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ORIGINAL PAPER

Use of laboratory scenarios as a strategy to develop smart factories for Industry 4.0

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Abstract

The intense pressures in the industrial environment and the academic field to adopt technological tools and concepts like product lifecycle management, digital factories, automation, the internet of things, process innovation, and bridges between real and virtual worlds have resulted in necessary new process innovations. All these are encompassed in the term "Industry 4.0." The evolution of teaching methods toward flipped classrooms, software advancements to support engineering topics, online studies, new skill requirements in Industry, and easy, affordable access to education have pushed universities to find novel ways to meet current conditions and prepare for future challenges. The need to link academic knowledge with Industry led us in our research project to create a methodology for the development and implementation of virtual and hybrid scenarios by using highly integrated, digital manufacturing tools as a teaching platform to explain topics like the automation of programmable logic controllers, robotics, manufacturing, and 3D virtual commissioning. The methodology was implemented successfully in a manufacturing system integration laboratory at Tecnologico de Monterrey by using virtual and hybrid commissioning scenarios as a strategy to develop smart factories.

Keywords Industry 4.0 · Virtual commissioning · Teaching platform · Digital factory · Educational innovation · Higher education

1 Introduction

It is a fact that Industry is being transformed by the accelerating evolution to "Industry 4.0," pushing universities in the same direction with technological tools that provide students the skills and knowledge necessary to satisfy modern industry requirements. Industry 4.0 has nine technical pillars. This research work explores and implements three of them, namely, (i) advanced simulation, (ii) robotics, and (iii) system integration, which are highlighted in Fig. 1. These pillars are supported by concepts such as smart factories, virtual commissioning, simulation, digital twins, and others shown at the bottom of Fig. 1, which are discussed later in this paper.

Smart factory products, resources, and processes can be characterized by cyber-physical systems (CPS) [1]. An essential keyword implicit in these is the *digital factory* (DF), which plays a significant role in all parts of planning for manufacturing processes and assembly systems [2, 3]. DF is a real factory model used for design, planning, and operations purposes. The digital factory developed during the engineering phase should be integrated into a "smart" factory with real-time data and information [1]. DF is the generic term for a vast network of digital models, methods, and tools; it includes simulation and 3D visualization, which are integrated by continuous data management. Its purpose is the comprehensive planning, evaluation, and constant improvement of all essen-

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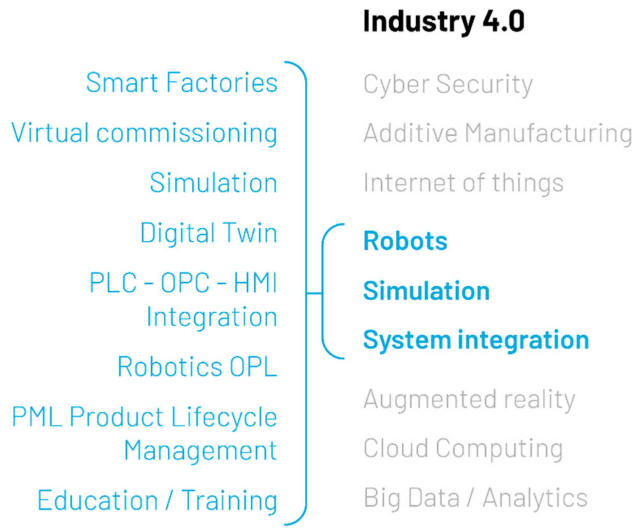


Fig. 1 Impact of pillars of Industry 4.0

tial structures, processes, and resources of the real factory in connection with the product [4].

New technologies, concepts, and trends require teaching platforms to adapt quickly; therefore, in the educational arena, we should use virtual tools to arrive at solutions because they are affordable and available. Engineering students with an industry profile need to know the available technological tools in manufacturing and automation under the DF concept.

This project used product lifecycle management (PLM) and automated solutions in a teaching platform for industrial engineering and mechatronics courses to link the three pillars of Industry 4.0 previously mentioned to satisfy the academy's need to develop virtual and hybrid manufacturing scenarios. In this case, we implemented these in the Manufacturing Systems Integration Lab (MSIL) course, where concepts like PLC automation, virtual commissioning, robotics, CAD/CAM, and process-planning are covered. The availability of various software—in terms of licensing, costs, and levels of integration—makes possible the implementation of these types of solutions. In this way, future engineers prepare professionally by learning new technology, concepts, knowledge, and automated software to meet the world's changing requirements.

Therefore, it is critical to take advantage of production-system-development technology, not only in Industry but also in Academia. Several engineering tools have emerged in recent years whose impact will be more significant in the future for both Industry and Academia. This research project implements mainly the PLM tool, which supports the production processes by reducing the development process and time to market, increasing the efficiency of the operations (time, resources—human, materials, and financial), due to the improvement of product structure management and the reduction of overhead activities [5].

This research paper contributes to interactive engineering development as it provides efficient and proved tools and methods for learning using the available resources. It does not limit the learning process but expands it to even to the learning from home.

2 Teaching platform using virtual/hybrid commissioning for MSIL as a solution

As the competition in the global manufacturing marketplace becomes increasingly intense, Industry has a growing need for graduates who are productive and "get to work" once they leave school. This need has been a challenge to engineering and technology educators: How do they effectively and efficiently prepare students with the most relevant knowledge, skills, and competencies so that they are adequately trained to address the needs of the manufacturing companies [6]?

It is essential to contextualize the PLM concept; therefore, we present the following eight aspects of the technological platform that we had implemented that increase the learning engagement thru the interaction with the system:

1. PLM tools used in the manufacturing process: In our study, we used PLM software applied to digital manufacturing. Although this kind of software is used sparingly in the educational environment, it has great potential in the training of future engineers because the students will apply not only CAD/CAM but also Digital Manufacturing (DM) tools.
2. Virtual commissioning using two leading tools (Delmia and Tecnomatix): For evaluating and implementing the simulation previously modeled by Valenzuela [7] in Delmia Automation and the work developed during this project using the simulation process software, Tecnomatix.
3. The consideration of Computer-Aided technology (CAXs) tools: Besides the use of digital manufacturing tools, the CAXs are also considered. The CAD aspect is used due to the nature of the project, and the CAM module is considered for G-code and the manufacturing of complex pieces.
4. An educational platform based on the use of a virtual/hybrid system: The new classification proposed by Valenzuela [7], where virtual and real components are combined into a fully functional automated manufacturing system. Four scenarios, depending on the user requirements and resources, are implemented to test the educational platform to increase the interactiveness of the student with the system.

5. Computer modeling and virtual/real simulations: Both the teacher and the student receive the benefit of a dynamic hybrid simulator and computer modeling. The teacher can prepare real-time and relevant exercises while explaining theory and concepts, thereby bridging the gap between theory and practice. The teacher can also create various faults and improve the troubleshooting skills of the student.
6. World Wide Web implementation: For the development of Web system architecture that allows the user to access a virtual laboratory via the internet. A web site is designed and developed for virtual interactions. This aspect is not covered in this project; however, it is implemented in other works referenced here.
7. Focus on the framework for manufacturing system integration: Manufacturing nowadays requires engineering at every phase, including production inception, design, and, increasingly, during and after the transition to the manufacturing itself/through this work, we become trained for the increasingly competitive manufacturing field.
8. Interaction between the PLC programming and the virtual/real manufacturing process: Students can develop their skills to program a PLC in a complex environment without the worry of damaging physical equipment because this is a virtual process.

Several teaching platforms developed through time focus on specific areas of manufacturing, such as those presented by Jianping et al. [8] and Shiue et al. [9], where a virtual or simulated teaching platform is implemented. Bengu [10] applied interactive multimedia to develop manufacturing courseware. The online platform of Saygin and Kahraman [11] is used to teach and operate a PLC in an automated manufacturing systems control area for distance education. There are other works like [12, 13], who develop an innovative instructional model to improve manufacturing courses.

Table 1 shows a summary and comparison of nine different authors' works and the main characteristics they cover on their studies—described above in aspects 1 to 8. In this research paper, we are addressing the eight aspects, whereas the other researches cover different aspects. In terms of interactivity, we consider our research to go beyond the simulation [6] and the communication capabilities [10] of the educational systems.

Next, a Venn diagram in Fig. 2 presents the context in which this work is based, as well as different concepts that are included in this work along with other manufacturing educative platforms. The teaching methodology assumes a set of formative and motivational processes that work well in the field of knowledge to get the best understanding. Each teacher must rework and adapt the methodology as a function of processes and expectations [19]. The method proposed here sets the structure for the complex decisions presented by a changing world; it responds to the continuous challenges and innovative approaches that we must foresee in the manufacturing field.

2.1 Technology software integration and virtual teaching in engineering education

Teachers need to be more creative when designing their class materials. When technology needs to be taught, teachers are usually limited by not being able to access technology because of cost, and students cannot practice with technology, or these practices are limited.

Educational research shows that a virtual teaching platform is a powerful tool for teaching innovation; thus, it is worth generalizing into teaching applications [20]. Software tools and technologies such as Java Applets, LabVIEW, MATLAB, and Working Model are used extensively at universities to supplement traditional online educational content that consists of handouts and multimedia [16]. Nowadays, it is mandatory to implement new DM technologies available in the market, such as Delmia Automation or Process Simulate.

Following up on the different points mentioned before, next is a description of the features implemented in our study, related to the software that we used.

1. The educational platform is based on the use of a virtual/hybrid system. The new classification proposed by Valenzuela [7], where virtual and real components are combined into a fully-functional, automated manufacturing system, is used in our study. Four scenarios, depending on the user requirements and resources, are implemented in the test of the educational platform.
2. Computer modeling and virtual/real simulations: Both the teacher and the student receive the benefit of a dynamic hybrid simulator and computer modeling. The teacher can prepare real-time and relevant exercises while explaining theory and concepts, thereby bridging the gap between theory and practice. This virtual/real simulation allows for better interactive student experience for the understanding of the manufacturing integrated systems.

2.2 Engineering assignment

New education reflects the real needs of Industry, which faces problems of integration across the traditional disciplines, such as:

- Working with digital tools for communication.
- Working in interdisciplinary, multi-skill teams.
- Working in a virtual environment.

Table 1 State of the art for this research

Author	Project name	Description	Aspects in this article							
			1	2	3	4	5	6	7	8
Valdez [14]	Methodology for the design of a Teaching Platform for a Manufacturing Systems Integration Laboratory using Digital Manufacturing	Methodology for a teaching platform for a Manufacturing System Integration Laboratory using virtual/hybrid scenarios supported by Digital Manufacturing tools under the PLM concepts Platform designed and proved both in Delmia Automation and Process Simulate, two of the leading software in DM Present the implementation of hybrid scenarios: Virtual Process/Virtual Controller, Virtual Process/Real Controller, Real Process/Virtual Controller, and Real Process/Real Controller The focus is on the framework of the Laboratory of Manufacturing System Integration PLC Programming using RSLogix5000 environment and the ones provided by the DM software An educative platform where, according to the scenario implemented, students can: Learn the use of DM software Simulate and handle the operation of a virtual and real manufacturing cell Program a PLC in different environment programming Learn topics related to robotics and PLCs	X	X	X	X	X			X
Jianping et al. [8]	Application of Virtual Teaching Platform of Digital Design and Manufacturing in Innovative Teaching for Numerical Control Technology Specialty.	Establishes a virtual teaching platform of digital design and manufacturing for teaching the reform of numerical control (NC) specialty. Based on analyzing current problems in teaching with traditional teaching methods The platform is integrated into four modules: CAD, CAE, CAM, and CNC. Students can experience the whole process simulation of product design, engineering analysis, machining processing, CNC programming, and machining profoundly It shows the integration of all these CAX tools in a Virtual Class CAD: Helps students establish their spatial concepts and enhance their understanding of the engineering process by applying the features of several programs CAE: Students can perform mechanical, structural, fatigue, reliability, modal analysis. CAM: Helps students to show a realistic display of parts and simulation of tool path processing; generates G codes of NC program	X		X		X		X	

Table 1 continued

Author	Project name	Description	Aspects in this article							
			1	2	3	4	5	6	7	8
Salazar and Macias [15]	Virtual 3D Controllable Machine Models for the implementation of Automations Laboratories.	Virtual Machine Models, which substitute the entire components of a fully equipped laboratory, for one or many virtual—not expensive cells—in the PLC automation field. The project emerged for educational purposes Based on the concept of controlled virtual machines applied in Engineering areas as PLC programming, automation, and tele-engineering laboratory Virtual cells programmed in LABVIEW PLC programming environments using Siemens and Simatic family. Use of Solidworks for mechanical design.				X	X			X
Fang et al. [6]	An Innovative Instructional Model for Improving Manufacturing Engineering Education	Develop a new instructional model to improve cognitive learning and student motivation in undergraduate manufacturing education Computer animation and simulation program is incorporated into a hands-on, real-world experiment It is applied in an undergraduate machining process course. It focuses on metal machining as an integral component of the manufacturing course. A computer program developed for animating and simulating The computer program consists of three interactive learning modules covering: a) cutting forces, temperature, and chip formation, b) tool wear and tool life, and c) machined surface roughness and residual stress					X		X	
Saygin and Kahraman [16]	A web-based programmable logic controller laboratory for manufacturing Engineering education.	Presents the design and development of a Web-based Programmable Logic Controller (PLC) system architecture that supports hands-on laboratory exercises in automated manufacturing systems control areas for distance education The system architecture allows remote users to access and control a PLC-based table-top manufacturing system via the internet A Web site has been designed and developed that facilitates interactivity and supports PLC programming and control The architecture represented is generic Utilizes physical equipment to teach PLC programming and control over the internet				X		X	X	X

Table 1 continued

Author	Project name	Description	Aspects in this article							
			1	2	3	4	5	6	7	8
Hsieh and Hsieh [13]	Intelligent Tutoring System Authoring Tool for Manufacturing Engineering Education.	The authors evaluated the feasibility of developing an intelligent tutoring system (ITS) authoring tool. They also assessed their instructional effectiveness. They developed a tutorial to use a CNC machine Focus on the use of a computer to deliver instruction. The authors have a particular interest in a class of computer-based instructional systems known as intelligent tutoring systems that hold great promise for manufacturing engineering education in the future The authors used XAIDA for development because of its availability and because other instructors have used it successfully in a variety of domains It was used to develop a tutorial explaining how to set up a computer numerical control (CNC) machine to machine apart The tutorial intended to familiarize students with the procedure before they use the device so that they get more out of their experience with the actual equipment			X				X	
Shiue et al. [17]	Integrated laboratory for manufacturing education.	Develops a laboratory environment to support courses on Manufacturing Processes Intermediate Manufacturing and Concurrent Engineering courses are considered This environment integrates a variety of computer-based tools, among them are Computer-Aided Design and Manufacturing workstations CNC machines Robotic assembly stations 3-D modeling packages			X		X		X	
Byrkett and Ettouney [18]	A model for developing and incorporating a computer-integrated Manufacturing laboratory into an engineering curriculum.	Present a model for integrating technology into an engineering curriculum in a way that involves students and faculty in the integration and development activities The authors highlight the importance of the evolutionary process over a turn-key system The model emphasizes the role of interdisciplinary work rather than one disciplinary approach							X	
Bengu [10]	Interactive multimedia courseware on manufacturing processes and systems.	Describes an ongoing effort to improve entry-level engineering education. Computer-aided interactive multimedia courseware is being developed by using multimedia tools, courseware, and the World-Wide Web The authors introduce a new manufacturing application of engineering systems Presents instructional and program information Provides simulations and administering assignments and exams					X		X	

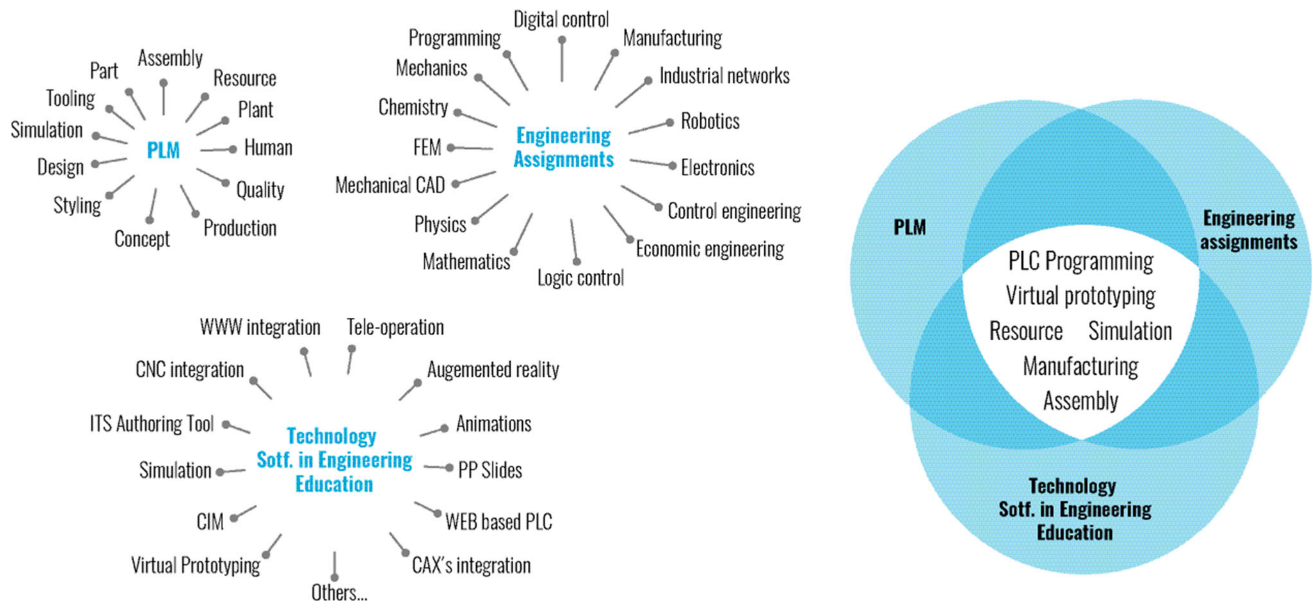


Fig. 2 Venn diagram of the areas considered in designing the teaching platform

Also, future professional engineers will have to think about the context. The choice of materials and the design solution cannot be based on purely technical and economic criteria but must also consider environmental and societal aspects, like recycling, pollution, and disassembly and reuse concerns, for example. All of this must be considered as we develop a new educative platform where technology integration and virtual teaching play an essential role.

Another critical aspect is PLC programming, which is the key to the success of every automation program. PLC programming is like the machine behind all automation programs used in Industry. Without it, the economy will stagnate because it leads to gains in productivity [21].

Next, we present two characteristics of the platform we used in this research, in terms of manufacturing engineering and PLC programming.

1. It is focused on the framework of manufacturing system integration. Current manufacturing processes require engineering at every stage.
2. Interaction between the PLC programming and the virtual/real manufacturing process: Students can develop their skills to program a PLC in a complex environment without the worry of damaging physical equipment because this is a virtual process.

In Fig. 3, we present an overview of the research methodology. We implemented the two cases for analysis and conclusions.

The new methodology for the development and implementation of a teaching platform introduced in this paper is a process having three main stages. The first two are the core of this project, while the last one is the evaluation of the case study.

In this section, we introduce the new teaching platform in three phases, where virtual and real components are combined with technological software in a manufacturing assignment using technological tools at the core. The three stages are shown in Fig. 4. The following methodology is valid regardless of the version and changes of the MD software used. However, it is necessary to be aware of the new capabilities that the software has to bring these advantages to the students' training. This methodology focuses mainly on educational purposes; however, it is also functional in industrial environments where there are no students, but paid operators. One advantage of virtual commissioning is that it simulates processes very close to real-life; thus, this can be very useful for training workers and teaching students similarly.

Phase 1

Phase 1 consists of creating the Flexible Manufacturing Cell (FMC) for the different scenarios proposed. Here is where PLM tools play a vital role in the design, control, and integration of the hybrid/virtual environments. It corresponds to the engineering development, where virtual and real components are combined with a high level of integration to create the different scenarios proposed: Virtual Process–Virtual Controller, Virtual Process–Real Controller, and Real Process–Virtual Controller. Concepts like Computer-Aided Design (CAD), Virtual Commissioning, Simulation, Digital Twin, PLC Code Programming, Open Platform Communications (OPC) Server connection, and Offline Programming

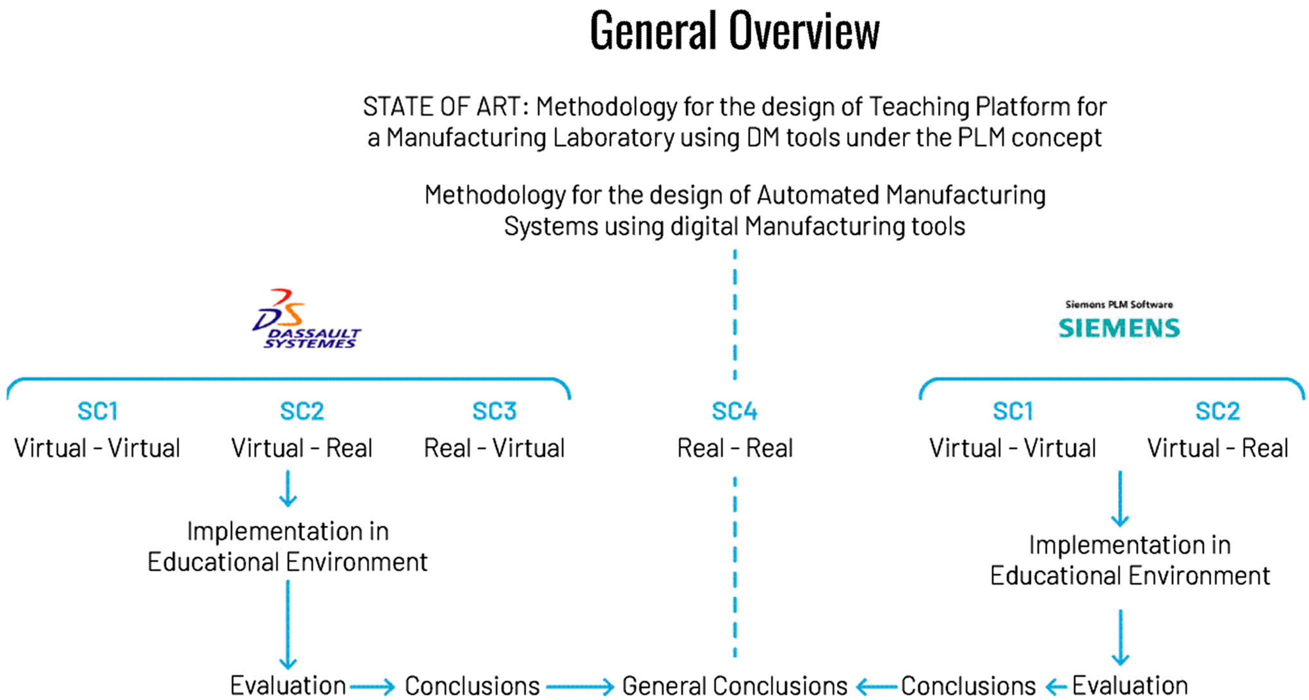


Fig. 3 Overview of this research methodology

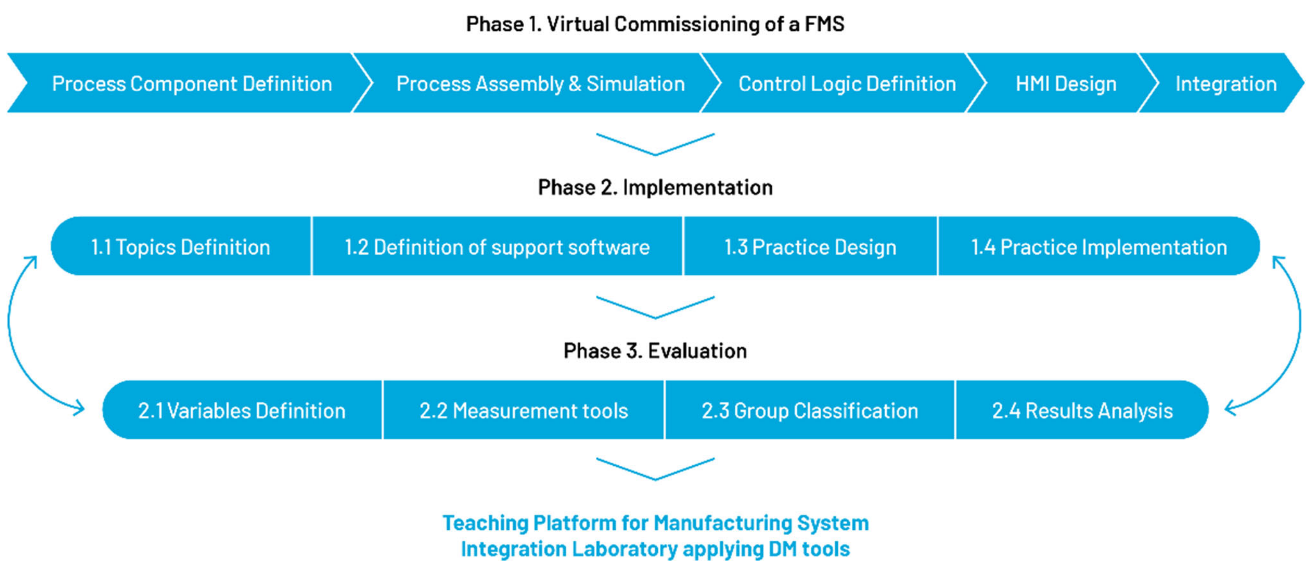


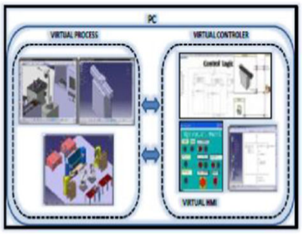
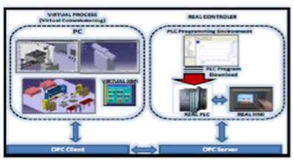
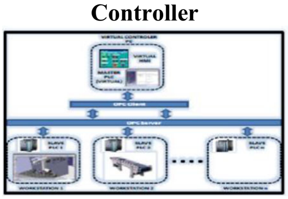
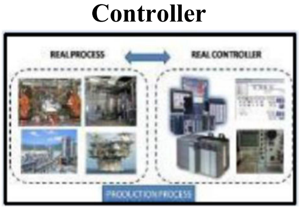
Fig. 4 The three phases of the teaching platform

(OLP) are implemented during this stage, with a methodology followed to its completion.

The virtual/hybrid real case scenarios are described in Table 2, showing the main features for each case. A *virtual environment* includes a Virtual Process and a Virtual Controller. Using one software to digitalize, simulate, and automate the manufacturing system avoids complexity in the lab [22]. PLM tools play an essential role in the development of this first case by allowing the virtualization of the physical manufacturing system. The scope of this paper focuses only on automated manufacturing systems and PLC programming. PLM tools, specifically DM, allow us to test and validate many different elements of a manufacturing system (such as design, material flow, production, layout, and ergonomics) to check a manufacturing process before it is built, making it more efficient.

A *hybrid manufacturing environment* combines virtual and real components into a functional automated manufacturing system (virtual-process → real-controller, or vice versa). The virtual process and the PLC can communicate by using

Table 2 Description of scenarios

Scenario	Description
Virtual Process / Virtual Controller 	The virtual process is designed and simulated using PLM tools in a PC. Similarly, the control hardware and control panels can be virtualized as well. By virtualizing the manufacturing environment, the virtual commissioning can be programmed too. Even though the virtualization and the commissioning require different software, the final control logic can be validated for the cases in the lab
Virtual Process / Real Controller 	The virtual process, with all its components, is controlled with a real PLC. The virtual process is programmed according to the PLC brand. The process is simulated by PLM tools, which is not necessarily in a PC. In this scenario, the virtual process, which can be either a computer or a PLC program, is connected to a real controller
Real Process / Virtual Controller 	This is the second hybrid scenario made up by a real process and a virtual controller—a virtual PLC and human–machine interface (HMI.) The HMI should be programmed to operate the complete manufacturing process. Using an IP allows remote control, as in scenario 2
Real Process / Real Controller 	In this case, both the process and the controller are real, which is the most common scenario. In this scenario, there is no simulation of the manufacturing process on any platform. A virtual environment is not used; the system is just implemented once the decisions are made about functionality and productivity designed for manufacturing

the OPC client/server protocol. The computer where the virtual process (the OPC client) resides does not necessarily have to include a specific OPC server because the server can be reached via IP, allowing remote communication of the virtual process with the physical PLC. This communication via IP makes remote education and training possible.

In real scenarios, both the process and the controller are real. There is not a simulation of the manufacturing process in any DM tool, and a virtual environment is not used. The system is simply implemented once the functionality and productivity are designed for manufacturing. Given this, there are not opportunities to validate "what if" scenarios, since both the process and controller are real [7].

The scenarios presented in this study combine virtual and real elements to form different systems where the primary purpose is to have a working automated manufacturing system that is a flexible manufacturing system (FMS). Table 3 presents the five stages that need to be followed to accomplish each one of the scenarios. For a more in-depth description, the reader can look at [7], where we obtained the methodology to develop the scenarios.

Phase 2

This phase is educative-oriented. Here, laboratory teaching experience, knowledge of manufacturing systems integration, and experience using manufacturing cells are required. This phase shows the planning steps to adapt the activities of traditional laboratory teaching to a virtual/hybrid context.

The objective of this phase is to design and plan the lab practice systematically, oriented to the use of DM tools. Usually, universities have a pedagogical department with teaching guidelines for the development of laboratory practices. The support of this department is vital to carry out the exercises. Below are the steps that we adapted from a guide of the Academic Development Department (ADD) in Tecnologico de Monterrey [23] for the planning and design of laboratory practice.

Planning:

1. Define the contents according to the previous steps.
2. Define who designs the practices.
3. Determine the purpose of the practice.
4. Define the general considerations in the planning.
5. Define the structure of the laboratory practice.
6. Define the experimental techniques that students learn.
7. Define the evaluation tools and processes.

Next, it is necessary to design and write the practice to be implemented, considering the points above and the following, adapted from [23]:

Design:

1. Consider the following elements, if applicable: Reference to the contents, Learning objectives, Practice objectives, Introduction, Applications, Theoretical Framework, Materials, Tools and Equipment required, General safety rules, Procedure.

Table 3 Methodology for the design of scenarios using DM tools

Process components definition	Process simulation	Control logic definition	HMI design	Integration
Scenario 1				
Process requirements identification Virtual process components definition and design Components digitalization Geometrical constraints Operations sequence pre-definition Layout distribution pre-definition	Virtual process components' task definition Virtual process components assembly Layout implementation Virtual process simulation Virtual process verification and validation Sequence of operations redefinition (if needed) Layout redefinition (if needed)	Virtual components I/O definition Components' internal logic behavior definition Control logic definition (simulated PLC, using PLM tool) Validate control logic Control logic re-definition (if needed)	Define HMI controls and indicators (simulated HMI) Define HMI design and component distribution HMI programming Link HMI components with control logic components	Integrate virtual process components, control logic, and HMI Integrate virtual process simulation Integrate virtual process validation Process components, control logic, and HMI redefinition (if needed, go back to the proper stage)
Scenario 2				
Process requirements identification Virtual process components definition and design Components digitalization Geometrical constraints Operations sequence pre-definition Layout distribution pre-definition PLC definition (if it is not already defined.)	Virtual process components' task definition Virtual process components assembly Layout implementation Virtual process simulation Virtual process verification and validation Sequence of operations redefinition (if needed) Layout redefinition (if needed)	Components' I/O definition Components' internal logic behavior definition (PLC native programming environment) Validate control logic Control logic redefinition (if needed) Download control logic to PLC OPC server host computer and physical PLC connection (ethernet) OPC server definition	Define HMI controls and indicators (physical or virtual HMI, as required) Define HMI design and component distribution HMI programming Connect HMI to PLC (if physical HMI is used) Link HMI components with control logic components (if virtual HMI is used.)	OPC client definition OPC client/server connection Map PLC program tags to I/O block in PLM tool Integrate virtual process components, PLC and HMI Integrated hybrid process simulation Integrate hybrid process validation Hybrid process components, control logic, and/or HMI redefinition (if needed, go back to the proper stage and repeat the procedure.)
Scenario 3				
Workstations' components identification Unneeded components dismissal Slave PLC's I/O ports analysis Currents sequence of operations identification (if any, per workstation) Make sure every component at each workstation works appropriately	Workstations interaction definition Individual (each workstation) and interactive (integrated workstations) sequence of operations definition Individual and interactive task definition Material handler workstation addition (if there is not already one.)	Make sure all slave PLC's I/O ports are connected to the proper sensors and actuators Slave PLC's controls code programming Slave PLC's programs download OPC server host computer and slave PLC's connection (ethernet) OPC server definition	OPC client definition OPC client/server connection Map slave PLC's shared program tags to master PLC program (via OPC) Master PLC programming (PLM tool) HMI controls and indicators definition Virtual HMI design (PLM tool) Link virtual HMI components with control logic components	Integrate hybrid system testing and validation Hybrid system components reconfiguration (if needed, go back to the proper stage and repeat the procedure.)

Table 3 continued

Process components definition	Process simulation	Control logic definition	HMI design	Integration
Scenario 4				
Process requirements identification Process components definition Sequence of operations definition Layout distribution definition Communication protocol definition	Assembly of components Implementation of layout design Electric, electronic and mechanical connections	Process components internal logic behavior analysis I/O definition PLC connections Control logic definition (PLC native programming environment) Download control logic to physical PLC	Define HMI controls and indicators Define HMI design and components distribution HMI programming Connect HMI to PLC Link HMI components with control logic components	Integrate process components, PLC and HMI Integrated manufacturing process tests and validation Process components, control logic, and/or HMI redefinition (if needed, go back to the proper stage and repeat the procedure.)

2. Design practice activities.
3. Design activities that support the pre-report (if applicable).
4. Design activities that support the development of the practice.
5. Design the assessment tools.
6. Design the lab manual.

The authors propose the following tips when applying DM tool exercises:

- Clearly show the title of the practice.
- Have detailed procedures to avoid students getting lost.
- Write clear objectives.
- Have criteria to ensure that the implementation of the practice will be successful.
- Develop the practices to be informative and lucid, considering that the students have not worked with the software.
- Show precisely where the different files and programs are located.
- Include tips and notes.
- Provide examples of common errors and the way to resolve them; this is valuable information for the students.

Practice implementation

Practice implementation has two stages, technical and educational. The technical stage is strongly related to the "Integration" step in Phase 1; here, the instructor must properly install the software, hardware, and all the technical aspects for the students to perform the practice satisfactorily.

On the other hand, the educational component has several steps that must be followed to implement the practice:

1. Laboratory practice explanation: the students must know how they will learn the content.
2. Purpose of the practice and how it will be assessed: Explain the purpose and objectives of the practice and show the instrumentation tools.
3. Organization and development of the practice: Organize the students and assign the materials.
4. Work commitment in the laboratory: Emphasize the security rules, respect for the time, and the care of materials and equipment.
5. Perform the practice: Do the first activity, the second, and the subsequent ones.

In general, for this whole stage, the instructor must:

- Know the practice very well so he can guide the students.
- Know the problems that the students may confront.
- Be able to solve the problems and use the software.
- Know the technical aspects involved in the practice.
- Be able to manage and carry out the practical activities efficiently and advise and guide the students so they can achieve the goals.

For more in-depth information about both stages (Design and Implementation), the following references can be consulted: [19, 23, 24].

Phase 3

Phase 3 corresponds to the evaluation stage. We have considered qualitative and quantitative assessments for each implemented scenario in the teaching platform. The following are the procedures to qualitatively and quantitatively assess each scenario and the proposed teaching platform.

Table 4 Performance variables

Variables	Examples	
User level	Safety in operations Ability to make changes Debugging Difficulty	Cost of maintenance Availability Diversity of cells design Knowledge requirements
Academic performance level	Experience acquired Motivation General understanding	Topics/contents' relationship PLC programming environment Ease of teaching
Designer/creator level	Viability Implementation time Investment cost Infrastructure required	Technical knowledge Software expertise Hardware and software required Easiness

This phase must be performed simultaneously with phase 2.

Definition of performance variables

Here it is essential to compare patterns between the actual teaching platform and the new one implemented using virtual/hybrid scenarios. In this case, performance variables are considered; several variables can be evaluated from different perspectives. Within the context of the scenarios implemented using the DM tool, we divide the performance variables into three main classifications, namely, user-level, academic performance level, and designer/creator level. Among many possible variables, the author proposes the following, as shown in Table 4. These variables are the ones that tell us how the users (students, instructors, teachers, and developers) perceive the scenarios.

Measurement tools

Research on student perspectives requires different approaches. In our study, for the educative purpose, the research objectives for implementing the different scenarios are:

- To know how the scenarios affect the students' performance.
- To test and assess the characteristics of each scenario to achieve the educational goals of the course.
- To provide a value judgment for implementing these scenarios in universities that cannot afford a real-real environment.
- To get information that may contribute to improving the teaching platform.

It is necessary to design several qualitative and quantitative instruments to gather information from the performers.

Table 5 Possible measurement tools

Measurement tools	Description
Observation log	The observation log is an interactive method. Some authors call this technique "active observation" because of the level of observer participation. Significant elements to consider in the observation are the environment, participants, their characteristics, group relationships, and motivations that unite them [25]
Interview	The interview is a technique to know and understand the subjective viewpoint of teachers and students, especially concerning expectations and knowledge processes that are being generated [25]
Reflective log	Reflective practice involves thoughtful consideration of experiences, situations, or topics, both positive and negative, resulting in a change of perspective [26]
Semi-structured interview	In the semi-structured or mixed interview, as its name suggests, the interviewer displays a mixed strategy, alternating structure questions with spontaneous questions
Survey	A survey is an observational study in which the researcher seeks to collect data using a predesigned questionnaire, and the environment does not change or control the process under observation (as it does in an experiment). Data are obtained from responses to a set of standard questions addressed to a representative sample or the whole population under study

The creation of these tools helps to get information from different perspectives, which can be compared to get valid data. This step requires the support of an educational or pedagogical advisor to design adequate measurement tools; however, we present some tools for consideration, as shown in Table 5.

Selection and classification of groups

Classification sorts people or things into groups or categories on a single basis of division. We constructed this step because of the structure that this thesis has.

The purpose is to create a control group to carry out the Prof of this teaching platform using the scenarios. First, it is necessary to make the student selection. They must meet specific requirements, such as a particular track or a certain level of knowledge so that they can achieve excellent results. The requirements must relate to issues, topics, software, and techniques to be applied.

After obtaining the control group, it is necessary to subdivide it according to other detailed characteristics such as learning styles (kinesthetic, visual & auditory) and the way of processing information (dependent or independent). The objective of this selection and classification is that all the scenarios have student groups with homogenous characteristics.

Results analysis

Results analysis refers to processing the data collected and obtained during the experimentation process—what is observed, what is discovered, what is found out—and then interpreting the data. Depending on the tool used, it is necessary to validate it through a methodology.

During this stage, we need to process the results according to standard procedures like organizing the data in tables, diagrams, or graphic representations. Then we need to interpret the data, consider the implications, and draw conclusions; here, we need to determine the qualitative and quantitative relationships. We also discuss the assumptions of the experiment and its limitations, explain the research findings, and generate new questions or identify new problems from the results.

The three phases are illustrated in Fig. 4.

3 Case study implementation of the teaching platform in an MSIL

The methodology described is now implemented for the virtual–hybrid–real automation scenarios previously presented. The manufacturing system automation cell of the Mechatronics Laboratory at Tecnologico de Monterrey was chosen. The subject where the learning platform was applied was the laboratory of the Manufacturing System Integration course (MR3018). The technological software used in this implementation was *Delmia Automation* from Dassault Systèmes and *Process Simulate* from Siemens PLM.

Next, we describe the implementation. The scenarios created using Delmia Automation were already developed in [7]; we developed scenarios 1 and 2 using *Process Simulate* and implemented all the scenarios using the proposed teaching platform.

3.1 Phase 1: virtual commissioning of virtual–hybrid scenarios

For the implementation of the proposed scenarios, the authors chose the manufacturing cell, shown in Fig. 5, of the Mechatronics Laboratory of the Tecnologico de Monterrey facilities, which are used to teach MSIL. The manufacturing cell is composed of the following elements:

1 Motoman UP6 robot with an XRC 2001 controller	Magazine tool with the following components:
1 EMPCO PC Mill 155 Vertical	1 pneumatic gripper
Machine Center	1 pneumatic screwdriver
AS/RS Storage	1 pneumatic suction cap
Two-line Conveyor	Assembly station
Inspection system	Magazine tool
Allen Bradley PLC	3 Containers
	1 dispenser
	1 pneumatic press

The tools and software implemented to build the scenarios in this study are Process Simulate/Delmia Automation, OPC Server, RsLogix500, NX Unigraphics/CATIA (CAD/CAM). Figure 6 shows the virtual–hybrid environment developed for scenario 2: Virtual Process developed in Tecnomatix and Real PLC programmed in Allen Bradley PLC.

3.2 Phase 2: implementation stage

3.2.1 Topics definition

During this stage, it is necessary to review the study plans of the courses modeled in each of the different scenarios to align the competencies to be taught. It is essential to consider the objectives to know the capabilities and features of the PLM tools that will be used. It is necessary to establish standards for traditional labs and then apply these objectives to virtual/hybrid laboratories. It must be clear that a scenario with a *real* part will have different topics and goals than those with a *virtual* part; this is for obvious reasons and should be planned from the beginning. To implement the platform properly, one must not only understand the curriculum and how the academic course is taught but also be empowered to adapt the curriculum to meet the instructional needs of the students and class. The implementer must have experience using an FMS and a comprehensive background in the use, application, and characteristics of the PLM tools.

The course taken as a case study is the Manufacturing System Integration laboratory taught at Tecnologico de Monterrey for the Mechatronics Engineering majors; it is usually taken by junior students. The four selected topics to be covered by this teaching platform using the hybrid scenarios are:

1. Fundamentals and operation of an FMS
2. Industrial robot handling and coordinate systems
3. Programming an industrial robot and application design
4. PLC programming and integration.

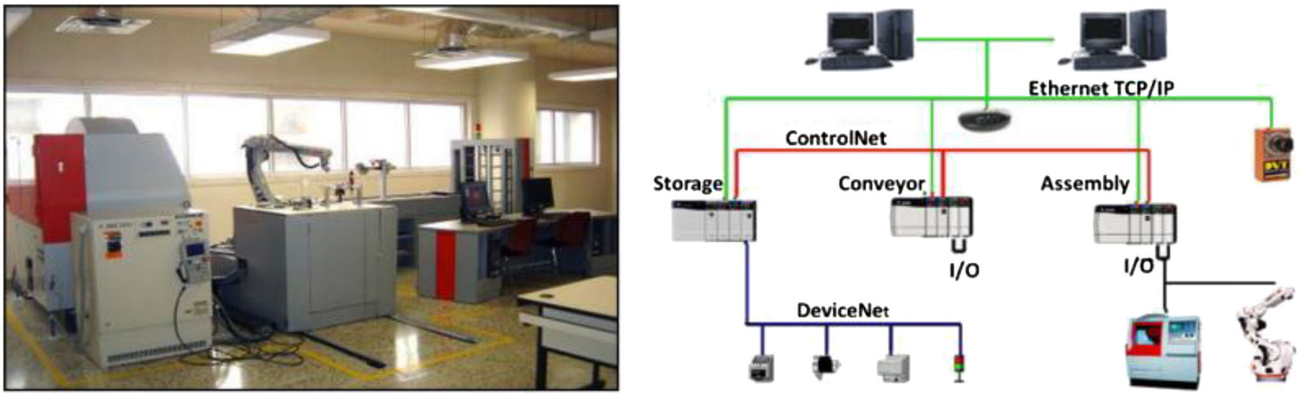


Fig. 5 Real manufacturing cell

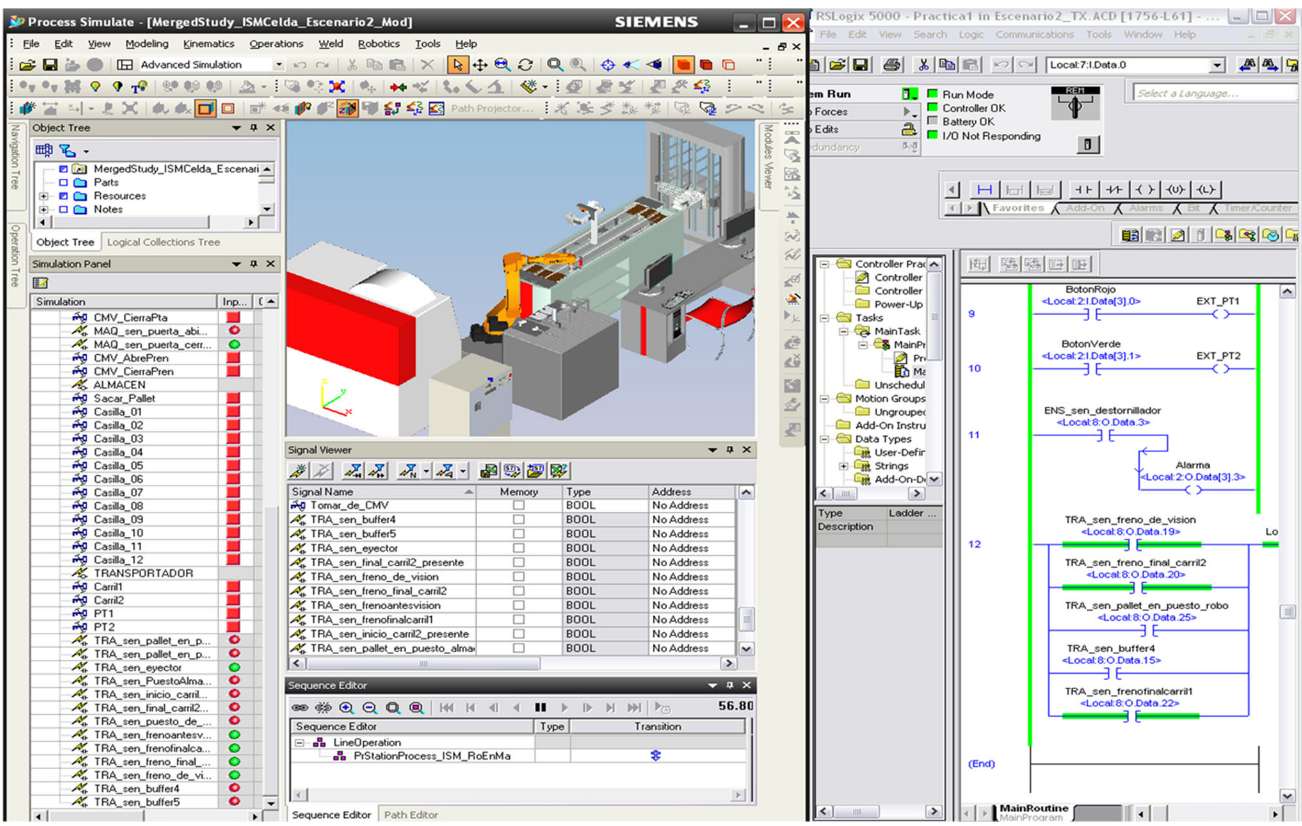


Fig. 6 Software implementation

3.2.2 Define the support software

As stated before, the leading software tools used were Delmia Automation and Tecnomatix. The PLC software was also essential; in this case, we used Allen Bradley, and the software was RsLogix5000. Although the rest of the topics were not considered, the authors suggest some software for teaching similar topics and objectives not fully covered in this case study in Table 6.

An essential part of a manufacturing course is G-code programming. To do this, CutViewer is a handy virtual tool to implement and to verify machining programs. Another vital part of the Lab course is the machining of complex parts using CAM tools; this topic could be covered extensively with the CAM module of NX, a software used very frequently in the different stages of the product life cycle. Vision-related topics are other subjects taught in the MSIL course.

Table 6 Structure of the MSIL course

Topic	Objective	Software proposed
1. Fundamentals and operation of an FMS	Identify and learn the essential elements that are in an FMS and watch its performance	TECNOMATIX DELMIA
2. Identification, operation, and setting of a CNC machine	Identify critical components of CNC technology, inputs and outputs of the robotic interface to integrate a CNC control system, and perform the setup for CNC machines	emco industrial training systems
3. Basic programming and machining of parts on a CNC machine	Perform programming and machining of parts using G and M codes	CutViewer ToolPath Verification Software
4. Advanced programming and machining of parts on a CNC machine	Perform the programming and machining parts using advanced programming concepts	CutViewer ToolPath Verification Software
5. Machining of parts on a CNC machine using software CAD-CAM	Generate code to machine a complicated part using the CAM tool of NX6 ST software and implement the code generated	NX
6. Industrial robot handling and coordinates systems	Identify the key components, types of movements, and coordinate systems of an industrial robot	TECNOMATIX DELMIA
7. Programming of an industrial robot and applications design	Design and program a routine with an industrial robot that performs a specific application	TECNOMATIX DELMIA
8. Robotic workstation design	Analyze engineering drawings, identify and implement new signals to the assembly station, and learn advanced robotics programming	MOTOMAN a YASKAWA company
9. Vision systems in flexible manufacturing systems	Design and program in vision software the tools to perform an optimal quality inspection from any part that is machined and assembled in an FMS	intellect In-Sight Explorer 4.6.0
10. PLC programming and integration	Program in different ways according to the scenario of a simple routine in a PLC environment	TECNOMATIX DELMIA

3.2.3 Laboratory practice design

The laboratory practices were planned and designed to be understandable and easy to follow by the student to accomplish the objectives of each topic. The method employed was deductive, and the professor proposed the experimental procedure, applying simulation techniques to connect the knowledge to a realistic practice situation. Each practice was divided into four sections:

Section 1: Identify the essential elements of an FMS and operate the manufacturing cell.

Section 2: Identify the components of an industrial robot and learn about the coordinate system; also, make basic movements with the robot.

Section 3: Program a basic routine with the industrial robot over six specific points and return it to the home position.

Section 4: Program the PLC to move a piston forward and backward from the FMS.

The authors designed one practice for each scenario, as shown in Fig. 3 (three for Delmia Automation, two for Process Simulate and one for the Real cell); nonetheless, some sections were shared among the scenarios.

3.2.4 Laboratory practice implementation

Before the laboratory practice implementation, the students were informed about the project research, the tool used to collect data, the characteristics of the scenarios, and the purposes of the practices, among other useful information. Here are all the steps followed to implement the practice (illustrated in Fig. 7):

1. Explanation of the overall structure of the practice.
    a. Explain the objective of the practice.
    b. Give an overview of the environment in which the cell is simulated.
    c. Provide exercise instructions.
    d. Clarify initial doubts and answer questions.
2. Perform the laboratory practices.
    a. Carry out Section 1. Fundamentals and operations of an FMS.
    b. Carry out Section 2. Industrial robot handling and coordinate systems.
    c. Carry out Section 3. Industrial robot programming.
    d. Carry out Section 4. PLC Programming.
3. Answer the perception survey of the scenarios.
4. Answer the semi-structured interview.
5. Answer the reflection blog.

3.3 Phase 3: evaluation

3.3.1 Definitions of the variables to measure

For educative and research purposes, the performance variables selected to compare the four scenarios were (1) General Understanding, (2) Motivation, (3) Relationship of contents, (4) Difficulty, (5) Debugging, (6) PLC programming environment, (7) Experience Acquired, and (8) Ease of teaching. These variables were the basis for designing the different measuring instruments in this research. These variables are described in Table 7.

3.3.2 Measurement tools

Four quantitative and qualitative tools were developed. The idea was to have not only numerical data to compare the scenarios but also the opinions and comments of the students for matching, concluding, and showing congruency in the results. The developed tool is described below.

Perception survey of the scenarios The perception survey is the only quantitative tool. Its purpose was to know the perception the students had about the laboratory practices, and the questions were linked directly with the defined variables.

Semi-structured interview This interview was a face-to-face interview where the students answered five questions about their performance during the practice.

Observation log of the performance The instructor used this tool during the implementation of the practice. It was a tool to register observations of the students' performance, the time required to finish the practice, common problems faced by the students, and the attitude they displayed.

Reflection blog The reflection blog was a homework activity done by the students. The tool was designed to gather information on:

- The expectations of the students.
- The issues they faced during the practice.
- The way they solved the issues.
- Moments in which they lost motivation.

3.3.3 Group classification

The implementation was done in two different semesters. A total of 47 students participated in the implementation of the hybrid scenarios using the Delmia Automation development, and 24 students in the second stage using Process Simulate. All of the undergraduate students were studying for a bachelor's in mechatronics. Other majors can take this class, but in this instance, they were all mechatronic engineers. The learning styles were organized into different control groups. These learning styles were (1) kinesthetic, (2) kinesthetic/visual, (3) visual, and (4) auditory.

Table 8 presents the comparison, showing the survey results by semester, the software used for the scenarios, and the number of students in each learning style. The scale used went from one to five, where one represents the best and five the worst.

3.3.4 Analysis results

The results of the perception survey are shown in Table 9. Several questions related to each variable were asked. The average of each variable is shown in Table 9. The scale used to measure the variables goes from 1 to 5, where 1 represents the best and 5 the worst.

The reliability of the previous survey was measured by the method of split-halves. It calculates the correlation coefficient between the scores obtained in each of the halves of the test. If the proof is reliable, then the scores of both

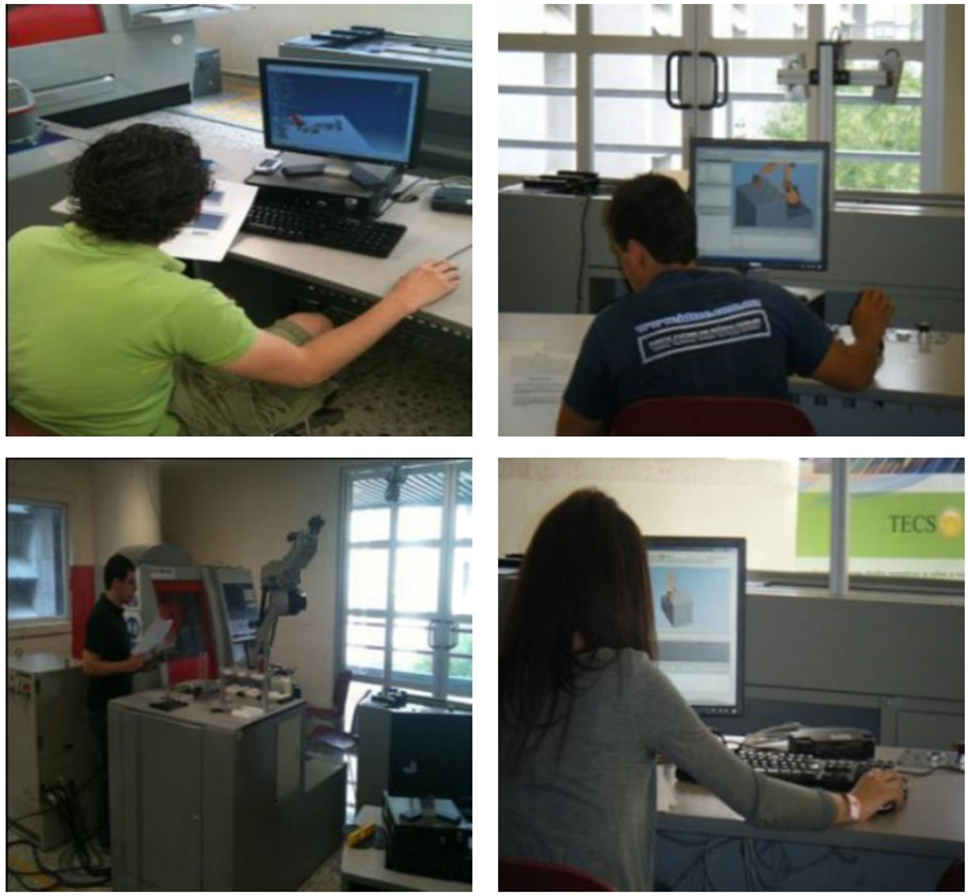


Fig. 7 Laboratory implementation

halves must strongly correlate. In this case, the Cronbach's alpha was used to measure reliability. This coefficient varies between 0 (no reliability) and 1 (perfect reliability). The test was done for the sample as a whole. The Cronbach's alpha coefficients for each half of the test gives results of 0.865 and 0.696; this means the reliability for each half is high. The correlation between both halves is 0.729; this also represents a high correlation, which means that both halves are not independent, and they are oriented in the same direction. The Spearman–Brown coefficient and the Guttman split-half Coefficient also suggest that the reliability of proof is high. These statistics are presented in Table 10. The authors used SPSS for statistical analysis.

Based on the previous results as well as the comments obtained from the qualitative tool, we reach the following conclusions:

General understanding: It is better obtained when students are immersed in a real scenario and in contact with the devices. Scenarios with a high level of virtualization complicate the understanding of the topics; however, virtualization is useful to understand the issues related to robotics.

Motivation: On one hand, scenarios 3 and 4 inspire the students more to attend the lessons, but they clearly articulated that they enjoy studying solo better. This is a circumstance that is not feasible in standard lessons because they have to share equipment with others. On the other hand, students like scenarios 1 and 2 better, because they are more personalized.

Relationship of contents: In a non-hybrid case, students tend to understand the content more quickly. Combining reality and virtualization generally makes interpretation of the material more challenging.

Difficulty: Scenarios that have a higher degree of virtualization are easier to manage, helped by software that produces more ease, so scenarios 1 and 2 have this benefit over 3 and 4; however, we explicitly advise the students to pass a programming course before enrolling in this course.

Debugging: Scenarios 3 and 4 allow the students to be comfortable about making mistakes, an unexpected finding; however, this is because the students already had experience working with the equipment.

PLC programming: This is a critical aspect because it defines the scenario. Students prefer situations in a broader PLC setting (like scenarios 2 and 4) rather than scenarios 1 or 3, enjoying a more constrained environment created by the DM software.

The experience acquired: This variable is differentiated between scenarios 3, 4, and 1, 2. The more realistic scenarios tend to provide the students better learning; however, we must

Table 7 Variables to evaluate

Variable	Meaning
General understanding	It gives an example of how the simulations provide students a complete grasp of the topics learned in the course in a regular laboratory session; this is critical because we want the students to conceptualize the knowledge taught
Motivation	It tests the students' motivation to attend a laboratory taught in this way. It let us experience the students' driving force to accomplish their objectives and see how they would feel if they were to take part in a particular scenario in a class. The motivation that students have to develop academic activities is one of the most important determinants of learning
Relationship of contents	It is essential to know if the scenarios let the students accomplish the topic's objectives and to evaluate if the students associate the topics of the virtual part with the real ones
Difficulty	It measures the level of challenge of each scenario for the students to resolve the proposed problems
Debugging	It measures how engaging every scenario is for the student to make errors. Every scenario has different hardware, and any error in real parts will evolve into some system failure, which can be impossible to fix or might be expensive. By using virtual components, the errors will result in the simulation being restarted
PLC programming environment	Knowing how the students feel when programming each scenario on the PLC and the benefits or drawbacks they may have is essential because this variable is one of the key characteristics that differentiates the scenarios
Experience acquired	This variable measures the knowledge the students have gained by using the resources and definition of the scenarios for their preparation and quickly adapting it to their professional needs after graduation
Ease of teaching	This aspect is mainly geared towards the instructor's performance to measure how easy it is to apply this type of scenario so that we can improve the transfer of knowledge

Table 8 Group division by semester and by learning style and scenario

Learning style/scenario	SEMESTER 1				SEMESTER 2	
	DELMIA				TECNOMATIX	
Scenario #	1	2	3	4	5	6
Kinesthetic	5	5	5	4	2	2
Kinesthetic/Visual	3	2	2	2	3	3
Visual	3	3	4	4	7	6
Auditory	1	2	1	1	0	1
Total	12	12	12	11	12	12

point out that, shortly, the use of DM software will be as important as knowing how to manage an actual robot.

Ease of teaching: Scenarios 3 and 4 are easier to teach than the virtual ones.

4 Conclusions

The use of DM and technological tools was explored in-depth, so the virtual commissioning of a flexible manufacturing cell was achieved successfully. The authors demonstrated the benefits, scopes, and applications that these tools can bring into the educative field. Virtual commissioning is beneficial in terms of economy, ease, speed, and availability.

We have developed a new teaching platform using a systematic approach that blends instructional planning with the integration of technology; this seems to be an ideal way to replace the traditional teaching scenario or complement it using these tools to provide students new ways to incorporate knowledge into their curricula.

Table 9 Scenarios evaluation

Variable	Delmia automation				Process simulate	
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2
General understanding	1.417	1.778	1.278	1.182	1.111	1.167
Motivation	1.333	2.000	1.167	1.182	1.125	1.250
Relationship of contents	1.300	1.617	1.783	1.255	1.567	1.183
Difficulty	1.375	1.917	2.292	2.227	1.583	2.542
Debugging	1.292	2.167	1.458	1.182	1.292	1.583
PLC programming environment	1.917	1.667	1.750	1.636	1.833	1.417
Experience acquired	1.458	1.958	1.292	1.136	1.208	1.167
Ease of teaching	1.833	1.750	1.583	1.364	1.500	1.333

Table 10 Reliability of the proof

Cronbach's alpha	
Part 1	
Value	0.843
N of items	13
Part 2	
Value	0.696
N of items	13
Total N of items	26
Correlation between forms	0.729
Spearman–Brown coefficient	
Equal length	0.843
Unequal length	0.843
Guttman split-half coefficient	0.840

The discussion suggested that students found these implementations beneficial and useful because it helped them to understand topics easier after the interaction with the system. They could grasp some fundamental teaching issues uniquely through modeling and simulations. Also, they found more significant opportunities to experience the whole practical process of an FMS; this enhanced their perceptual experiences. It allowed the teacher to deal simultaneously with a large number of students and increase practical teaching. The concept presented offers excellent potential for the Industry by providing students' knowledge of technological tools requested in Industry 4.0 concept.

5 Future research work

Next, we present new lines of research which may improve our work.

- Developing customized industrial applications to train operators for real situations so they can apply the training in the plant.
- Developing a more in-depth evaluation, implementing the scenarios in academic courses. Students taking classes in a virtual environment vs. other students receiving the traditional method, so that the impact on the academic performance of the students in the two groups can be compared by their learning outcomes (scores).
- Complementing the current educational platforms used in the teaching of Manufacturing Processes Automation with DM tools, mainly in scenarios 1 and 2. As we can see from the results, the implementation of DM tools as a complement to the traditional courses taught is an outstanding innovation that students can appreciate very much.
- Developing teleoperated applications using an IP connection. In this project, the OPC server was hosted on the same computer where the DM tools were installed. However, the OPC server can be hosted on another server reached via an IP connection.
- Using Collaborative Robots: The openness of the "cobots" to all the parameters and the ease of connectivity can bring a comprehensive solution to the implementation of the scenarios.
- Improving the case study presented in this research by adding more features. This work presents a virtual environment built at a device/machine level; that is, no ergonomics, collision analyses, or security measures were added to the process. Thus, these conditions could be added to the already created environment to provide a more realistic approach.

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