry 4 Laboratories and Learning Factories in Academia

R. Marian[1], D. Campbell[1], Z. Jin[1], M. Stumptner[2], and J. Chahl[1,3]
[1]School of Engineering, University of South Australia, Mawson Lakes, Australia
[2]School of Information Technology and Mathematical Sciences, University of South Australia, Mawson Lakes, Australia
[3]Joint and Operations Analysis Division, Defence Science and Technology Organisation, Melbourne, Australia
(romeo.marian@unisa.edu.au)

Abstract – **Industry 4 laboratories, Learning Factories and Testlabs are vital facilities for the development and dissemination of the new industrial revolution. However, as they are implemented and reported in the literature at present, they are lacking the specific constituents and their combination and integration that would qualify them as revolutionary – i.e. being clearly distinctive from carefully implemented state of the art technology that has been the norm in the last decades. An essential attribute of Industry 4 systems, as presented in the literature, is the capacity for collection, processing and recording of critical data that describe and characterizes their state and the use of information extracted from the data to monitor, control and optimize the operations. Industry 4 laboratories need to provide real life context for teaching, research, business and industry purposes. This paper discusses the minimal required infrastructure for establishing relevant Industry 4 laboratories.**

Keywords – **Industry 4 laboratory, digitalization, Cyber-Physical Systems, integration in supply network**

I. INTRODUCTION

In our other article - in this same conference and by the same team of authors - 'Challenges in Implementing Industry 4 Laboratories and "Learning Factories" in Academia'- the difficulties of defining and selecting what such laboratories comprise are examined along with key considerations. Once the problem is defined, the next step is to propose the type of infrastructure that can address the requirements of an Industry 4-relevant laboratory.

The term Industry 4.0, introduced in Germany in 2011, proposes better production and distribution of goods by radically improving manufacturing through a high level integration of intelligent manufacturing, by combining several high-tech concepts - Cyber-Physical Systems (CPSs), The Internet of Things (IoT), Big Data analytics, and cloud computing [1].

This paper refers to the fourth industrial revolution in industry as Industry 4 (I4) rather than Industry 4.0 (except for cases where Industry 4.0 has been used as such in specific references in literature). The I4 concept also includes similar/complementary definitions like Industry Renaissance by Dassault [2].

Compared to previous industrial revolutions, I4 implies collecting and using relevant information at an unprecedented scale in heavily interconnected co-evolutionary systems. These systems have the potential and ultimately the capability to aggregate, integrate, adapt, learn and improve automatically over time.

An important distinction needs to be made: Industry 4 is a philosophy that involves technology, not a technology. A collection of high-end equipment and processes become an I4 system when and only when the philosophical alignment is present: that is, when data is collected, information is inferred and used for the continuous control and improvement of the system.

Efficient application of I4 relies heavily on cognitive computing for implementation - sensing and making sense of the data about the state of the system and environment (although computing is not mandated for conceptual or micro-scale implementations). This might seem counter intuitive, but it can be illustrated with a similar example: Finite Element Analysis does not need a computer to be demonstrated, however, it cannot be implemented on any useful scale without a computer.

I4, when fully implemented, permits the design of smart products, produced efficiently in smart facilities, then distributed, supported and maintained by smart services. Brettel *et al*. pointed out that fundamental for Industry 4.0 for the manufacturing stage are Cyber-Physical Production Systems (CPPS) which are able to merge real production with a virtual environment so as to enable factories to become smarter [3]. Also, the horizontal and vertical integration alongside of whole value chain need to be taken into account while designing Industry 4.0 systems [4]. Thus, an adequate IT system and a robust physical infrastructure are playing key roles in establishing a relevant I4 ecosystem.

Education and academic research have been driving the development of industries and the innovation of technologies for centuries. Universities are expected to play a crucial role in advancing and fulfilling the promise of I4 by Governments all over the world. Although, there have been many laboratories and learning factories developed in Universities for educational purposes, only some of them have characteristics of I4, and even fewer have achieved recognisable I4 capability. Also, as a subset of I4, Testlabs [5], learning factories are mainly focused on design and manufacturing sections and have paid less attention to logistics and after-sale service, which is the key feedback loop to the plant on quality, price and demand.

To better demonstrate the authentic characteristics of I4 for the purposes of education, research and industry, learning factories and Testlabs need to become broadly established.

This paper attempts to identify minimal physical and Information and Communication Technology (ICT) infrastructure required to enable a University laboratory to become an authentic Industry 4 facility.

II. LITERATURE REVIEW

A. Physical Infrastructure

There are nine major technologies that are associated with Industry 4.0 systems [6], Fig 1. The trends of I4 from the point of view of product output include individualization and mass customization in association with higher productivity and reliability, as well as lower response time [4]. To achieve this, a more flexible manufacturing system that collects and extensively exploits data generated as it operates is required. Cyber-physical systems are used to enable machines, e.g. 3D printers, CNCs, industrial or collaborative robots (cobots) to seamlessly communicate with each other to increase productivity and reliability, [7]. To integrate workstations with CPS, Industrial Internet of Things (IIoT) is introduced for digitalizing and interlinking all equipment from end to end and integrate it with the whole value chain.

Within the factory, robots increasingly transfer items between machines and Automated Guided Vehicles (AGVs), and are broadly organized within the manufacturing flow to carry out and transport products/parts between workstations [3].

Radio frequency identification systems (RFID) and Data matrix codes (DMCs) are introduced to enable each individual product, having its own unique information, to be traceable through the system and to independently communicate with machines to trigger specific operations and to reduce the total response time [6]. Thus, efficient mass customization can be achieved.

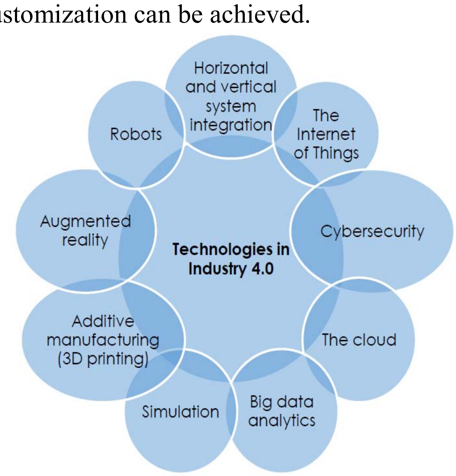

Fig. 1. Technologies Related to Industry 4

Elbestawi *et al*. equipped their SEPT Industry 4.0 Learning Factory with RFID reader/writers [3], allowing data to be captured from or written to individual products.

In the context of I4, modularity is another key aspect that needs to be considered. It provides factories a solution to address the decentralization and globalization of I4 [8].

B. IT Infrastructure

The I4 concept focuses on high degrees of integration, both horizontal and vertical, instead of optimizing and improving each individual stage within the value chain. IT infrastructure plays a central role in interconnecting all components within the system. Also, the involvement of IoT requires potentially massive data exchange in real-time. It is obvious that I4 systems require reliable, adequate and secure IT infrastructure to enable data exchange.

To establish a smart manufacturing context, it is necessary to enable decentralised decision making and real-time decision making for machines, workstations, and transfer systems [9]. Cloud-based data exchange is, in many cases, an attractive alternative or the best/only solution. I4 facilities rely on large amounts of data being collected, and consequently, rely on big data and data analytics methodologies. This can be challenging to implement in individual systems scattered around the world. Simons *et al.* present an Industry 4.0 learning factory, called AutFab, in the University of Applied Sciences Darmstadt in Germany [7]. Within the system, all control systems, actuators, and human machine interfaces (HMIs) are networked through Open Process Communication Unified Architecture (OPC UA) - a more robust and flexible data management technology.

C. Software

Virtualization is one of cores for I4 that need all internal and external processes along the value chain to be digitalized. In the stage of product design and development, Product Lifecycle Management (PLM) Software have been widely used. PLM packages can reliably collect and process manufacturing data, product infomation, etc., and manage it through the whole product lifecycle - from concept and design - in a digitalized manner. PLM can significantly shorten product lifecycle and can follow the product through all stages, through manufacturing, assembly, maintenance, through to disposal. Also, PLM allows virtual commissioning by 2D and 3D simulation, virtual testing, project and quality management, full traceability leading to massive savings in time and cost for product development.

Programmable logic controllers (PLCs) have been employed by industry since the 1970s. To better integrate within I4 system, traditional PLC have been optimized with new features to seamlessly link to manufacturing execution systems (MES) via the field bus [6].

Enterprise resource planning (ERP) software is utilized on top of the hierarchy of the Industry 4 systems [10]. ERP can directly collect manufacturing data from the factory floor level through a vertical integrated system to optimize the production plan.

In addition, the technology of digital twins has been considered and employed in many of Learning Factory projects. It was firstly introduced by aerospace and defence industry to improve the performance and the availability of military aircraft [11].

D. The Knowledge Gap

Existing Industry 4 facilities around the world are, at this stage, mainly aspirational in terms of those which embody the full spectrum of the Industry 4 philosophy.

A genuine Industry 4 facility needs to be clearly distinctive in certain key attributes when compared with the state of the art. Simultaneously, it needs to incorporate and exceed the progress made by the previous industrial revolutions. Specifically:

- It needs to be energy efficient. Mechanical power was the solution in the first industrial revolution. Utilising that energy efficiently and cost effectively is both a sustainability and business priority and an open-ended problem;
- It needs to efficiently make products that fulfil the needs of the customers. Mass production was the answer in the second industrial revolution. Cost was the constraint needing to be overcome. Mass customisation where each product item may have variations in a cost-effective manner is an open-ended problem;
- It needs to extensively and efficiently leverage computing and communication. Efficient information collection and processing was possible with digital electronics and communication which was the answer in the third industrial revolution. What still needs to be done is the development of efficient algorithms to fully exploit the technological capability of digital electronics and communications, to make sense of the data. This is a step beyond contemporary factory automation techniques.

The capacity of a facility to qualify as an Industry 4 requires a minimal physical and ICT infrastructure, which is presented in the following sections.

III. THE PRODUCT IN THE INDUSTRY 4 LABORATORY

The critical, *sine qua non* element in an Industry 4 facility irrespective of size and complexity, the reason for existence for the facility, is the product to be made. The product is not necessarily a single artifact that is made at a large scale, but shall be, at the very least, a family of products that incorporate occasional variations from one to another. Indeed, each item could be different from the previous based on specific orders and requirements (e.g. dental implants). The product can have different degrees and dimensions of complexity:

- single or multi-material,
- single or multi components,
- single or multi-machines/workstations to make/ assemble,
- fully mechanized (no direct human intervention) or human needed in the production/ assembly, etc.

The possible combinations are numerous and a full I4 facility needs to aspire to deal with a multitude of combinations, Table 1. The various combinations of product characteristics are highlighted, with clear indication what would be insufficient, what would be minimally required, what would be the best option (maximum quality vs price) and what options are only really possible, on large scale, in an I4 ecosystem. The legend is common for the rest of tables.

For an academic Industry 4 laboratory or learning factory, at the very least, a single material, single component product that is meaningful for customers, and one that can be customized can at least demonstrate some of the key characteristics of Industry 4. A fully representative product is fully customized (designed, analysed, simulated – a digital twin – then manufactured and supported to end of life).

TABLE 1
I4 LABORATORY PRODUCT CHARACTERISTICS

materials	product complexity and customisation	single part or assembly	product lifecycle in I4 lab
			designed
			Simulated
	set design		Simulated and tested on digital twin
single material	small number of product variations	single component	manufactured
multi material	multiple product variations	multi component	assembled
	each item is uniquely customised		tested
			packaged
			stored awaiting delivery

	below I4 specifications
	minimally required for I4 level
	good I4 level
	I4 needed

IV. CRITICAL INFRASTRUCTURE FOR INDUSTRY 4 LABORATORIES IN ACADEMIA

A. The Industry 4 Laboratories Production Infrastructure

The purpose of creating relevant Industry 4 laboratories/Learning Factories in Universities is to provide contexts of I4 systems at small scale that are manageable from the point of view of cost and complexity. They do not only benefit education and research, but also offer to small and medium enterprises (SMEs) an opportunity to discover market niches, entering a larger supply chain, pathways to develop into the future. Thus, the selection of a real product family and manufacturing methodology to make it and be demonstrated greatly influences the University based facility design and capability.

The product or family of products to be made inform the decision regarding the production system and the physical infrastructure of I4 laboratory. It is true that machines and equipment tend to be more capable and offer more flexibility at the top end of the price scale, but the decision regarding complexity of product and envelope of flexibility needs to be made early.

When the product family is selected, the types and mix of workstations can then be decided. Workstations shall be established and networked in cyber-physical production systems. At minimum one workstation is required, but it is highly recommended that at least three workstations are utilised as this will provide demonstrations with greater flexibility and at least two transfers between workstations, either by machines or by humans. All workstations, machines, tools need to be connected with a central control platform, e.g. manufacturing execution system, to fulfil full horizontal and vertical integration which is the constituent characteristics of an I4 ecosystem.

In terms of transfer between the workstations and within the I4 lab, industrial robots or cobots are preferred in terms of agile and precise positioning. AGVs could be employed to transport heavy parts between workstations or for long trips. Humans may be part of these processes, which opens opportunities for human-machine cooperation development and demonstration. In-house drones can also be considered as a transportation solution for specialized cases. Short term storage and automated storage/retrieval systems can add a touch of realism to the system to create a buffer before the dispatch, Table 2.

TABLE 2
I4 LABORATORY PRODUCTION INFRASTRUCTURE

production	human/ machine production	human/ machine interaction	workstations	transfer between workstations
	manual production		single machine/ workstation	manual transfer
single workstation	machine production	humans and machines separate, interlocked	multiple machines/ worktstations	simple transfer system
multiple workstations	manual/ machine production	humans and machines actively and simultaneously share same space	integrated machines/ workstations exchanging critical information to enable sequencing/ schedulling optimisation	robots
flexible/ intelligent integration of workstations			flexible workstation simultaneously incorporating machines, robots and humans.	AGV(s) Automated storage and retrieval
				short term storage

B. *The Industry 4 Laboratories IT Infrastructure*

The CPPS based Industry 4 systems require numerous smart sensors, CPS workstations, controllers and actuators, robots, cloud computing, and intrinsically safe interconnectivity. Data transport varies from low volume/low bandwidth, to high volume/high bandwidth. Typically, data communication needs to be real time or near real time. Gateways, network switches, controllers (e.g. PLCs) and SCADA systems will perform an increasingly critical role in maintaining essential data communications for production, diagnostics and maintenance. Failover management, cyber-security, interoperability and traceability are increasingly key considerations as production systems form part of a broader ecosystem and supply chains and are exposed beyond the immediate production environment. The increased demand of the ICT infrastructure is characterised in Table 3. Physical safety of ICT infrastructure also becomes more critical [12], such as protection from fire and natural elements.

In a University I4 laboratory environment, the notions of failover management and physical safety may not be as critical as in the industrial production context. Maintaining 100% production may not be a key objective for the demonstration in that laboratory. However, the I4 lab may provide the opportunity to test and demonstrate these aspects should the host institution opt to do so.

An Enterprise Service Bus (ESB) is needed to provide physical connection between different system and control levels, i.e. ERP, MES, SCADA system [12].

TABLE 3
I4 LABORATORY ICT INFRASTRUCTURE

Sensing and data collection	Data	Data processing and process control	Software
no sensing of data	data used as generated	process monitoring	descriptive conceptual digital twin
sensing of critical data	data capture and recording	process control	single direction integrated digital twin
redundant sensing of critical data	data storage	process improvement	fully integrated digital twin
redundant sensing of critical data plus non-critical data	data transfer data security data backup	process optimisation	intelligent digital twin - machine learning and new inferences

C. *Software infrastructure for Industry 4 Laboratories*

The application of the technology of digital twin is a must for I4 laboratories, as digital twin provides a real-time and life-time information of and for the production situation to help make decisions. Digital twins assist with product/production improvement, preventive or reactive maintenance, tuning, energy efficiency and simulation for process optimization purposes, all towards optimizing product performance and reducing production cost.

MES software provides the connection from the shop floor level to the business level to fulfil vertical integration, which is a key element of the I4 system. Specific implementations of I4 laboratories may opt to omit the implementation of ERP as the number of processes may be limited. However, once again, the opportunity exists when designing I4 laboratories, to demonstrate scalability and to enable upgradability, as demonstrated in other studies [13].

Augmented reality (AR) and Virtual reality (VR) technologies can play an increasingly important part in Industry 4 labs. Humans remain a part in many aspects of an Industry 4 ecosystem. AR and VR enable multidimensional visualization of physical and abstract properties in the product lifecycle, as well as education.

The PLM software can optimize product lifecycle and shorten lead time. A number of products exist in the market, some examples being 3D Experience PLM [14], Windchill PLM [15] and Siemens PLM [16]. As a mature technology, PLCs shall be used with Industry 4 academic laboratories and on the factory floor and be linked with sensors, controllers and actuators, as well as MES.

Once the on-ground ICT infrastructure is set, consideration may be given to fee-for-service models to outsource data analytics. Specialised data processing facilities (server farms with high end computing power, redundancy and reliability, with continuously maintained software) reduce the complexity of on-ground processing and infrastructure required, and benefit from economy of scale as provided by a third-party.

V. DISCUSSION

Well implemented I4 laboratories are important as they have the capacity to illustrate and demonstrate the key elements of the Industry 4 ecosystem, and interactions within. An I4 laboratory provides a platform to assist (under)graduates to develop the skills and knowledge for a viable career path and provides a testbed for research and industry to experiment and conceptualize opportunities. I4 laboratories, in Universities should include minimum demonstrable components representing the key functional value adds of an authentic I4 ecosystem. All critical functions can be emulated at a manageable and affordable scale at lower level of complexity. In addition, the scalability of I4 laboratories allows a growing system to incorporate new technologies or accommodate a wider range of future research directions. I4 laboratories and facilities should have the ability to be integrated into a global supply network (as a fractal-like concept), Table 4.

TABLE 4
EXTENSION/INTEGRATION OF I4 LAB TO SUPPLY NETWORK

integration in larger supply network
materials and products buffers
input-output information and materials/ products exchange
integration in I4 supply network
intelligent integration of I4 lab/facility as a component into a fractal-like global supply network

VI. CONCLUSION

This paper recommends requirements for Industry 4 laboratories in Academia, various components and infrastructure elements, a variety of combinations of attributes to choose from and the need for catering for complexity in even demonstrator I4 implementations. I4 systems transcend the contemporary manufacturing framework, process digitalization models and digital twins. The systems are highly integrated in three dimensions: horizontal integration, vertical integration and end to end integration. To embody the philosophy of Industry 4, all components need to be digitalized and interact intelligently with each other. Thus, to establish proper Industry 4 laboratories in Universities, both physical and ICT infrastructure need to be fit-for-purpose for I4 ecosystems. Machines and workstations need to be designed to enable CPS integration that fully exploits the capabilities of the manufacturing environment. Also, the ICT infrastructure need to be robust to support large scale data transport, collection, transmission and processing.

The possibility of integrating I4 laboratories at a global scale to form a world-wide demonstrator and greater supply network in a fractal-like, self-similar integrating systems offers exciting perspectives that need to be further analysed and is the plan for our future research.

REFERENCES

[1] Zhong, R.Y., et al., *Intelligent Manufacturing in the Context of Industry 4.0: A Review* Engineering, 2017. 3: p. 616–630.

[2] Kitchingman, J. *From Industry 4.0 to Industrial Renaissance*. 2018; Available from: https://www.industry40summit.com/wp-content/uploads/2018/03/John-Kitchingman-.pdf.

[3] Elbestawi, M., et al., *SEPT Leaning factory for Industry 4.0 education and applied research.* Procedia Manufacturing, 2018. 23: p. 249-254.

[4] Brettel, M., et al., *How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 perspective.* World Academy of Science, Engineering and Technology International Journal of Information and Communication Engineering, , 2014. 8, No:1, 2014.

[5] Subic, A. and S. Gallagher, *Industry 4.0 Testlabs in Australia*. 2017, Prime Minister's Industry 4.0 Taskforce

[6] Bahrin, M.A.K., et al., *Industry 4.0: A review on industrial automation and robotic.* Jurnal Teknologi, 2016. 78,: p. 6-13.

[7] Simons, S., P. Abe, and S. Neser, *Learning in the AutFab – the fully automated Industrie 4.0 learning factory of the University of Applied Sciences Darmstadt.* Procedia Manufacturing, 2017: p. 81-88.

[8] Leitao, P., A.W. Colombo, and S. Karnouskos, *Industrial automation based on cyber-physical systems technologies: Prototype implementations and challenges.* Computers in Industry, , 2016. 81: p. pp. 11-25, 2016.

[9] Vaidyaa, S., P. Ambad, and S. Bhosle. *Industry 4.0 – A Glimpse*. in *2nd International Conference on Materials Manufacturing and Design Engineering*. 2018. Procedia Manufacturing

[10] Lee, J., B. Bagheri, and H. Kao, *A cyber-physical systems architecture for Industry 4.0-based manufacturing systems.* Manufacturing Letters, 2015. 3: p. 18-23.

[11] Glaessgen, E.H. and D.S. Stargel, *The digital twin paradigm for future NASA and U.S. air force vehicles*, in *53rd Structures, Structural Dynamics, and Materials Conference: Special Session on the Digital Twin*. 2012: Honolulu, HI; United States.

[12] Pereira, T., L. Barreto, and A. Amaral, *Network and information security challenges within Industry 4.0 paradigm.* Procedia Manufacturing, 2017. 13: p. 1253-1260.

[13] Babiceanu, R.F. and R. Seker, *Big data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook.* Computers in Industry, 2016. 81: p. 128-137.

[14] 3DEXPERIENCE, *3DEXPERIENCE® PLM Collaboration Services*. 2019.

[15] PTC, *Windchill PLM Software*. 2019.

[16] SIEMENS, *SIEMENS PLM Software*. 2019.