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Cyber-Physical Systems using Open Design: an approach towards an Open Science Lab for Manufacturing

Hélio Castro^{a,b,*}, Nuno Pinto^a, Filipe Pereira^a, Luís Ferreira^c, Paulo Ávila^{a,b}, João Bastos^{a,b}, Goran D. Putnik^d, Manuela Cruz-Cunha^c

^aSchool of Engineering, Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 431, 4249-015 Porto, Portugal

^bINESC TEC, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

^c2Ai - Applied Artificial Intelligence Lab, School of Technology, IPCA, Barcelos, Portugal

^dUniversity of Minho, School of Engineering, Campus de Azurém, 4800-058 Guimarães, Portugal

Abstract

Cyber-Physical Systems (CPS) are fundamental in Industry 4.0 and manufacturing research communities, and research and technologies organizations (RTO) are keen to implement CPS laboratories. Due to the strong investment in these laboratories, it is unaffordable the investment in CPS laboratories. This paper proposes a CPS architecture based on Open Design (an open-source approach for hardware and software), and the implementation of the laboratory created as an *open-source* and truly *low-cost* solution, designated as Open Science Lab for Manufacturing (OSLab4Man), addressing the reproducibility and replicability (R&R) practices for manufacturing research laboratories. An *open-source* and truly *low-cost* solution of the OSLab4Man and the bill of materials (BOM) of the physical components and some alternative components *open-source* and/or *low-cost* is presented, that enables a ubiquitous manufacturing system.

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* Corresponding author. Tel.: +351 22 83 40 500; fax: +351 22 83 21 159.

E-mail address: hcc@isep.ipp.pt

1. Introduction

There is a broad consensus that Cyber-Physical System (CPS) is a critical element in Industry 4.0 (1). One of the major challenges with CPS is the integration of physical equipment processes and computational processes (2). Industry 4.0 requires Smart Factories and to achieve this state of evolution it is required to infrastructure support as Smart hardware and software (3).

Due to the increase of the engineering problems complexity, it is required a greater need to have research teams and work with multiple physical and computational systems (4). Dynamic and integrated manufacturing systems are necessary to predict, react and align within complex and turbulent surroundings, and to support an evolutionary system Intelligent CPSs (1) are mandatory.

Many research and technology organizations (RTOs), such as universities, applied universities and research entities, are financially supported by state subsidies and public contracts and, due to the turbulent environment, there is a trend of shrinking budgets (5). RTOs that study in the CPS field are developing many architectural infrastructures and it is essential for the concept proof to verify and validate these infrastructures with testbeds in research laboratories for industrial environment and, consequently, industrialization. Research laboratories may represent heavy investment (6), and, in CPS research, hardware and software infrastructures and services could mean an onerous financial challenge.

To overcome research challenges Open Science (OS) is gaining importance among research communities. According to (7), OS is “a new approach to the scientific process based on cooperative work and new ways of diffusing knowledge by using digital technologies and new collaborative tools”. The trendy concept of open approach (8) is a core principle in OS and multiple variations and ramifications are address and comprises within OS. In Figure 1, an OS taxonomy proposal is presented to better represent the variations and ramifications of OS.

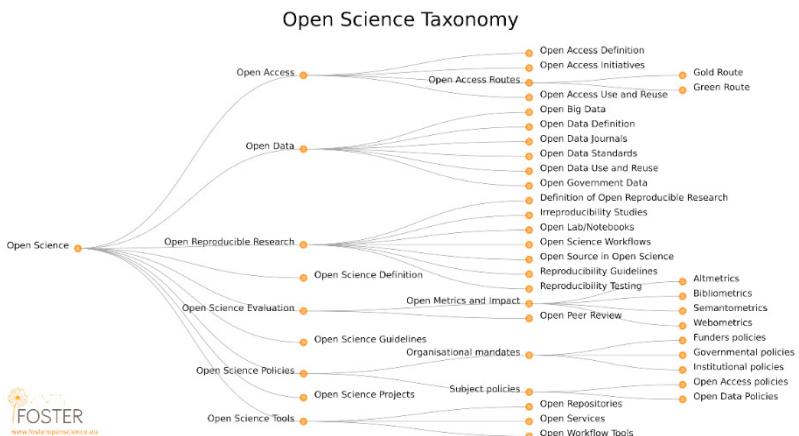


Fig. 1. Open Science Taxonomy (9).

To significantly reduce the high investment in laboratories there is a need to resort to Open Lab (6) by RTOs, in which Open Design (OD) concept must be adopted. Following the open approach, such as OS, OD addresses software and hardware design development based on open source, freely and digital available, and supported by communities of members with common interests. Supported in digital repositories or platforms, OD is considered to be community-based generative process with fast-growing (10). According to Yen et al (2021), many communities are oriented to develop research projects adopting reproducibility and replicability (R&R) practices and could be considered as OD a design method for R&R practices.

This work proposes an approach of an Open Science Lab for Manufacturing (OSLab4Man) addressing a R&R and, for this reason, open source and low-cost CPS supported by OD. Relating the OS taxonomy, in Figure 1, the

OSLab4Man in this work addresses the Open Reproducible Research branch and the following sub-branches of OS: Open Lab/Notebooks, Open Source in Open Science, and Reproducibility Guidelines.

Section 2 introduces a CPS architecture adopting open-source and low-cost approaches for hardware and software and section 3 proposes a dedicated laboratory using GitHub and low-cost resources, designated Open Science Lab for Manufacturing (OSLab4Man). Finally, section 4 discusses an example of an OSLab4Man implementation.

2. Proposal of a Cyber-Physical System (CPS) architecture supported by Open Design (OD)

The main goal is to create a R&R manufacturing laboratory oriented to the research community, adopting OD practices, whose production dynamics are controlled by a Cyber Physical System (CPS), called Open Science Lab for Manufacturing (OSLab4Man). The proposed CPS architecture aims to be social, scalable, replicable, and with remote and open access to the infrastructures, capable to be considerate an exponential technology and leading to true ubiquitous system. Within this architecture OD repositorium of digital products are available, in which the OSLab4Man is also available, to customize and replicate these products. It is emphasized that all the resources and services included in the system, whether at a physical or computational/digital level, meet the *open-source* and/or *low-cost* premise (12) and addresses *Cloud Manufacturing* (13), the *Industrial Internet of Things (IIoT 4.0)* (14) and the *Smart Factory* (15).

Members of a community are allowed to free access to a repository where a wide range of product is available, which are provided by the members of the community itself. To make the processing of congruent information achievable without limitations, most of it is hosted in the cloud, process best known as *Cloud Computing* (16), which will be supported by a Multi-Agent System (17). Creating a connection bridge with the physical world, through a CPS interface composed by an low cost Operational Computer and an low-cost IoT device, which connects and controls physical resources (17), such as Additive and Subtractive Manufacturing.

A CPS interface communication infrastructure (under appropriate communications protocols (18): BLE, NB-IoT, others) allows the information to circulate between the cloud to the information and control (sub)system in the first layer of the “physical world”. CPS interface explores a local Industrial IoT (IIoT) infrastructure to spread and coordinate the previously processed information to the production layer, which is in charge of manufacturing the intended product, using open-source design manufacturing equipment (e.g., design robotic arm, 3D printer, CNC router and conveyor belt). This communication can be done indirectly, through a complementary layer, namely, the automation system.

After the information has reached its proper destination and the production system has started, the operator and community(ies) are able to monitor in real time all actions and operations performed by the physical resources, since the device is connected to them. For this to be feasible, the global system uses the communication and surveillance system, as it offers means that allow for total control and monitoring of the entire process surrounding the production, as well as the collection of data relating to it. In addition, this layer is also embedded in the application offered by the cloud, which allows the operator to communicate directly with the members of the community(ies), which, in turn, is also granted access to such monitoring and control.

At this level where the cyber computation is relevant towards cognitive capacity, in which a real-time collaborative environment integrates people, equipment and processes. A set of processes continuously receive data from the current manufacturing process (from each production unity), from the operator analysis and the expected metrics, and react towards the refinement of involved algorithms, the realignment (substitution, reconfiguration settings, etc. (19) of involved equipment or any other production unity, as well as, if necessary, redesign or reengineering of proposed products. Event-driven programming for synchronous dynamics, Edge computing (20) on IoT devices and Message-Oriented Middleware (MOM) (21) for interoperability support, will sustain the required real-time and distributed behavior of such cyber computation level. The dynamic reconfiguration and integration between the physical and the digital world will be assured.

The Database layer corresponds to a database where community(ies) and members, as well as their respective data. Additionally, to provide an intelligent system, a copy of all the processed and generated code is also created and stored in the same information library. This means that it is not necessary to process all the information again in case of correspondence to a product previously executed by the system.

Like the Database layer, the Management, Documentation and Security layer appears as a protective layer to all information and data that run in the system, ensuring that it is available, legible and true only to those who are entitled to it (22). In addition, data recovery is made possible through a backup system.

In Figure 2 is shown where all the layers/subsystems mentioned are illustrated, as well as their high-level connections.

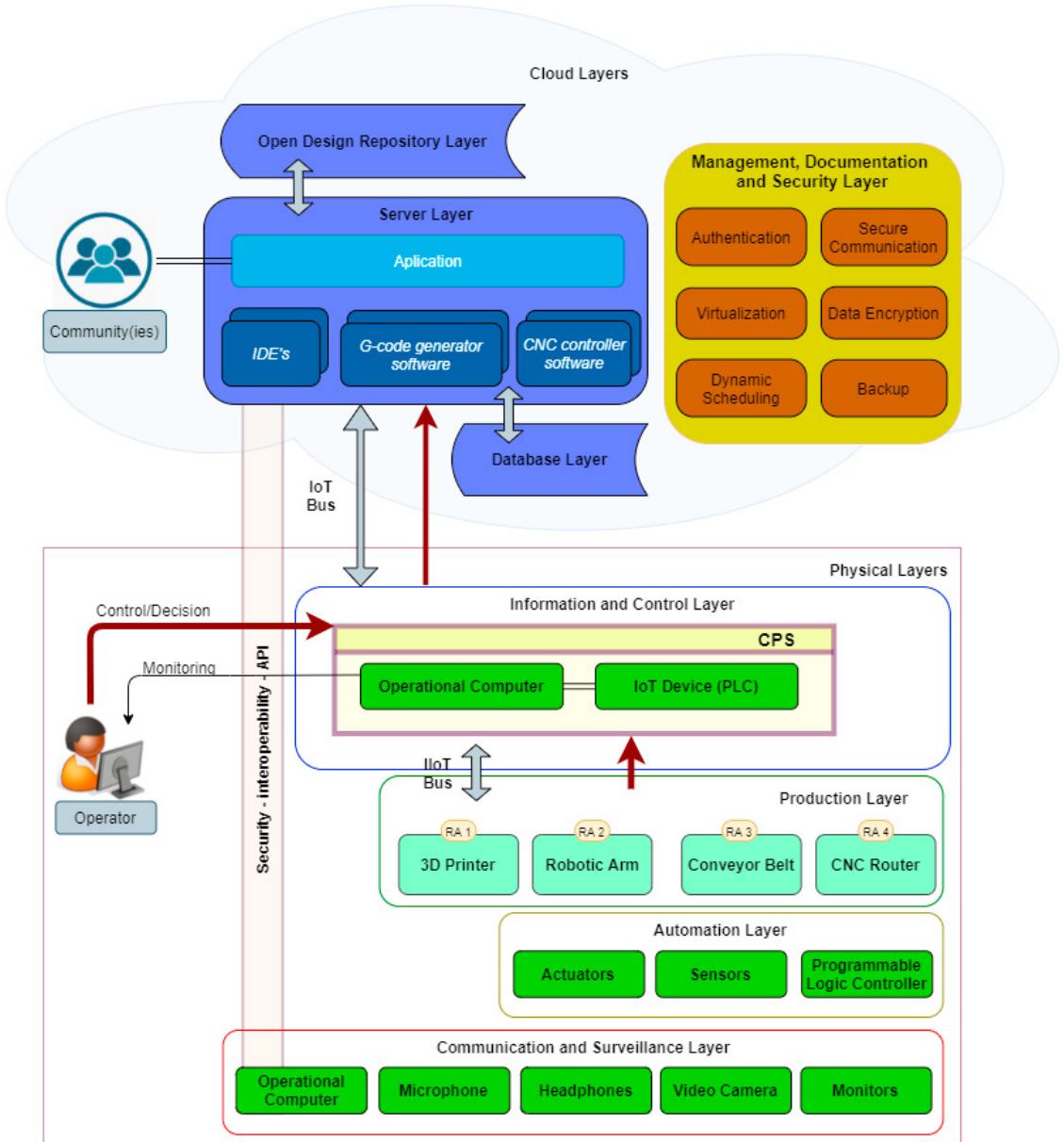


Fig. 2. Architecture of the proposed CPS supported by OD.

3. Implementation of Open Science Lab for Manufacturing (OSLab4Man)

The Open Science Lab for Manufacturing (OSLab4Man) implementation is also established by layers, which are equally distinguished between computational and physical. Effectively, in the cyber world, GitHub is used as a

repository, both at a documental level and at a source code level, given its wide variety of files accepted by it. The next layer is the servers, which have *as RunTime Environment (RTE)* the Apache HTTP Server. As a frontend, the open-source application Rocket.Chat is reused, as it enables communication and monitoring, still being added the function of selecting the desired product. As a backend, that is, the server-side code, there are IDE's that allow its elaboration. In fact, NetBeans is an IDE that enables the programming of a MAS, with the help of the *Java Agent DEvelopment framework (JADE)*. The other is the Arduino IDE, where code is written based on a library that provides many common procedures based on input and output signals. In addition, servers can also resort a set of G-code generation software, in case the file acquired in the repository is not yet in the desired format. This software is OctoPrint, in the case of 3D printing, and dxf2gcode, in the case of CNC. Finally, it only remains for the servers to request the services of the software in charge of communicating with the physical resources, namely, OctoPrint for the 3D printer, Grbl for the CNC router and Pronterface for the robotic arm.

OSLab4Man physical system is centralized by a Raspberry Pi 400 and a Controllino, which, respectively, correspond to the information and control system. The first ensures the connection to the cloud and receives information from it, as well as enabling direct communication with the 3D printer. The second, besides being connected to the first, is basically an industrialized Arduino board, as it offers the security, robustness and reliability of an industrial-grade PLC (23). However, its main function is to communicate with and control the manufacturing system (Figure 3), which is composed of a BeeveryCreative B2X300 (3D printer), a BCN3D MOVEO (robotic arm), a 3018 PRO (CNC router) and a conveyor belt. From this system, the focus is on the specified robotic arm, since it is an *open-source* and truly *low-cost* solution, in which its structure is fully printed using additive manufacturing technology, being "only" necessary to acquire the accessory material. Furthermore, its electronic components are controlled by Arduino (24).

Connected to the Raspberry Pi 400, there is also the communication and surveillance system. Effectively, it consists of two monitors and four ArduCAM video surveillance cameras, given the compatibility of its shield with Arduino boards and its quality/price ratio. As for headphones and microphone, these are at the discretion of each operator. It should also be noted that this layer of materials facilitates direct communication with the members of the community(ies), as well as the monitoring of production.

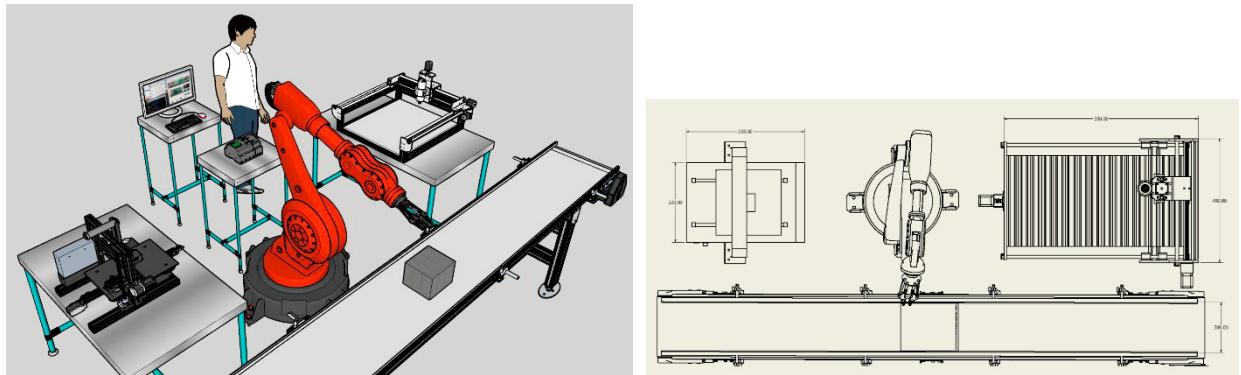


Fig. 3. Manufacturing System layout (3D, in left side, and 2D, in right side, models)

A flow sheet is represented in Figure 4 to better understand the hardware communication flow between the various components of the OSLab4Man physical system.

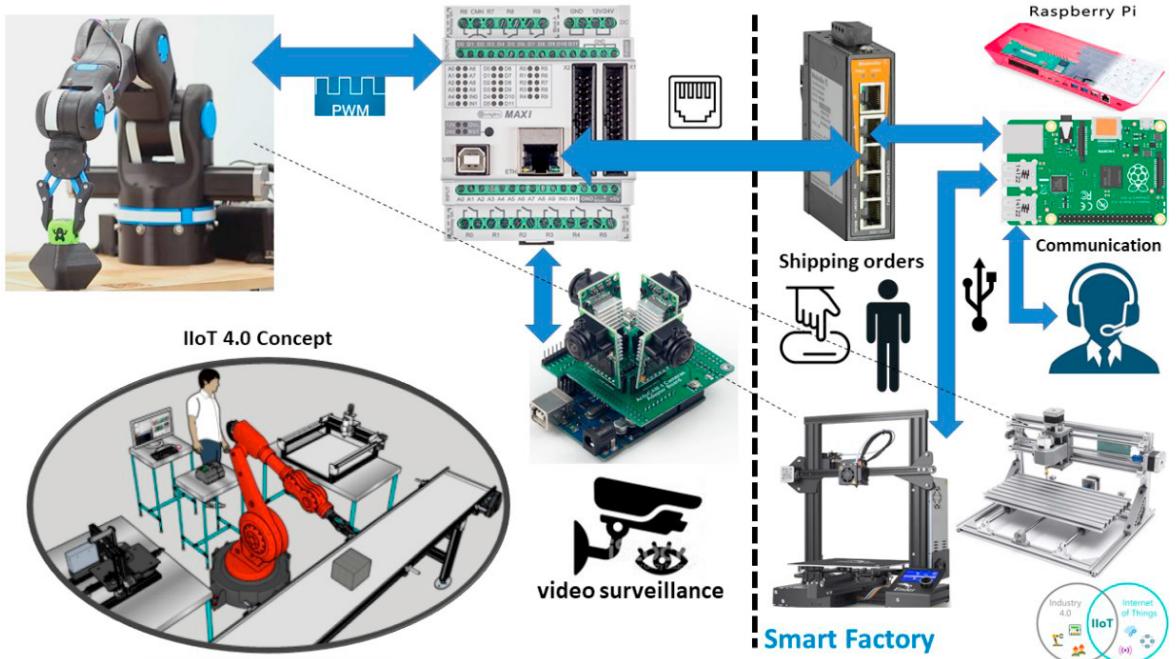


Fig. 4. Flow sheet of the OSLab4Man physical system.

In the following, it is provided a bill of materials (BOM) of the OSLab4Man physical components mentioned above and some alternative components also possible based on *open-source* and/or *low-cost* and listed in Table 1.

Table 1 – BOM of the OSLab4Man Physical System

Component	Component Model in OSLab4Man	Quantity	Some Alternative Open-Source and/or Low-Cost Component Model(s)
Operational Computer	Raspberry Pi 400	1	<ul style="list-style-type: none"> Raspberry Pi 4 Raspberry Pi 5 Raspberry Pi 3 Model B
PLC	Controllino	1	<ul style="list-style-type: none"> PLC Arduino Ardbox & DALI OpenPLC RepRap
3D Printer	BeeveryCreative B2X300	1	<ul style="list-style-type: none"> Creatality Ender 3 Anet A8 Original Prusa i3 MK3S
Robotic Arm	BCN3D MOVEO	1	<ul style="list-style-type: none"> Dorna 2 UFactory uArm Zortrax Robotic Arm rBotCNC
CNC Router	3018	1	<ul style="list-style-type: none"> Carbide 3D Shapeoko 4 Ooznest Workbee
Conveyor Belt	Customized from spare parts	1	--
Video Camera	ArduCAM (OV9782)	4	<ul style="list-style-type: none"> ESP32-CAM Waveshare OV9655 SaintSmart Surveillance Arduino Camera
Headphones with Microphone	Tacens AH118 Headset	1	<ul style="list-style-type: none"> 1Life Sound One Headset Ngs Ms103

4. Conclusions

Research and technologies organizations (RTO) to keep at the forefront in their research area need to attract investment, especially from the public sector, to invest in state-of-the-art laboratories, namely a Cyber-Physical System (CPS) laboratory for those RTO that develop in manufacturing area. Due to the trend of less public investment in R&D and the need of dissemination of knowledge among research communities, Open Science (OS) is a new approach to support collaboration and dissemination among researchers, based on digital tools. In the specific case of laboratories, the branch of Open Reproducible Research of OS forwards to Open Lab as a key element to address the reproducibility and replicability (R&R) practices of research laboratories.

Considering the importance for the research on manufacturing field of CPS and, consequently, implementation of a dedicated laboratory for this subject, this paper proposes a CPS architecture based on Open Design (an open-source approach for hardware and software), and the implementation of the laboratory created as an *open-source* and truly *low-cost* solution, designated as Open Science Lab for Manufacturing (OSLab4Man). The CPS architecture is social (community-based), scalable, replicable, and with open access and remote control, aiming for a truly ubiquitous manufacturing system. All physical and computational/digital resources consider the *Cloud Manufacturing*, the *Industrial Internet of Things (IIoT 4.0)* and the *Smart Factory* and compress the *open-source* and/or *low-cost* premise for the implementation of the OSLab4Man.

Based on this work, an example of an OSLab4Man is being implemented. Firstly, the OSLab4Man physical system and then, the computational/digital system. Future works will present the results and new findings of the OSLab4Man implementation.

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References

1. Putnik GD, Ferreira L, Lopes N, Putnik Z. What is a Cyber-Physical System: Definitions and models spectrum. *FME Trans.* 2019;47(4):663–74.
2. Lee EA. Cyber physical systems: Design challenges. *Proc - 11th IEEE Symp Object/Component/Service-Oriented Real-Time Distrib Comput ISORC 2008.* 2008;363–9.
3. Wang S, Wan J, Li D, Zhang C. Implementing Smart Factory of Industrie 4.0: An Outlook. *Int J Distrib Sens Networks.* 2016;2016.
4. Xu L Da, Xu EI, Li L. Industry 4.0: State of the art and future trends. *Int J Prod Res.* 2018;56(8):2941–62.
5. Coccia M. Metabolism of Public Research Organizations: How Do Laboratories Consume State Subsidies? *Public Organ Rev.* 2019;19(4):473–91.
6. Pearce JM. Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs. *Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs.* Elsevier Inc.; 2013. 1–271 p.
7. European Commission. EU Open Innovation, Open Science, Open to the World [Internet]. European Comission. 2016. 108 p. Available from: http://europa.eu/rapid/press-release_SPEECH-15-5243_en.htm
8. Castro H, Putnik G, Castro A, Dal Bosco Fontana R. Open design initiatives: An evaluation of CAD Open Source Software. In: *Procedia CIRP.* 2019. p. 1116–9.
9. Pontika N, Knoth P, Cancellieri M, Pearce S. Fostering open science to research using a taxonomy and an elearning portal. *ACM Int Conf Proceeding Ser.* 2015;21-22-Octo.
10. Castro H, Putnik G, Castro A, Dal Bosco Fontana R. Could open design learn from wikipedia? In: *Procedia CIRP.* 2019.
11. Yen A, Flowers B, Luo W, Nagesh N, Tueller P, Kastner R, et al. A UCSD view on replication and reproducibility for CPS & IoT. *CPS-IoTBench 2021 - Proc 2021 Benchmarking Cyber-Physical Syst Internet Things.* 2021;20–5.
12. Vieira G, Barbosa J, Leitao P, Sakurada L. Low-cost industrial controller based on the raspberry pi platform. *Proc IEEE Int Conf Ind Technol.* 2020;2020-Febru:292–7.
13. Xu X. From cloud computing to cloud manufacturing. *Robot Comput Integr Manuf [Internet].* 2012 Feb [cited 2011 Sep 12];28(1):75–

86. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0736584511000949>
14. Boyes H, Hallaq B, Cunningham J, Watson T. The industrial internet of things (IIoT): An analysis framework. *Comput Ind.* 2018;101(March):1–12.
15. Chen B, Wan J, Shu L, Li P, Mukherjee M, Yin B. Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges. *IEEE Access.* 2017;6:6505–19.
16. Díaz M, Martín C, Rubio B. State-of-the-art, challenges, and open issues in the integration of Internet of things and cloud computing. *J Netw Comput Appl [Internet].* 2016 May;67:99–117. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S108480451600028X>
17. Ramião AL. Sistema Ciber-Físico de Produção Modular usando Raspberry Pi [Internet]. Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa; 2017. Available from: <https://www.rcaap.pt/detail.jsp?id=oai:run.unl.pt:10362/36905>
18. Al-Sarawi S, Anbar M, Alieyan K, Alzubaidi M. Internet of Things (IoT) communication protocols: Review. *ICIT 2017 - 8th Int Conf Inf Technol Proc.* 2017;(October):685–90.
19. Cunha MM, Putnik GD, Gunasekaran A, Avila P. Market of Resources as a Virtual Enterprise Integration Enabler. In: *Virtual Enterprise Integration [Internet].* IGI Global; 2005. p. 145–65. Available from: <http://services.igi-global.com/resolveddoi/resolve.aspx?doi=10.4018/978-1-59904-891-8.ch007>
20. Shi W, Cao J, Zhang Q, Li Y, Xu L. Edge Computing: Vision and Challenges. *IEEE Internet Things J.* 2016;3(5):637–46.
21. Rausch T. Osmotic Message- Oriented Middleware for the Internet of Things. 2018;(April):17–25.
22. Caldas MP. Management information systems: managing the digital firm. Vol. 7, *Revista de Administração Contemporânea.* 2003. 223–223 p.
23. Siyad AA. Design and development of IP based automatic bottle inspection system Controllino Maxi automation [Internet]. Faculty of Engineering, University of Malaya; 2019. Available from: <http://studentsrepo.um.edu.my/11449/6/aziz.pdf>
24. BCN3D Technologies. BCN3D MOVEO: A fully Open Source 3D printed robot arm [Internet]. 2021 [cited 2021 Jul 2]. Available from: <https://www.bcn3d.com/bcn3d-moveo-the-future-of-learning-robotic-arm/>