PROJECT-BASED LEARNING FOR ENGINEERING STUDENTS IN THE CONTEXT OF INDUSTRY 4.0: APPLICATION TO AUTOMOTIVE ASSEMBLY SYSTEM

Al khatib, Ahmad (1,2);
Malhaire, Jean-Marie (1,2);
Dauvé, Stéphane (1,2);
Fougères, Alain-Jérôme (1,3)

1: ECAM Rennes - Louis de Broglie, Bruz, France;
2: Dept. of Mechanical and Industrial Engineering;
3: Dept. of Informatics & Telecommunications

ABSTRACT

Fourth industrial revolution called Industry 4.0 has radically transformed production systems in manufacturing companies by the integration of emerging technologies. However, manufacturers must overcome several barriers, such as the lack of qualified talent to develop and manage various high-technology systems. Assembly system design aims to define proper assembly line configurations with the optimal performances to overcome increased competitiveness in the market. Nowadays, assembly system design should consider industry 4.0 concepts integration beyond traditional aspects like system balancing and sequencing. In this paper, we introduce a project-based learning approach to teach engineering students assembly system design taking into account industry 4.0 dimension. This project is carried out in collaboration with an industrial partner to design and implement car doors assembly line. The project demonstrated students interest and prepared them better for industry 4.0 era.

Keywords: Industry 4.0, Education, Design education, Assembly system design, Learning factory

Contact:
Al khatib, Ahmad
ECAM Rennes - Louis de Broglie
France
ahmad.al-khatib@ecam-rennes.fr

Cite this article: Al khatib, A., Malhaire, J.-M., Dauvé, S., Fougères, A.-J. (2023) 'Project-Based Learning for Engineering Students in the Context of Industry 4.0: Application to Automotive Assembly System', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.297

1 INTRODUCTION

Nowadays, manufacturing companies are transforming their production systems to face increasing competitiveness and market evolution to mass customization. Advancements in industry 4.0 technologies have revolutionized the industrialization making it possible to access to high-quality and low-cost products, and diminishing the environmental impact of the production process. However, there are barriers that must be overcome by companies, such as the high investment needed, not having qualified talent, data safety issues, and the need to shorten the innovation cycles (Mohamed, 2018). On the other hand, engineering education institutions should evolve their programs to take into account this paradigm shift of industry 4.0 and provide qualified engineers needed by manufacturing companies. Actual assembly systems are sought to seize the opportunities that the industry 4.0 offers in designing and operating phases. The aim of this paper is to present an original approach to teach assembly system design and industry 4.0 integration to engineering students. It is based on project-based learning approach, team-based learning approach and academia-industry collaboration which are required to consider all the dimensions of assembly systems 4.0 beyond traditional aspects like assembly line balancing and scheduling. This approach is applied to automotive assembly system for car doors assembly in the final year engineering students' curriculum at our engineering school. A subjective evaluation is done by semi-structured interview to collect students' feedback at the end of the project.
The second section of this paper presents a state of the art about industry 4.0 concepts and its education and in the second time assembly system design with its different dimensions. The third section presents the proposed approach, the course, the industrial partner, and the available resources. In the fourth section, the results of students' projects and the learned lessons are presented. Finally, conclusions and further research opportunities are drawn in the section 5.

2 STATE OF THE ART

2.1 Industry 4.0 education

Industry 4.0 is known as a changing paradigm based on several concepts, innovative technologies, and organization process which are integrated to traditional manufacturing processes to upgrade production systems to cyber-physical systems (Gunal, 2019). Nine key technologies are identified in the core of industry 4.0: Big Data; Autonomous and Collaborative Robots; Simulation of Processes; Horizontal and Vertical Integration of Systems; Industrial Internet of Things; Cybersecurity; Cloud Computing; Additive Manufacturing; Augmented and Virtual Reality (Rüßmann et al., 2015).
Nowadays, many manufacturing companies integrate industry 4.0 technologies on their production systems, and more and more other companies are focusing on possible future integrations. So, training and human resources development represent a fundamental issue for achieving industry 4.0 objectives. To do this, manufacturing companies and educational institutions should work more closely together to bridge the gap of new knowledge and skills between the academic and industrial worlds (Motyl et al., 2017; Wermann et al., 2019).
Many works investigate the needed competencies, hard and soft skills for engineers to be ready for industry 4.0 (Motyl et al., 2017; Hernandez-de-Menendez et al., 2020). They are categorized as: a) technical (e.g. state of the art knowledge, technical skills, coding skills, etc.); methodological (e.g. creativity, problem-solving skills, decision making, etc.); social (e.g. team work, communication skills, etc.); and personal (e.g. flexibility, motivation to learn, etc.) (Hecklau et al., 2016).
Industry 4.0 represents one of the most challenging themes for engineering education. One of the challenges is to deal with the broad multidisciplinarity of industry 4.0. Looking to this multidisciplinarity, it is difficult for mechanical or industrial engineering students to deal with cyber aspects of industry 4.0. On the other hand, Informatics and Telecommunication students have difficulties to understand the physical part of cyber-physical system. So, departments and institutions with different specializations need to work with each other to be able to teach the concepts of industry 4.0 in all its dimensions (Wermann et al., 2019).
Moreover, engineering education should offer hands-on experiences with new technologies to students to better prepare them to industry 4.0 environment. Learning factories are solutions to put engineering students in a real learning environment including realistic production processes (Wagner et al., 2012). So, theoretical knowledge can be more effectively communicated and tested for practical applications by offering open access to different tools, technologies, and training resources. Learning factories can

https://doi.org/10.1017/pds.2023.297 Published online by Cambridge University Press

take multiples formats ranging from the original physical spaces to digital environments or simulators (Wagner et al., 2012). They are proposed in several institutions to deal with industry 4.0 concepts like Smart Factory and IoT integration (Spillane et al., 2020; Koch et al., 2021), Augmented Reality (Mourtzis et al., 2018), using Robotics (Tosello et al., 2019), both Horizontal (machine to machine) and Vertical (machine to MES/ERP) Connectivity (Wermann et al., 2019), Additive Manufacturing (Chong et al. 2018).

Unfortunately, however, many of these works are just interested by the technical skills and the ability to use and interact with industry 4.0 technologies. More attention should also be paid to the methodological and soft skills like creativity, problem solving, decision making, communication, etc. Furthermore, industrial partners should be integrated to the developed learning factory to put students in a realistic industrial context.

Moreover, learning factories are usually a preset environment making difficult for students to develop creativity and problem solving skills. Learning engineering students of industry 4.0 should be achieved on collaborative project-based learning and team-based learning in a learning factory associated to real industrial application.

2.2 Assembly system design in industry 4.0

In competitiveness industrial environment, a well-designed production system is essential for manufacturing company (Rösiö and Bruch, 2014). Attention is especially important to assembly system design where assembly processes integrate human factors and human-robot collaborations with respect to all safety and health standards. Assembly system design allows to make choices and decisions about the configuration of the future line. These decisions made in the design phase are noted for their long impact on development costs and assembly line performance.

Bortolini et al. (2017) define six dimensions to consider in assembly system design:

- *Balancing*: station number, cycle time, precedence relations and task attributes (like time, cost or space to perform).
- *Sequencing*: Mixed-model assembly system and work overload.
- *Equipment selection*: total profitability and flexibility.
- *Ergonomic risk*: impact on workers, legislation, aging workforce and musculoskeletal disorders.
- *Material feeding*: material storage and feeding policy.
- *Learning effect*.

Industry 4.0 integration in the design and management of assembly systems leads to the concept of assembly systems 4.0. Six main possibilities are identified for assembly system 4.0: aided assembly, intelligent storage management, self-configured workstation layout, product and process traceability, late customization and assembly control systems (Bortolini et al., 2017). All these possibilities need to be considered during assembly system design.

Simulation tools is an indispensable technology used in the design of future assembly system. They include process simulations, robot programming simulations, ergonomic evaluation simulations and information technology simulations. They help to simulate multiple configurations and make decisions to optimize the performance and reduce the risks on human operators.

Nowadays, traditional courses of assembly system design are not sufficient to take into account the dimension of industry 4.0. Assembly system design and industry 4.0 education are related and cannot be separated. Integrating engineering students in the assembly system design project in the context of industry 4.0 should give them the opportunity: a) to understand assembly system in all its dimensions; b) to propose configurations and to make decisions in the design phase by using simulations of industry 4.0 c) to integrate industry 4.0 concepts for operating phase; d) to see the impact of their choices after the implementation of the physical assembly system. So, in the next section, we introduce the proposed approach to teach engineering students assembly system design and development in industry 4.0 context.

3 PRESENTATION OF THE PEDAGOGIC PROJECT

3.1 The course and students' background

The developed project is designed for the final year engineering students of ECAM Rennes engineering school which have mainly industrial and mechanical engineering background with limited skills in Informatics and Telecommunication Technology acquired during their studies. These limited skills could

be a challenging issue for the students to deal with industry 4.0 concepts. However, these students should be prepared to their future jobs in manufacturing companies where industry 4.0 concepts are more and more implemented. So, the proposed learning approach should help these students to develop skills to integrate industry 4.0 concepts. The proposed project has two main objectives: a) to offer a synthesis project that could enable them to applicate industrial engineering knowledge learned during their studies; a) to develop new skills to integrate the concepts of industry 4.0 in the design and development of assembly systems. This project should prepare them to the real industrial environment after their studies.
The project is the result of internal collaboration between two departments at the engineering school: "mechanical and industrial engineering" department and "IT and Telecommunications" department. It is also a consequence of external collaboration between ECAM Rennes and an industrial partner.

3.2 Industrial partner

EXCELCAR is an industrial FabLab (Fabrication Laboratory) platform offering shared resources to accelerate industrial innovations and to transform production systems by the integration of different 4.0 concepts. The means and skills of this platform are intended to benefit the entire industrial ecosystem in west France region for all industrial sectors and especially automotive one. The platform is installed in the site of well-known car manufacturer to solve industrial problems related to its production lines. Moreover, many industrial innovations, implementations of assembly lines and operators' training programs are developed by the platform for the car manufacturer. Working with this platform represents a real advantage for the engineering students.

3.3 Proposed framework

The framework is articulated on a project-based learning and team-based learning. Teams of seven engineering students work in the projects to design and develop the assembly line during the first semester from September to January (100 hours in total). Students' projects take place in two sites:

- The engineering school site where students design the assembly line and develop industry 4.0 applications.
- the industrial partner site where the engineering students implement and turn on the physical assembly line with the developed industry 4.0 applications.

The proposed framework as presented in the figure (1) consists of several key steps:

- *Project definition*: with the complexity of the project (many tasks, many actors, many resources), project management is crucial for success. Students should first understand the project and its objectives. They also organise the team and the different roles in the project. They establish a planning in Gantt chart to organise tasks and resources.
- *Product definition*: students should understand the assemblies, the components, the specifications and how the components are assembled together.
- *Assembly line design*: in this step, manual and automated assembly workstations, and tasks are defined. So, balancing study is needed between workstations to optimise flows. Sequencing of the different models of the assembly, needed equipment, and tools are fixed. Attention should be paid to human factors for each workstation to avoid musculoskeletal disorders and anticipate needs for training.
- *Assembly 4.0 concepts integration*: in this step, the students should exploit the industry 4.0 resources in the assembly line design and propose applications for the physical assembly line (e.g. product process traceability, assembly control, aided assembly, etc.).
- *Implementation of the physical assembly line*: the students carry out the physical installation of the assembly line in the industrial partner site. They turn on the line and take the roles of operators to assemble the products and test their design choices for one-hour production.

During the project, three strategies of learning are used: a) Punctual classroom training about different technologies: simulation process solution, cobot formation, ergonomic analysis solution, security training for the industrial partner site access, etc.; b) Laboratory experimentations to develop solutions for industry 4.0 integration in the assembly system. c) Real application and hand-on experience on the site of the industrial partner.
The project includes autonomous work by teams. However, professors from the school departments are available like human resources for students' questions. Three project milestones are done with teams to exchange about the project advancement.

https://doi.org/10.1017/pds.2023.297 Published online by Cambridge University Press

3.4 Assembly line description

The chosen scenario of the production line consists of different tasks to assemble parts on the front right and rear right car doors as shows figure (2). It includes the following tasks:

- Install the door on the Automated Guided Vehicles (AGVs).
- Assemble the window regulator on the door.
- Assemble the seal strip in the door.
- Marking the door and human-robot collaboration task.
- Quality control of the assembled door.
- Uninstall the door at the end of the circuit.

The AGVs circulate between the different manual or automated workstations to realize these tasks. This pedagogical scenario should encourage students to innovate, to show creativity during the preparatory and implementation phases. So, a great liberty is left for the students to make decisions to design the assembly line and to integrate the industry 4.0 concepts. The only fixed element is the AGVs circuit for practical reasons. The AGVs circuit is shown in the figure (3).

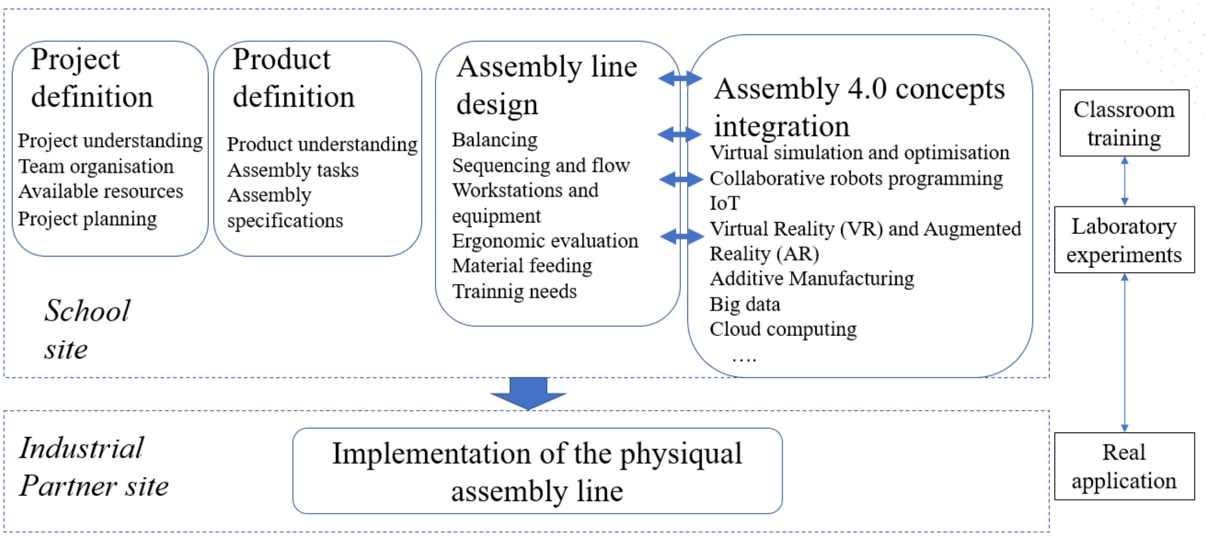

Figure 1: Proposed framework

3.5 Material resources

These resources are available at ECAM Rennes site and in the site of the industrial partner. They can be used for the design and development phases in the laboratory and for the final implementation of the physical line.

- COBOT UR10e and RobotDk solution for robot programming
- 2 Automated Guided Vehicles (AGVs) ASTI
- Virtual Reality Headsets (HTC Vive Pro)
- Augmented Reality headsets (Microsoft Hololens2)
- Several industrial sensors (Radio Frequency Identification (RFID), barcode scanners, proximity sensor, etc.)
- Additive Manufacturing Printers (Zortrax)
- KIMEA solution of Moovency for real-time ergonomic postures analysis. It can compute rapid upper limb assessment (RULA) score in a real environment based on Microsoft Kinect technology.
- Visual Components Software for production system simulation: this solution is based on Discrete Event Simulation (DES). In DES, a process is represented as a sequential series of events with a focus on what the event does, at what time it occurs, and how does it affect the other events. The key point of this solution is the pre-defined and ready-to-use components, the Visual Components eCatalog contains a robust library of virtual models of robots, machines and equipment from dozens of leading brands in industrial automation. With this software, we also have the possibility to visualize and control the dynamic simulation in a Virtual Reality environment. The

https://doi.org/10.1017/pds.2023.297 Published online by Cambridge University Press

Process Modelling workflow was designed to resemble how real-world production design. It consists of the following 5 steps: 1) Configure the 3D layout of the production system; 2) Define products and assemblies; 3) Define processes, like machines, workstations, inventories and buffers using task statements; 4) Define flows by creating sequences of processes that products must complete; 5) Run simulation; 6) Collect Key Performance Indicators (KPIs) from the simulation; 6) Optimise and make necessary changes to achieve goals.

- Agent-based simulation for the assembly line developed in the engineering school which models how different parts of an assembly system interact with each other.
- CAD solutions (CATIA, SOLIDWORKS).

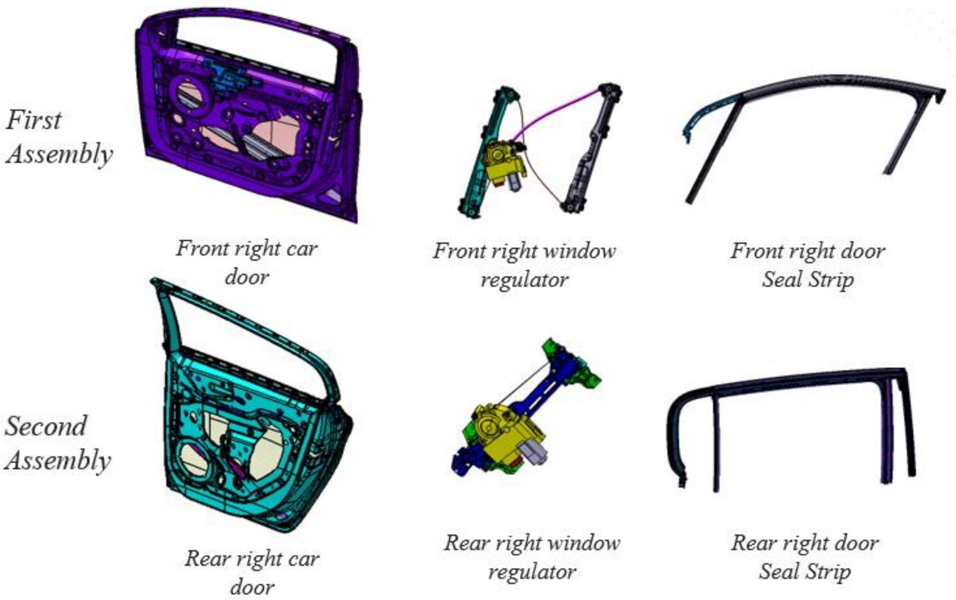

Figure 2: Assembly components

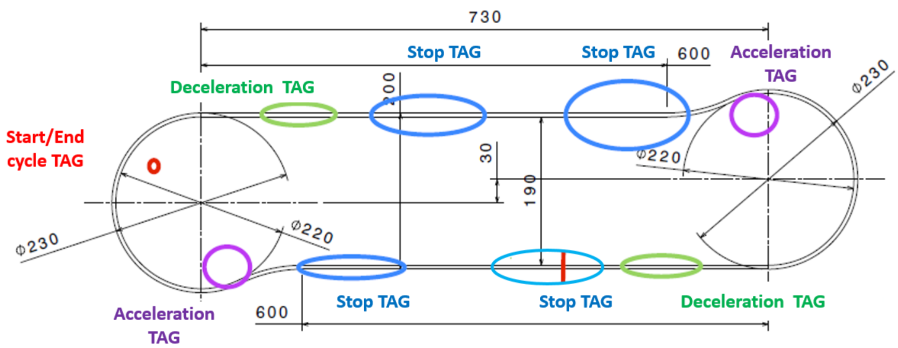

Figure 3: AGVs circuit for the assembly line

4 STUDENTS PROJECTS AND RESULTS

4.1 Students' realizations

Twenty-one students followed the course. They were divided to three teams. In this section, we focus on the presentation of students' effort to integrate industry 4.0 concept. After an organisation step to understand project objectives and to define a Gantt planning of the project tasks. An assembly system configuration is proposed by each team based on balancing studies, effective product and material flows, needed equipment and operators (Figure 4).

https://doi.org/10.1017/pds.2023.297 Published online by Cambridge University Press

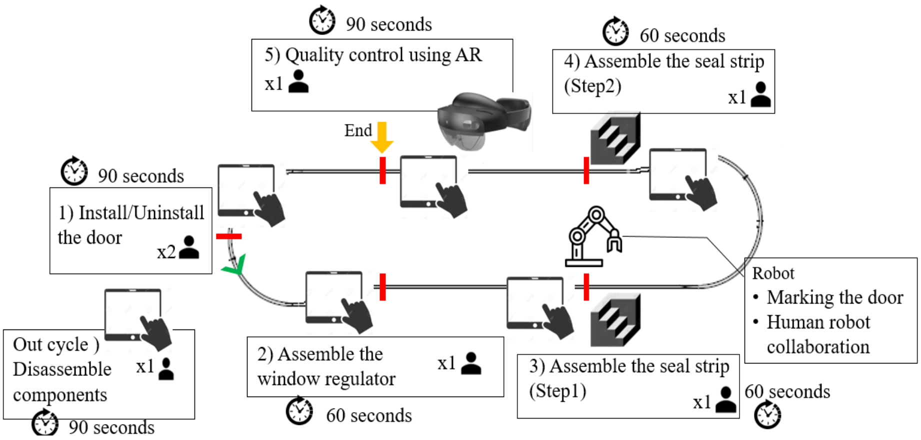

Figure 4: One of the configurations proposed by the students

The students' realizations to integrate industry 4.0 concepts during the project can be seen from two perspectives:

1. Industry 4.0 offered tools to help the students to make decisions and to evaluate the future assembly line in the design phase (figure 5). In this perspective, we can identify different applications to integrate industry 4.0 concepts:
   - 3D process simulation by Visual Components helped the students to evaluate the performance of the assembly line configuration by several indicators (line fluidity, cycle time, workstation idle time%, workstation busy time%, number of produced door in one-hour, bottlenecks, etc.). Moreover, the produced simulations facilitated communication between students.
   - Virtual Reality simulation enabled a virtual immersion of the students in the future assembly scenario. It allowed the students to evaluate some subjective ergonomic constraints like accessibility, height and security.
   - Ergonomic simulation by KIMEA made it possible to identify the critical postures of the operators on the physical door in the design phase (figure 5).
   - Robot simulation helped to optimize the cycle time of the cobot and facilitate programming.
   - CAD solutions and 3D printing are used to print prototypes to test the future interface tools of the cobot (figure 6).

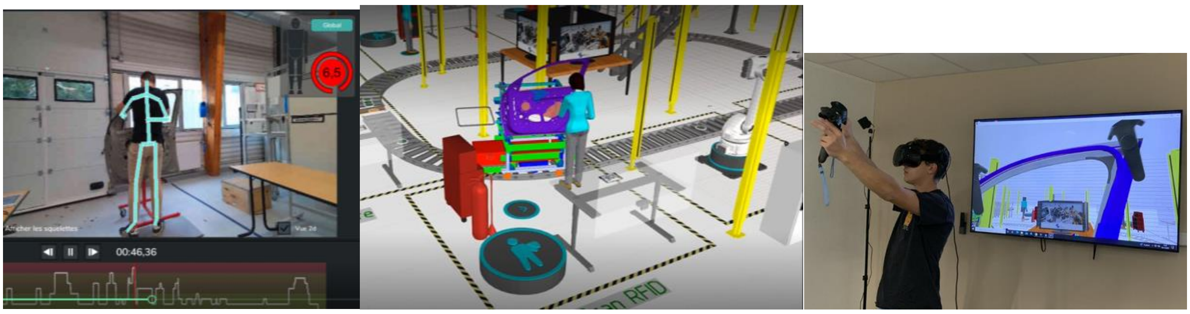

Figure 5: a) Ergonomic simulation b) Process simulation c) Virtual Reality simulation

2. Different possibilities were identified to integrate industry 4.0 concepts in the operating phase of the assembly line. In this perspective, different solutions were proposed and implemented by the students using IoT applications, Cloud, RFID, barcode scanners (figure 7):
   - Product and process traceability: it was possible to trace every door assembly at each workstation. So, we can know when it was assembled at which workstation by who operator.
   - Assembly control system: the robot was controlled automatically for the marking task depending on the type of arriving door. At each workstation, the operator had access to digital tablet to see in advance the type of arriving doors.
   - Performance monitoring: a monitoring screen was installed in the factory to see performance indicators of the assembly line (doors number, cycle time, qualities, non-qualities).
   - Quality control: Augmented Reality was used to control several quality points on the assembly.

https://doi.org/10.1017/pds.2023.297 Published online by Cambridge University Press

- Aided assembly and training: training supports in Augmented Reality were developed to train new operators on the manual operations to assemble door seat strip and door window regulator.
- Human-robot collaboration: in this task, the cobot took the seal strip to lift it to a suitable height for the operator. Then the operator took this seal strip to assemble it to the door.

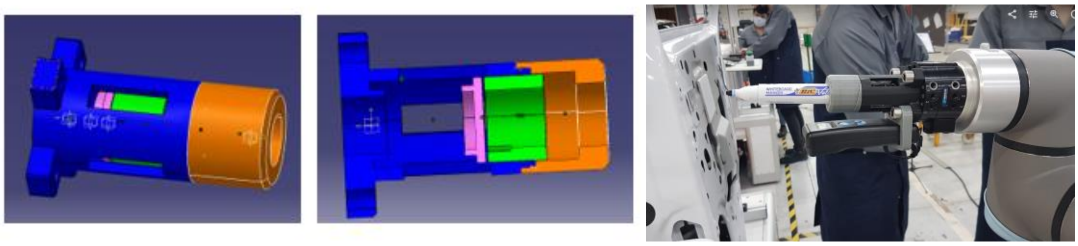

Figure 6: Prototype for interface tool for the cobot

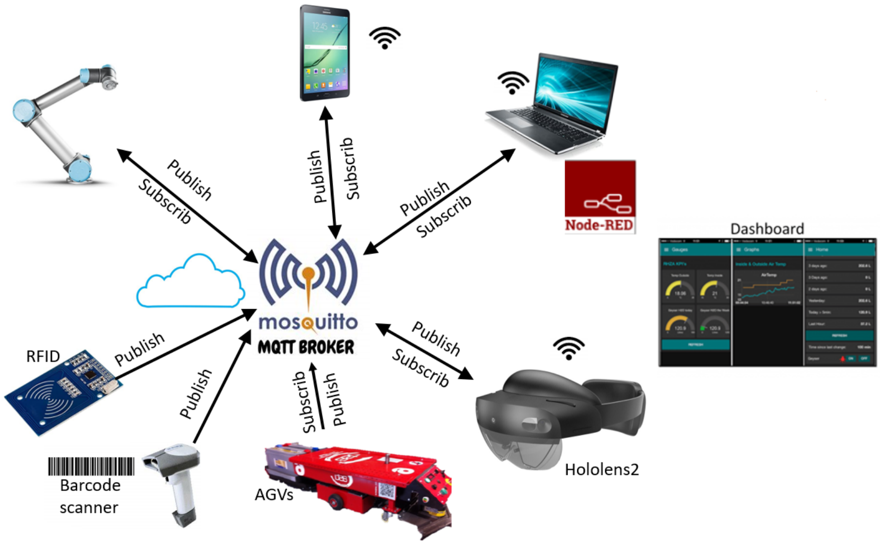

Figure 7: IoT architecture used by the students

Figure 8: Physical implementation and the run of the assembly line

4.2 Lessons learned and students' feedback

Participation and engagement of the students during the project was very positive. The project was motivating for the students and held their interest to propose ideas. Most of the times, they auto-learned methods, tools and technologies to develop their solutions on their own initiative. One of the learning successes of the proposed approach is that the engineering students with limited informatics and telecommunication skills before the project have learned many tools and techniques to integrate industry 4.0 in the future assembly line. They developed applications based on IoT, Robotics, VR, Simulation, Cloud that they have never used before.

At the end of the projects, we held a semi-structured interview with nine students to exchange about the usefulness of the course. All students would recommend this course to other students (7 strongly agree, 2 agree). They considered that the interest of the project compared to traditional courses was excellent (8 Excellent, 1 very good). They appreciated the link to industry. They were agreeing with the fact that the

https://doi.org/10.1017/pds.2023.297 Published online by Cambridge University Press

course content was interesting for their professional life (8 strongly agree, 1 agree) and the project helped them to find internships/opportunities in industry (2 strongly agree, 4 agree, 2 neutral). The contribution of the project to improve skill/knowledge about industry 4.0 was considered relevant (6 Excellent, 3 very good). The developed skills as defined by the students during the project were assembly system design, project management, communication, informatics development and IoT, mechanics and CAD, process simulations and 3D printing.

According to the students, the most useful and valuable aspects of this project were:

- Using a wide variety of new technologies and implement them in industry.
- Auto-learning, autonomy and freedom in the project group to develop the assembly line.
- Proximity to industry and working with the industrial partner.
- Team working and project management aspect.

One interviewed student indicated "*Unlike most of the projects in our studies, we had great freedom for almost all the points in the project that offers a wide choice of 4.0 technologies to master (VR/AR, digital process simulation, ergonomics, IoT, etc.) then to use in a practical way. Although this freedom was a source of distraction at first, having to find solutions on our own brought us closer to what it means "to be an engineer in a company 4.0"*, *which in my eyes is one of the most important points in a project. The fact of having applied it in a real industrial site is also one of the most interesting points of the project"*

Another one said "*During my research for my last year internship, I was able to enhance the Factory 4.0 project through the use of innovative technologies. During my job interviews, I was able to see that companies are looking for these new skills, so this made me stand out and allowed me to obtain an industrial internship that fits into the vision of the factory of the future"*.

However, students revealed some organisational issues to access to several materials needed during the project. The materials were a shared resource for all teams. So, organisation between teams was a crucial issue.

The observation of the project by the supervisors and the students' interview allow us to establish some lessons learned:

- Liberty in the project is a source of creativity but also a source of frustration: the students were frustrated in the first steps of the project. But, they understood the objectives and were the leaders of the project to propose the different solutions and to take decisions.
- Industrial context of the project is motivating: working in the site of the industrial partner about real assembly line that could be used by a real automotive manufacturing company was very motivating for the students.
- Industry 4.0 technologies are also education 4.0 tools play the role of boundary objects (Oonk et al., 2022) to gap the bridge between students: tools like Virtual Reality, Augmented Reality and Process Simulation helped the students to understand the assembly line and the impact of different choices on the cycle time and bottleneck zones. They helped communication and collaboration between the students.
- Competences in communication, project management and decisions making are crucial to lead changes into industry 4.0. The students improved these competences during the project. This evolution was observed clearly during the different milestones done all along the project.
- Understanding the limits of technologies: For example, using Augmented Reality headsets during the quality control on the physical assembly line was very tiring and problematic from security viewpoint.
- Finally, industry 4.0 integration depends on the industrial context. So, education should take into account the industrial reality by the integration of industrial partner to academic project of engineering students. Moreover, such project can be beneficial also for the industrial partner and bring creative solutions by students for industrial problems.

5 CONCLUSION AND FUTURE WORKS

In this paper, we introduced a project-based learning approach to teach assembly system design and the integration of industry 4.0 concepts to engineering students. In conclusion, this integration could be done from two perspectives: a) Firstly, industry 4.0 technologies (like process simulation, and ergonomic simulation) facilitate assembly system design and decisions making by the students; b) Secondly, in assembly system design, students define opportunities to integrate emerged technologies in the operating phase of assembly line and to increase its performance. The proposed project demonstrated positive participation of engineering students who play the role of professional actors to propose solutions, to research information and to learn and test methods, tools and applications on their own. It allowed them to acquire technical and soft skills needed by industrial companies. The effectiveness of our proposal is proved by students' satisfaction through semi-structured interview. Industrial-academia collaboration of the project was motivating for engineering students.

The application of the project was about the assembly of car doors. It could be completely possible to change this application case to adapt the project to the industrial partner's needs in future works. It could also be interesting to link more this project to scientific research to develop solutions in parallel with the projects that students do not have time or skills to develop.

ACKNOWLEDGMENTS

The authors would like to acknowledge the industrial partner (EXCELCAR) for his collaboration to develop this project, the course staff and the different students who followed the course. This project was supported by the French "Pôle de compétitivité ID4CAR" and "la Filière Automobile et Mobilités", as part of the program PIA-ACE.

REFERENCES

Bortolini, M., Ferrari, E., Gamberi, M., Pilati, F., and Faccio, M. (2017), "Assembly system design in the Industry 4.0 era: a general framework", *IFAC-PapersOnLine*, Vol. 50, No. 1, pp. 5700-5705. https://doi.org/10.1016/j.ifacol.2017.08.1121

Chong, S., Pan, G. T., Chin, J., Show, P. L., Yang, T. C. K., and Huang, C. M. (2018), "Integration of 3D printing and Industry 4.0 into engineering teaching", *Sustainability*, Vol. 10, No. 11, pp. 3960. https://doi.org/10.3390/su10113960

Gunal, M. M. (2019), *Simulation for industry 4.0. Past, Present, and Future*, Springer Cham, pp. 1-17. https://doi.org/10.1007/978-3-030-04137-3

Hecklau, F., Galeitzke, M., Flachs, S., and Kohl, H. (2016), "Holistic approach for human resource management in Industry 4.0", Procedia *Cirp*, Vol. 54, pp. 1-6. https://doi.org/10.1016/j.procir.2016.05.102

Hernandez-de-Menendez, M., Morales-Menendez, R., Escobar, C. A., and McGovern, M. (2020), "Competencies for industry 4.0", *International Journal on Interactive Design and Manufacturing (IJIDeM)*, Vol. 14, No. 4, pp. 1511-1524. https://doi.org/10.1007/s12008-020-00716-2

Koch, J., Gomse, M., and Schüppstuhl, T. (2021), "Digital game-based examination for sensor placement in context of an Industry 4.0 lecture using the Unity 3D engine–a case study", *Procedia Manufacturing*, Vol. 55, pp. 563-570. https://doi.org/10.1016/j.promfg.2021.10.077

Mohamed, M. (2018), "Challenges and benefits of industry 4.0: an overview", *International Journal of Supply and Operations Management*, Vol. 5, No. 3, pp. 256-265. http://doi.org/10.22034/2018.3.7

Motyl, B., Baronio, G., Uberti, S., Speranza, D., and Filippi, S. (2017), "How will change the future engineers' skills in the Industry 4.0 framework? A questionnaire survey", *Procedia manufacturing*, Vol. 11, pp. 1501-1509. https://doi.org/10.1016/j.promfg.2017.07.282

Mourtzis, D., Zogopoulos, V., and Vlachou, E. (2018), "Augmented reality supported product design towards industry 4.0: a teaching factory paradigm", *Procedia manufacturing*, Vol. 23, pp. 207-212. https://doi.org/10.1016/j.promfg.2018.04.018

Oonk, C., Gulikers, J., den Brok, P., and Mulder, M. (2022), "Stimulating boundary crossing learning in a multi-stakeholder learning environment for sustainable development", *International Journal of Sustainability in Higher Education.* Vol. 23, No. 8, pp. 21-40. https://doi.org/10.1108/IJSHE-04-2021-0156

Rösiö, C., and Bruch, J. (2014), "Focusing early phases in production system design", *IFIP International Conference on Advances in Production Management Systems*, Springer, Berlin, Heidelberg, pp. 100-107. https://doi.org/10.1007/978-3-662-44733-8_13

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., and Harnisch, M. (2015). "Industry 4.0: The future of productivity and growth in manufacturing industries", *Boston consulting group*, Vol. 9, No. 1, pp. 54-89.

Spillane, D. R., Menold, J., and Parkinson, M. B. (2020), "Broadening participation in learning factories through industry 4.0", *Procedia Manufacturing*, Vol. 45, pp. 534-539. https://doi.org/10.1016/j.promfg.2020.04.074

Tosello, E., Castaman, N., and Menegatti, E. (2019), "Using robotics to train students for Industry 4.0", *IFAC-PapersOnLine*, Vol. 52, No. 9, pp. 153-158. https://doi.org/10.1016/j.ifacol.2019.08.185

Wagner, U., AlGeddawy, T., ElMaraghy, H., and MŸller, E. (2012), "The state-of-the-art and prospects of learning factories", *Procedia CIRP*, Vol. 3, pp. 109-114. https://doi.org/10.1016/j.procir.2012.07.020

Wermann, J., Colombo, A. W., Pechmann, A., and Zarte, M. (2019), "Using an interdisciplinary demonstration platform for teaching Industry 4.0", *Procedia manufacturing*, Vol. 31, pp. 302-308. https://doi.org/10.1016/j.promfg.2019.03.04