Faculty of Engineering

INDUSTRIAL ENGINEER

Grade Project – Second Semester 2019

[183023] Implementation of a virtual reality tool, to verify a PLC programming routine of an industrial process.

Valeria Rojas Pérez[a,d,e] , Juan David Pesca[b,d,e]

Ing. Iván Mondragón[c,d,e]

[a]Valeria Rojas Perez, [b]Juan David Pesca
[c]Ing. Ivan Mondragon, Director of the Degree Project, [d]Departamento de Ingeniería Industrial
[e]Pontificia Universidad Javeriana, Bogotá, Colombia

Abstract

Virtual reality has become a tool used in several industries for its ease in simulating spaces and interacting with objects without the risks and limitations of the real world. In production plants, automated machinery can be managed in a way that the programming of a PLC and the interaction of an operator are involved. When wanting to make changes in the lines of production it is required to make modifications in the programming of the machines that compose the line, implying tests prior to their physical implementation. In these environments, making this type of modification implies risks and time which translates into costs that could be anticipated or diminished by means of a previous simulation of the activities to be carried out and that do not consider the man-machine interaction between the operators and the equipment. Likewise, the remote programming of PLC´s implies limitations towards the feedback that the programmer gets about the operation of the automated machines and about the program. Therefore, it is proposed the implementation of a tool to simulate industrial equipment in a production line environment where the user can interact with automated equipment connected to PLC´s by using immersive nature virtual reality devices. Within the results of the simulation the user can interact with the virtual space, modify the programming of a virtually recreated PLC for certain industrial equipment, so that it can understand and be trained on engineering tools. According to the impact generated by the simulation, this project hopes to have a reach in areas of personnel training, the teaching in a practical way and visualization and interaction with simulated industrial spaces.

Keywords: Virtual Reality, Simulation, Field Training, Production Lines, Programmable Logic Controller.

1. Justification and Problem Approach

1.1 Problem Approach:

In labor contexts within a production plant, industrial engineering is a discipline that involves aspects such as design, machinery, systems, people, quality, safety and efficiency (Niebel, 2014). In contexts of teaching or training that are based in a purely theoretical teaching strategy with no dynamism, the student must acquire and develop skills that may be difficult to apply at its full potential outside an academic environment. Due to this, there have emerged alternatives such as web-based platforms and immersive platforms that are aimed at the incorporation of new technologies in the teaching process, seeking greater motivation, commitment and improvement in learning (Lingard, Lingard, & Barkataki, 2015).

A historical moment where workers were required to learn about specific tasks was experienced along the industrial revolution, from which methods that seek to make workers more efficient in their tasks have been designed. Particularly in the Second World War, the Training Within Industry (TWI) methodology was implemented given the need to considerably increase the production of war material (Dooley, 2001). This method consists in the execution of a manual designed for each work station where an intermediate command can train others and so the operator learns through practice how to do their work efficiently thanks to the supervision of the leaders of the work teams. The adaptation of this method in Japanese industry will start the KAIZEN methodology. Despite the impact it had in its time, this methodology focuses on training purely mechanical tasks using valuable time and assets, leaving no room for more detailed and complex tasks training. Thanks to technological advances, some limitations for training and improvement in industrial environments have been exceeded.

In production plants, a large part of the processes tends to involve machinery that can be handled by an operator or work in an automated way. In both cases, trained personnel are required for human-machine interaction, either to operate the equipment properly or to program the routines that must be followed. In the case of automated machines, it is commonly used a PLC (Programmable Logic Controller) which is an electronic device that controls the logic of operation of machines, plants and industrial processes, processing digital and analog signals, seeking to analyze the system, training and reconfiguration in real time. The problem with the PLC programing is that, in most cases, to verify how the routine works it is needed to run it in the machine.

Currently, within the most common tools used for the verification of PLC are those of CAPE (Computer Aided Production Engineering) (IEEE, 2012), where the simulations provided by the tool only show the general and simplified information of the programming of a PLC. As an aid or help to this limitation there is the implementation of "hardware-on-the-loop" (Ledin, 2001), a simulation in real time where reliable hardware is embedded in the simulation to see the effects on programming in a detailed way. Unfortunately, just like the current CAPE tools, the other simulation tools for PLC verification involve high costs compared to the limited information or verification options they can provide.

An alternative that involves few limitations consists in the use of virtual reality (VR), a tool introduced by Dennis Gabor in 1948 that allows the production of three-dimensional optical images of almost any object (Filho, 2018). Thanks to technological advances, it has been created VR spaces that facilitate the simulation of a reality through visual forms that are embodied in an interactive computer generated environment to create collaboration spaces where the user can interact with elements that are not at their scope and that can, in this context, improve the way in which it understands the functioning and characteristics of the generated space (Guzmán, Dostert, & Karols, 2007). Likewise, it is important to keep in mind that 3D simulation will help to verify the operation of the machine remotely, avoiding unnecessary contact for programming and dimensioning of its functions, considering that the operator may develop their work in an ergonomic way and without risks to its health.

Currently there are uses of VR focused on increasing efficiency and reducing errors inside companies. For this, they offer instruction services and workflows guided by augmented reality and virtual reality in smart mobile devices, smart glasses and helmets (Reality, 2018). With these tools, information is provided in real time as a map to help operators complete specific tasks through texts, icons, images and 3D models. These tools have the limitation that most are not interactive in nature due to the limitations of the software and hardware used.

The disadvantages of automated machines and physical systems are mainly that they require constant maintenance, investment and adaptation of a large space for their use and verification (Guzmán, Dostert, & Karols, 2007). Fortunately, the use of virtual spaces can bring a solution to almost all these problems, which in addition to provide less effort in space and use, it’s been shown in studies that teaching a topic through virtual tools is very useful in the academic environment (McConnell, Parker, Eberhardt, Koehler, & Lundeberg, 2013).

Considering the problems mentioned above, it is expected to show how and in what way the proposed simulation will help solve. For this it will be considered the interaction that a worker has with a specific industrial environment and a PLC (programmable logic controller). To verify the advantages or disadvantages of the tool it is necessary to evaluate if the virtual tools used in the creation of the simulated workstations that includes a PLC integrated with a factory configurator and virtual automation, is effective under certain criteria such as visualization of the programming of the devices, the recognition of how the operator interacts with the operation of the machines and the times used for them, to finally carry out the possible reconfigurations of the PLC control system.

1.2 Project Justification:

Traditionally, several simulation languages, including ARENA® and AutoMod®, have been used for the simulation of manufacturing systems (Angliani, A. 2002). Such programming languages have been widely accepted both the industry and in academy, however they remain as analysis tools for the design stage of a production line, since their simulation is not realistic enough in terms of detailed design or implementation. For example, as real production lines are usually controlled by programming routines of a PLC, the conventional simulation languages fail to describe the control logic within the flow of independent entities (job flows) between processes. For a more detailed design of a production line, it is necessary to create a simulation of the model that allows the prediction of not only the production capacity of the system, but also the validity and efficiency of the machines (Sang. C, 2008) under a controlled programming routine.

The use of VR as an educational tool has been proposed and discussed by different authors (e.g., (Wickens, 1992); (Winn, 1993)). Among its greatest advantages there is the possibility of providing experiences to the user from a context that can be repeated as many times as necessary in an ergonomically adapted and safe environment for the user to develop its skills in the best way possible (Betancur & Estrada, 2015). Despite this, the VR is limited by the costs involved in the hardware required for the application of an immersive virtual environment that includes multiple projectors and output devices for 3D vision, meaning that the availability of these tools is scarce. However, the development of new technologies such as the Head Mounted Displays, or HMD for short (Sorvali, 2018), has allowed more people to access the VR since these tools are portable and much cheaper compared to more specialized hardware.

The Pontificia Universidad Javeriana, more specifically the CTAI, together with the Centro Ático has installed the first CAVE room (Cave Assisted Virtual Environment) for the use in immersive 3D engineering applications in Colombia. The CAVE allows 3D immersion applications in areas of engineering, basic sciences, architecture and design as well as animation and multimedia content. The room is operative with Engineering and Design software. Its purpose is to consolidate CTAI's offer in the areas of design, manufacturing and industrial robotics.

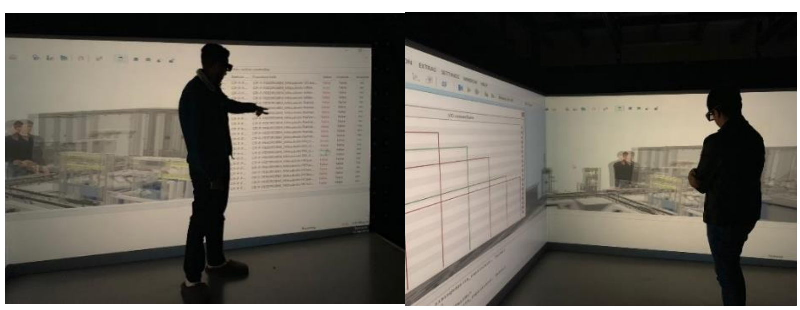

Figure 1. Cave Assisted Virtual Environment.
Source: Own authorship, 2019.

The current man-machine interaction methods are limited by the assets managed by the institutions and/or organizations focused on providing the student or operator with the tools and experiences necessary to perform their work effectively. Likewise, within the companies, the training for certain positions requires that the operator or employee have direct contact with machinery and material that must be handled according to the rules and protocols that the company manages. For these situations the VR proposes spaces where the user reduces the danger of training at lower levels thanks to the high quality of its execution, reducing costs in creating facilities with adequate software and hardware, and replacing them with services that may be offered in terms of technology by certain universities. It is then, for what is mentioned above, that the following research question is proposed:

¿Is it possible to evaluate the functionality of the programming of an automated system in an industrial environment with the use of a simulation tool in VR?

To answer this question different templates were evaluated in a preliminary research based on how good it can measure the characteristics of the simulation. Given the available time of the tool, limited population for the study and limited space of the CAVE, for this project the System Usability Scale (SUS) was selected. The SUS is a standardized questionnaire considered as a reliable tool for the measuring of the perceived usability in a wide variety of services and products that include software, hardware and applications (Lewis, 2019). Although the SUS was invented in 1986 it has been used for almost 30 years as it has proven to be a dependable, quick and cheap method that is mostly used in projects related with new interaction environments such as VR, video games and simulations (McLellan, Muddimer, & Peres, 2012).

2. Background

In the last decades a great technological advance has been experienced in the industrial engineering, more specially for process engineering. Simulation tools have been useful for this field as it avoids possible costs and risks at designing and implementing a process that may present errors when executed that were not considered before. A regular simulation consists on the "process of designing a model based on a real system seeking to generate experiences with it, with the end purpose of truly understanding and evaluating the system's functioning" as told by R.E Shannon.

The early studies where simulations were applied dates from the 40s as a solution for the high costs and rough analysis that involved the neutron diffusion when designing the hydrogen bomb (Zio, 2009). Keith Douglas Tocher, in 1960, developed a program that sought to simulate the functioning of a production plant (Wilson & Fitts, 2012). In the simulation the machines operated in cycles under simple states: occupied, waiting, not available and failure. With these indicators it was possible to know the final state of the production process through the simulation. From these simulations the reach and applications of simulation tools have grown to the level that it allows the user to visualize how a system would behave under certain conditions, to detect, repair and avoid failures, thus reducing costs for the industry.

As the automated machines were introduced to maximize the production as well as reducing costs in different industries so was the need to guarantee its good functioning for they require some preparation and a well-designed programming. An operative automated machine implies an operative PLC, which requires a programed routine that the machine will follow. Tremendous increase in the use of PLCs has also rise the number of PLC manufacturers and so the diversity in programming features (Ovatman, Aral, Polat, & Ünver, 2016). And so, PLCs are mostly used in environments where critical systems can present flaws that generally lead to produce dangerous effects. This situation makes the verification and testing of PLC very important because of the precise mathematical rigor behind the programming that tells if the desired model is operating correctly and because an early verification on different steps of the design allows the well development of the system.

CAPE (Computer Aided Process Engineering) tools are the most common when simulating production environments that seek to analyze the performance or product flow within a factory or company. One advantage of these tools is their ability to integrate different types of production scenarios along with a variety of robots, machines, manufacturing resources and logical control representations. As a disadvantage, its simplified PLC models fail to execute the real control functions (IEEE, 2012). The use of "hardware-in-the-loop" seeks to break the limitations of CAPE tools given the importance of software within industrial environments (Maclay, 1997).

Within the existing functional software, WinMOD appears, a program based on Fieldbus emulation that seeks to test the real PLC code with correct addresses and real complexity. This emulation is modeled within a CAPE tool and therefore has limitations in the verification of the simulation (IEEE, 2012). Under the same principle but with additional hardware SIMBA Pro and SIMIT can be found, programs that offer the possibility of simulating different models under the OPC connection to CAPE tools. Despite this, these last two programs are specific solutions for Siemens S7 and can't be found generically. Finally, it exists CAPE software with OPC functionality that presents Delmia automation, visual components and process simulation (McGregor, 2002), but provides information on offline programming, verification and optimization.

Even though with today´s general OPC interface it is possible to connect certain simulation tools with a PLC for verification purposes, the results given by this method can be asynchronous as the PLC and the simulation tool are not directly connected. These PLC programming verification methods tend to bring problems among which are the delays in time, understood as the time difference between the simulation and the PLC; the inaccurate synchronization, understood as the lack of a good connection between the PLC and the simulation; and the delay in sampling, understood as the rate of delay to gather feedback information on the behavior of PLC programming. Likewise, this information is always presented in an impractical way and without the possibility of visualizing the real effect in the industrial environment (IEEE, 2012).

After mentioning these alternatives it is worth noting that within this project it is expected to use PLC inside the simulation in a virtual way, after carrying out the research work it can be examined the possibility of integrating physical tools with virtual simulations given the existing OPC connections and that so could allow the connection between the simulated environment and a physical PLC (hardware in the loop).

To make the simulation as real as possible it is proposed the use of a VR environment, since these tools have acquired a lot of attention in recent years as a way for making the human-machine interaction smoother (Deloitte, 2018). Usually for the testing of how a human-machine interaction is developed some simplified scenarios and laboratory environments are applied, since reproducing these cases is often complex. In that way, the results presented in the common procedures are not representative of the actual interaction. VR on the other hand, may be considered as an alternative tool as some studies show results in which virtual reality allows a faithful reproduction of the environment and the human-machine interaction (Human-Robot Interaction Systems, 2018).

With the VR environment, the applications that have been given can be found in sectors of entertainment, tourism, industries of refineries and mines, renewable energies and education (Cantón Enríquez et al., 2017), and can go from videogames to basic education with didactic programs (Carrillo-Villalobos, 2016). This type of VR is based on the simulation of a three-dimensional space where the user's body perceives a sensation of immersion through multi-sensory stimuli that seek to recreate real environments. As a characteristic of this type of VR, gloves, goggles, helmets, special suits (Wearables) or specially adapted spaces are used to capture the real time movements of the person inside the environment (Cantón Enríquez et al., 2017).

Considering that the quality of the simulation may depend on the VR assets available according to previous research's, the display type with the nature of the VR affects significantly the engagement and experience of the user with the simulation (Types of Virtual Reality Display, 2018). Using the common categories of immersive and semi-immersive VR it is easier to stablish the boundaries as to what the user will experience in the simulation. Several studies addressed the effects of using different types of displays for different disciplines. For example, a case showed that an immersive application inside a CAVE for statistical visualization had better results than a traditional desktop tool regarding the identification of the data and the experience of the users (Arns, Cook, & Neira, 1999). Unlike the studies found, in this paper the applications given to the simulation tool searches to approach its benefits in the engineering field, for which is used an immersive VR tool.

Mel Slater (Slater, 2009) distinguishes two ways of experiencing immersive virtual reality: an HMD virtual reality helmet and a cave-like three-dimensional environment. The HMD helmet is placed right in front of the eyes to keep the user's attention on the screen without distractions; it contains an internal magnetic sensor that detects the movement of the user's head; that way, when the user turns his head, the appearing graphics can show the changing point of view (Furht, 2008). The CAVE environment usually consists of four or six walls, which function as stereo projection screens. The images are determined as a function of tracking the head so that, at least with the visual system, the participants can physically move through a limited space and orient their heads arbitrarily to perceive the virtual reality. Usually, the audio is delivered by a set of speakers in discrete positions around the CAVE (Carbajal, Zarate, & Quiteria, 2008). These types of environments provide a better experience for the user in terms of visualization and understanding of the problems and opportunities.

Considering what was mentioned above, it is concluded that the proposed project must make use of the available CAVE hardware and the analysis of software tools for 3D CAD simulation, through a correct linkage of the programmable PLC with those mentioned above so that a simulation tool is well designed and implemented.

3. Objectives

General Objective:

Implement a simulation tool in VR for industrial processes, which allows to validate the functionality of this type of environments as a tool for feedback and verification of changes in a programming routine of a PLC.

Specific Objectives:

A. Design the VR model that allows the verification of a PLC programming routine.
B. Implement the virtual simulation of the industrial system and the simulated logic of the programmable control system (PLC).
C. Validate the simulation tool.
D. Verify the performance of the tool under indicators such as the reduction of costs, times, risks and energy consumption.

4. Design of a simulation to verify a PLC programming routine of an industrial process through a virtual reality tool.

4.1. Software and system selection

As a first step before designing the simulation, a proper software and system must be selected to guarantee that the interaction between the different components of the simulation, such as the PLC and the designed model, will operate properly. This software selection is focused on production simulation software that can satisfy the needs of the simulation and that can execute it in VR environments in the best way possible. The following options of software were included for their use in the industry, their reliability, availability and their ease to integrate with other platforms.

a. Considered software

i. CIROS Automation Suite

The CIROS suite developed by FESTO comes with five different software centered on certain needs. CIROS Production is mainly for manufacturing processes centered in the layout configuration and logistics for production facilities. CIROS Robotics allows the user to program robots and introduce them in a 3D environment with work stations. In CIROS Mechatronics the user can control industrial level manufacturing plants through pre-designed models or by uploading models made in CIROS Studio. In this version the simulation is controlled with an internal simulated PLC that can read different programming languages. CIROS Advanced Mechatronics is an improved version of the previously mentioned software with the advantage of an easily coupling, control and functioning of different work stations ("CIROS® - Software & E-Learning - Learning Systems - Festo Didactic", 2019).

ii. CODESYS

CODESYS is a development environment for PLC programing that follows the IEC 61131-3 international standards, which deals with the basic programming languages and software architecture to control a PLC, defining five language standards: Ladder diagram (LD), Function block diagram (FBD), Structured text (ST), Instruction list (IL) and Sequential function chart (SFC). It has features for engineering projects and commissioning of automation applications, such as data monitoring, scanning for application errors, and changing the application during operation via online. This software doesn't allow the import of 3D files for a better visualization, but it is useful for the remote programming of the PLC via OPC while giving a real time visualization of the simulation states (Events, 2019).

iii. IRAI Virtual Universe Pro

This licensed software works similarly to a video game in the way the user interacts with the system, is an innovative software for Windows XP, Vista, 7 and 8 enabling to create and simulate virtual machines in a 3D environment with a physical engine. The platform doesn't come with working stations but allows the import of CAD models, program and simulate them in a high visual quality with the advantage of being able to connect the simulation with a simulated PLC. Simulations are fully interactive, users can catch and move objects in the 3D world. Human-machine interfaces can also be created. If this software is selected it would be needed to acquire the complete license because the free trial can only be extended to 30 days (iraifrance, 2019).

iv. LabVIEW

This platform is specialized for the test, control and design of a system´s hardware and software in a programming language that can be visualized graphically. Provides a host of other facilities including debugging, automated multithreading, application user interface, hardware management and interface for system design. The software operates in three modules, first a visualization and analysis of data, second the possibility to operate the instruments in the simulation, and finally a validation tool with a reach for many instruments and technologies. A main issue with LabVIEW is that the interface works exclusively in two dimensions, which is why it won't fulfil the needs to simulate the system in a 3D environment ("LabVIEW 2019 - National Instruments", 2019).

v. FESTO COSIMIR

This software has three different versions (Educational, Professional and Industrial) that allows the user to model, design and simulate industrial systems in a 3D environment. Depending on the version the simulation has certain limitations. The educational version doesn't let the user to create new stations, which is why it has pre-defined work stations that can't be modified and are meant for teaching purposes. The professional version has three tools under the same user interphase, a 3D modeling and simulation and robot programming. This version allows the user to create new work stations from the available libraries that include industrial robots that are programable in different languages, and hooks, sensors, machines, etc. Finally, the industrial version is focused on the offline programming of Mitsubishi robots with the same basic tools of the professional version. The downside of the entire COSIMIR software is that it is not designed to interact with a PLC programing (festo-didactic, 2019).

b. Evaluated software

i. Evaluated Aspects

To make the selection of the software that best suits the needs of this project, eight (8) aspects where analyzed in a Baremo table with a Likert Scale that classified each proposed software in a low, medium low, average, medium high, and high score. The analyzed aspects were:

- Available designs: how rich are the software´s available libraries of parts and working stations.
- Models import: how easy it is to import models from other platforms into the software.
- Simulation quality: how detailed is the simulation in terms of components, modifications and PLC connections.
- Signals synchronism: how good are the software´s signals in terms of the simulation status when modeling and running.
- 3D Representation: how good is the software´s 3D modeling in terms of visualization quality and response.
- OPC Interface: how easy is to stablish a connection between the software and an OPC server.

- Production management: how well does the software represent and simulate the levels of productivity of the proposed model.
- Manual control environment: how good does the software enables the user to interact manually with the simulated environment when modifying or running it.

The results are shown in the following table:

Aspect	CIROS Suite	CODESYS	IRAI	LabVIEW	COSIMIR
Available designs	4	1	1	1	3
Models import	4	1	4	1	3
Simulation quality	4	1	3	1	3
Signals synchronism	4	4	1	4	1
3D Representation	4	1	4	1	3
OPC Interface	3	4	1	3	2
Production management	3	4	2	4	2
Manual control environment	4	4	2	2	2
Total	30	20	18	17	19

Figure 2. Baremo for Software Selection

Likert Scale: 1, 2, 3, 4

#Aspects	Score		
8	4	32	Highest score
8	1	8	Lowest score
		24	5 Interval
5	Values between intervals		

	Total
Low	8 to 13
Medium low	13 to 18
Average	18 to 23
Medium high	23 to 28
High	28 to 32

Figure 3. Software selection score classification

The Figure 2. shows how the software's were rated with the total score obtained based on each analyzed aspect according to the Likert Scale. The results show CIROS Suite as the clear winner as it excels in almost all the aspects, especially in the ones related to the representation and interaction of the simulation. The other four software´s score classify as an average or medium high. CODESYS, in the second place, has strong scores in OPC connection and management related aspects. For these reasons CIROS Suite is selected for the design, modeling and execution of the simulation, and because CODESYS allows the programing of the PLC routine while stablishing a connection via OPC with CIROS, it will be considered for simulating and modifying the model´s routine while visualizing the 3D representation.

ii. CIROS Suite

Because CIROS Suite involves five different software that unifies different aspects of simulation, modeling and programming in a single platform for industrial use, it is necessary to select one that suits the needs of the simulation to reduce the costs of licenses and minimize the integration of more programs. In Annex 4 are some of the most relevant advantages proposed by FESTO for the different versions of CIROS.

Comparing the software, CIROS Studio integrates the most relevant features for this work, including: 3D representation, PLC simulation, modeling, manual control environment and production management. In CIROS Studio the user can begin with a work station as a template and then include new machines, robots or different automatization components in the simulation. The reach of the simulated systems is only limited by the user as the different libraries included in the program allows the configuration of every piece in almost every way possible.

With a full license this platform can perform the simulation in a 3D environment, can upload, create or modify reliable models, can track and give a real time feedback of the systems behavior and allows the connection between the simulation and a PLC. Because this software is developed by FESTO, all the work stations that can be found in its libraries are compatible with the existing equipment in the CTAI (Technological

Center of Industrial Automatization) and theoretically in the future engineering building of the university. With this in mind, and two acquired licenses of the software by the CTAI, CIROS Studio will be the selected program for the model, execution and analysis of the simulation.

To execute and model the simulation, in a first instance the user must have deep know on the operation of CIROS Studio, specifically the programing tabs for the model´s libraries and editing to add new work stations and edit the components if necessary. CIROS Studio comes with a first user course that can be fulfilled to know the basic instructions. After making a simulation, the connections and layout can be used as a base to make new projects, the only thing to have into account are the I/O connections that must be modified to match the simulation purpose. Aside from this, the user must pay attention that each connection between the work stations is properly made with the guidance of the warnings that CIROS Studio grants. The proposed simulation in this paper uses only the available machines in the libraries that come with the software.

iii. CODESYS

Since the purpose of the simulation is to verify the programming routine of a PLC it is expected to make a bridge between the simulation and the PLC programming. CODESYS will be useful for the remote control of the simulation as it allows the user to modify the designed routine for the system and visualize its behavior with the connection with CIROS Studio via an OPC configuration. The programmed routine is made in ladder language, depending on which machine is being programmed the user can use CODESYS or in default the pre-installed settings that allows the configuration of work stations such as robots in their own programming language inside CIROS Studio.

4.2. Description of FESTOS´s Stations

The layout considered to the simulation is a linear distribution; Meaning a one direction route with no back flow. Starting with the raw material and ending with the whole piece assembled in the same station AS/RS. This configuration is done after considering the future layout of the CTAI in the new engineering faculty building. The future configuration integrates the use of CyberFactory 4.0 systems that opens a new path with the use of Industry 4.0, that is later explained in this document, for training, optimization and testing industrial environments. The following layout is proposed to develop a base simulation that can integrate more or less actuators or work stations and maintain the I/O connections so that a new user doesn't need to verify each connection and make the production of new models easier.

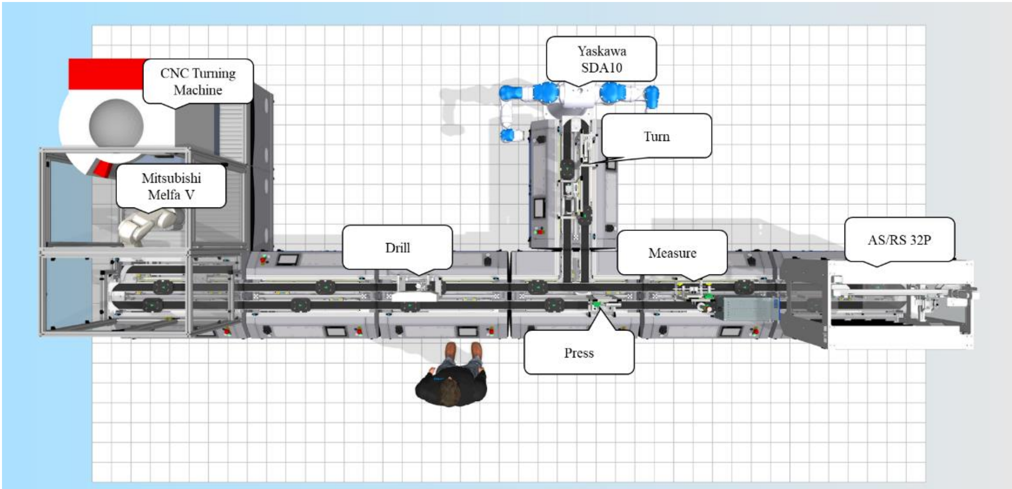

Figure 4. Simulated FMS Layout

As seen, the FMS layout considered for the simulation is a loop or rectangular distribution; it´s a one direction route with no back flow.

a. Module selection

The main goal of the simulation was to recreate a production line taking as a basis the stations available in the new CTAI. Considering the architecture within the simulated models, the SCADA based modules are explained in Figure 5. relating the most important physical features and the functions performed inside the simulated production line. The simulation consists of two robots (Mitsubishi-Melfa RV-2A & Yaskawa Motoman SDA10), an EMCO PC Turn 125, AS/RS and four MPS.

Module	Description	Simulated functions
Robot: Mitsubishi - Melfa RV-2A	6 axis vertically articulated robot's load capacity is 2kg. offers speed and high Precision performance over conventional industrial robots, boasting a maximum speed of 3500mm/sec, 621mm reach and a position repeatability of +/-0.04mm.	Pick & Place: This robot was used in order to place the product inte CNC Machine and put it back in the conveyor line
Robot: Yaskawa Motoman SDA10	15 Axis Dual-Arm Robot. Max. Payload: 20 kg, (10 each arm)	Assembly mode: Used for assembling the pieces of the process flow
EMCO PC Turn 125	Distance between centers: 236 mm Swing over bed: 180 mm Spindle speed: 150~4000 rpm Turret: 8 stations Fanuc control system	This Turn would recreate the functionality of turning the assembled piece.
AS/RS	Computer-controlled systems for automatically placing and retrieving loads from defined storage locations	The storage was designed according to the order of product requirements, so that the assembly material would be available first and the final product at the end.
MPS	Measure	An important component part of measuring is the comparison of characteristics (ACTUAL values with specified reference values (REQUIRED values).
	Turn	The module turns workpieces. The workpieces on the conveyor belt are detected by an optical diffuse sensor
	Drill	The drilling module can be attached to a transfer line. Two drilling spindles can be advanced in the Z direction and moved in the X direction. Those pairs of holes can be introduced into a workpiece
	Press	The pressing process is implemented via proportional pressure regulation

Figure 5. Stations description

b. PLC´s connection

Figure 6. indicates how the PLC´s connections were made according to the internal and external OPC based on the different stations that integrate de simulated model. To make these connections one must make the proper link between the OPC server and OPC client with the respective IP directions so that the connection works in real time. For this project CODESYS works as the OPC server and CIROS Studio is the OPC client. After stablishing the connection, it is only needed to launch the linkage every time the software is opened.

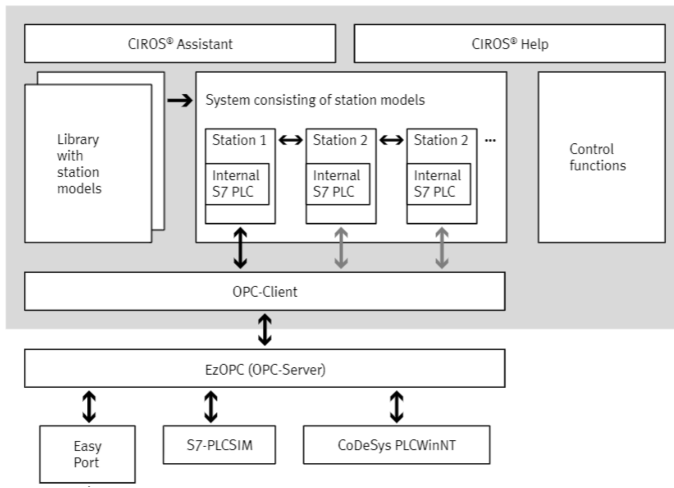

Figure 6. PLC connection steps

There are different ways to connect and edit the connection of I/O Ports on every single item of a module in CIROS Studio, while it was decided to use the CODESYS software. To edit a connection the user must open the programming window in the top part of CIROS Studio and open the tab of I/O connections or the Inputs and Outputs panel. Thanks to the friendly interface, every connection is illustrated with an arrow that can be green if the connection is active or can be red if the connection is off. When running the simulation, the user can visualize the behavior of each connection as the arrows change their colors when each component is on or off. If the PLC programming is modified, it will affect the simulation in real time.

4.3. 3D modeling and simulation

a. Definition and characteristics of the model

A model can be defined as a visual, theoretical or graphic representation of one or more objects that make a system or process in a way that enables the user to understand, verify and improve its functioning. This model can be composed of one single device or an assembly with the real measurements for the interaction to be as real as possible. As an advantage, at the same time the model can be zoomed in and out to get a better visualization of the operation of all the components in the simulation.

The main features of the model are the truthfulness of each simulated part including the way they operate and look; the real time conditions, such as physical laws, that interfere with the simulation; the different variables and defined parameters included in the simulation that interact with each other; the real time connections between the simulated and the real devices; the flexibility to change and re-start de model; and the realness of the man-machine interaction with the model during the simulation.

This modeling must be aligned to the expectations and the path that de CIM CTAI is following to go from a main line of ASRS, transport, robotics and CNC that are all based on sensors and actuators and reach a 4.0 industry environment. This evolution is better represented in Figure 7. in a way that each step taken is focused on ending different processes in a gateway IoT, storage and cloud level.

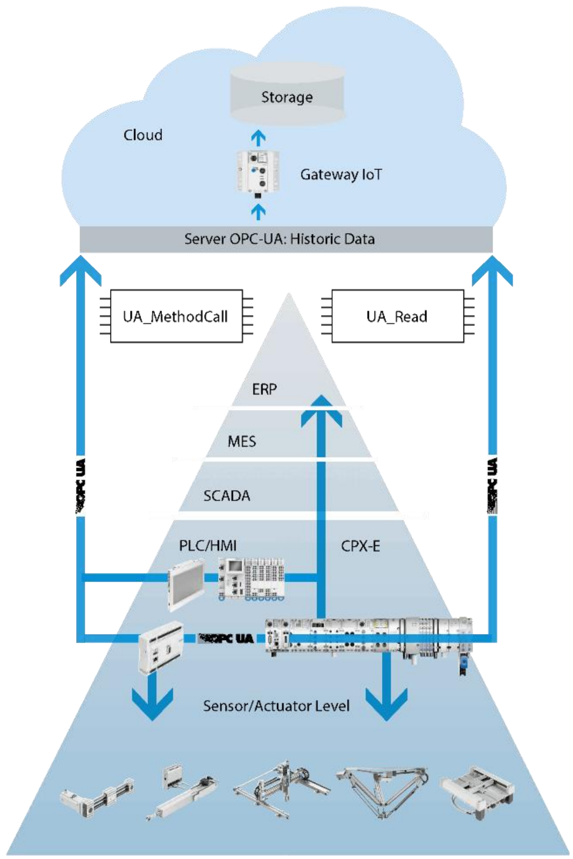

Figure 7. Industry 4.0 flowchart

The actual CIM CTAI performance can be classified and compared with a 4.0 industry environment such as CIROS Studio in four relevant aspects as shown in Figure 8. For the "costs" a high score means a reduction of investment for maintenance or acquisition of new industrial equipment. For the "times" a high score means low times of modeling and testing industrial processes. The "risks" aspect has a high score if the environment implies less risk involving machinery usage for both the user and the machine. "Energy consumption" as the last aspect has a high score if it requires less energy from both the user in terms of effort and the environment in terms of the electrical energy used for its correct functioning.

Aspect	CMI CTAI	CIROS Studio (Industry 4.0)
Costs	2	4
Times	1	4
Risks	1	4
Energy consumption	3	3
Total	7	15

Figure 8. Baremo for Performance indicators

Likert Scale: 1, 2, 3, 4

#Aspects	Score		
4	4	16	Highest score
4	1	4	Lowest score
		12	4 Interval
3	Values between intervals		

	Total
Low	4 to 7
Medium low	7 to 10
Medium high	10 to 13
High	13 to 16

Figure 9. Performance indicators score classification

From the classification in Figure 9. the 4.0 Industry has a high score and shows an improvement compared to the current CIM CTAI and what is expected to be for the four aspects in industrial environments. For this project the 4.0 industry is a relevant topic because it differentiates the performance of a regular environment compared to the new technologies approach.

b. Definition and phases of the simulation

The simulation implicates the use of the previously generated model to analyze its behavior in an environment with different conditions and situations, with the purpose of resolving any adversity that may appear. The process of implementing the simulation consists on different stages:

- Definition: in this stage the tool where the model will be designed is selected, as well as the limits and restrictions.
- Relevant variables: the relevant variables and parameters that the model will handle are defined so that they comply with the limits and restrictions. An example is the limiting positions that a robotic arm or an automated machine can reach so they don't interfere with each other.
- Simulation model: build the simulation with the selected software.
- Execute the simulation: run the simulation according to the desired parameters and variables that want to be analyzed.
- Analyze the results: apply the corresponding repairs for any error arising error so the model is reliable.
- Evaluation: evaluate the performance of the simulation with a standardized test.

c. Simulation advantages

The following advantages are extracted from the studies made by Anglani A, Grieco A, Pacella M, Tolio T., 2002 and Coro, Montanet, G., Gómez, Sánchez, M., Suárez, & García, A. 2017.

- Analysis: the timely evaluation of the results from the simulation allows the user to identify the real time factors that affect the system and change them if necessary.
- Optimization: the simulation allows the user to modify any aspect of the system without the need of interacting with the real system, optimizing assets and improving the efficiency of the process.
- Teaching: with the availability of the CAVE space it is possible to use the simulation as a pedagogic tool in industrial environments to educate new workers in the use of equipment, or in the case of some classes the students can interact with the simulation without the risk of damaging any machine.
- Time: the time invested in designing a simulation can be minor compared to the one needed to design a real prototype, as well as the times needed to correct errors or making modifications in the system.
- Costs: the simulation reduces costs as the main thing needed is the software used and because in the long term it can be reused in other projects.

5. Design Component in Engineering

5.1. Design statement

Implementation of a simulation tool in VR environments for industrial processes as an analysis model of physical, operational, ergonomic and training functionality for industrial engineering tools through the reprogramming of PLC.

5.2. Design process

The design process of the program to run in Ciros was made based on the steps shown in the Figure 10.

Figure 10. Design Process

- Module Definition: By defining that the used stations for the simulation were those available in the new CTAI, the goal was to recreate them in the CIROS Studio layout, even though the MPS stations available in the software are a most generic version of the ones in real life. Also, it was necessary to define the robots (Mitsubishi Melfa RV 2A and Yaskawa SD10) functionality to place them correctly in the production line.
- Module Programming:

Programming	**Modules**
Ladder (CODESYS)	It was used to program all the MPS stations (Measure, turn, drill, press) as well as the conveyor lines and sensors.
Melfa Basic V	Used to program the robots (Mitsubishi, Yaskawa)
AS/RS Interface	CIROS Studio has a special tool for programming AS/RS and CNC stations, so that it requires all the information of the routine to simulate and translate it into IRL Language

- OPC- PLC Connection: This type of connection was only required for the MPS stations in which CODESYS simulates a virtual PLC that is linked via OPC to the CIROS Studio Software, the main difficulty is that it is only possible to use one PLC, so every MPS I/O must be programmed and declared in one routine, it is not possible to execute one PLC for each station.
- I/O Connection: Once the Virtual PLC is being executed, it is necessary to set the PLC Inputs and outputs to its corresponding actuators.
- Testing: Finally, in case the evaluated program failed, it´s necessary to go back to the CoDeSys code and make the corresponding changes. Otherwise, it has successfully run, and it can be simulated in the VR system (CAVE).

5.3. Performance requirements

The designed simulation, proposed in the previous section, works in the CAVE room of the Pontificia Universidad Javeriana to explore and verify the advantages of immersive VR, allows the simulation of an industrial process in immersive environments and permits the PLC programming. It also allows an operator to interact with the simulated environment.

Design requirements; the design process and the hardware-software architecture needed that allows to emulate the productive system is explained in the Figure 11. Keeping in mind the specifications of the CAVE room the proposed model can be found on Annex 2.

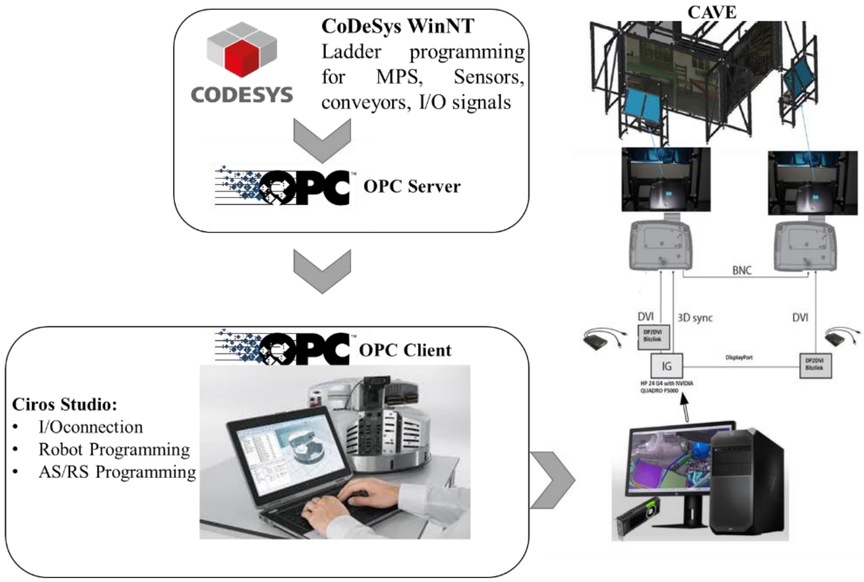

Figure 11. Design process

Performance; the tool achieves to effectively simulate, based on the reaction time and functionalities, the environment where the user of the study case performs, generating a visualization of the equipment and laboratory machines reconstructed in a three-dimensional space at a real scale together with the main functions of the equipment and/or simulated elements. Considering that the user interacts with the operation of the PLC, the tool can show a real time feedback of the process and the program that operates the production line.

5.4. Validation of simulation tool

As it was mentioned at the end of chapter 1.2, the SUS standard format was used to validate the simulation with an extra question referred to the recommendation they would give to the simulation tool. In addition, the Game Experience Questionnaire (GEQ) was introduced as another validation tool as the simulation performance is like a videogame, and because it is more extensive and may give a better appreciation of the user´s perception on each of the three modules that conform this tool (Ijsselsteijn, & Poels, 2013). The Annex 1 includes the original usability questions for the GEQ and the SUS questionnaire along with the assessed person´s responses. At first a pilot test was performed to find aspects to improve in the way the simulation was validated. To do this different persons were called to the CAVE in the Pontificia Universidad Javeriana´s "Centro Atico" at a pre-defined schedule. After explaining the steps to follow in the CAVE they were asked for their consent for photograph each test. Both tests consisted on searching for a glitch inside the PLC routine, that could affect the correct perform of the production line, with the use of the different vizualizations, tabs and available tools inside CIROS Studio. The evidence for this tests can be found in Annex 2.

a. Pilot test

The people cited for this test had a non-related background with PLC programming or industrial environments, they were under-graduated persons from careers like business administration or social communication. For the data collection each assessed person was asked to fill each format at certain moments, because the GEQ consist of three different modules relevant for this project (Core, In-game, Post-game), the core and post-game module with the SUS questionnaire were filled after performing the simulation and the in-game module was filled when performing the simulation. After consolidating all the answers for the pilot test, the SUS and GEQ results were evaluated in their respective ways. For the SUS a ponderation was performed where a unit of the answer for the questions identified by an even number is taken, instead for the odd questions the answer is subtracted from 5 (e.g. for question 2 an answer is 5, the ponderation is 5 - 1 = 4), once the ponderation is made the results are added for each person and then multiplied by 2.5 to obtain the qualification of the simulation (McLellan, Muddimer, & Peres, 2012).

According to Bangor, A., Kortum, P. T., & Miller, J. T. (2008), the results for the SUS questionnaire can be interpreted as follows:

- If the weighting obtained is less than 25, the usability of the product/system is worse than contemplated.
- If the weighting obtained is between 25 and 39, the usability of the product/system is considered low.
- If the weighting obtained is between 40 and 50, the usability of the product/system is considered acceptable.
- If the weighting obtained is between 51 and 73, the usability of the product/system is very good.
- If the weighting obtained is between 74 and 85, the usability of the product/system is excellent.
- If the weighting obtained is greater than 85, the usability of the product/system is higher than that contemplated.

Because the GEQ is meant to give information about certain aspects and be a support tool, it doesn't have a scale to grade how good is the simulation but can give relevant information for the following aspects:

Core Module	
Features	**Questions**
Ability	2, 10, 15, 17, and 21.
Sensory and imaginative immersion	3, 12, 18, 19, 27, and 30.
Fluency	5, 13, 25, 28, and 31.
Annoyance/Tension	22, 24, and 29.
Challenge	11, 23, 26, 32, and 33.
Negative Effect	7, 8, 9, and 16.
Positive Effect	1, 4, 6, 14, and 20.

In-game Module	
Features	**Questions**
Aptitude	2 and 9.
Sensory and imaginative immersion	1 and 4.
Fluency	5 and 10.
Tension	6 and 8.
Challenge	12 and 13.
Negative Effect	3 and 7.
Positive Effect	11 and 14.

Post-game Module	
Features	**Questions**
Positive Experience	1, 5, 7, 8, 12, and 16.
Negative Experience	2, 4, 6, 11, 14, and 15.
Fatigue	10 and 13.
Back to reality	3, 9, and 17.

Figure 12. GEQ Evaluated Aspects

For each of the eight evaluated persons a GEQ and a SUS questionnaire was handled at certain moments during or after the simulation. After consolidating, digitalizing and weighing the results, they are presented in Figure 13. for the SUS and Figure 14. for the GEQ.

Question	Assessed person							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	3	3	2	1	1	1	1	2
2	4	5	5	4	4	3	3	3
3	2	2	1	4	3	2	3	2
4	2	4	3	1	2	4	2	2
5	2	2	1	1	2	2	2	1
6	3	3	3	1	3	2	2	3
7	1	1	2	3	3	2	2	3
8	4	4	5	3	4	4	3	4
9	3	1	1	2	3	2	3	2
10	4	4	2	1	2	3	2	2
Total	29	31	28	25	32	31	30	32
Average	30							

(green)	Positive Response - Agree or Strongly Agree for positive questions (even), Disagree or Strongly Disagree for negative
(yellow)	Neutral - neither Agree nor Disagree
(orange)	Negative Response - Agree or Strongly Agree for positive questions (odd), Disagree or Strongly Disagree for positive

	Ponderation							
Question	Assessed person							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	2	2	3	4	4	4	4	3
2	3	4	4	3	3	2	2	2
3	3	3	4	1	2	3	2	3
4	1	3	2	0	1	3	1	1
5	3	3	4	4	3	3	3	4
6	2	2	2	0	2	1	1	2
7	4	4	3	2	2	3	3	2
8	3	3	4	2	3	3	2	3
9	2	4	4	3	2	3	2	3
10	3	3	1	0	1	2	1	1
Total	65	78	78	48	58	68	53	60
Average	63							

Assessed person	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Average**
Recomendation	8	9	10	10	10	10	8	9	9

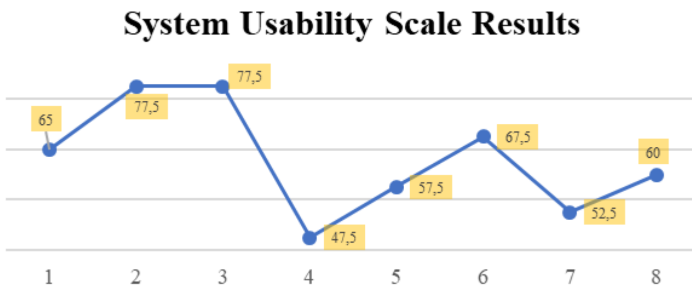

Figure 13. SUS Results, Pondered Results and Recommendation

In first place, the SUS results show an average of 63 for the weighted data, which translates in a very good usability of the product/system according to Bangor, A., Kortum, P. T., & Miller, J. T. (2008), with the lowest and higher scores being 48 and 78 respectively. In second place, questions 6 (I thought there was too much consistency in this system) and 10 (I needed to learn a lot of things before I could get going with this system) presented the lowest scores. For statement number 6 this may be due to a misconception as the assessed persons said the consistency of the simulation was very good, so the response was redirected for how consistent the simulation was. Question number 10 on the other hand showed how this first interaction between the users and the CAVE room was because they needed to learn several things regarding the procedures, the visualization inside CIROS Studio and the interaction they had with the VR environment. Finally, an average of 9 was the response for how likely they were to recommend the simulator to other people.

The SUS results indicate that there is no strong correlation between the recommendation of the tool with the results of the pilot test. This can be due to the striking visualization of the tool and the lack of knowledge about PLC by the people evaluated. Also, a slight variability is detected after the ponderation is made due to the score obtained by assessed person number 4.

		Assessed person								
	Features	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
Core Module	Ability	2	3	3	3	3	3	2	3	22
	Sensory and imaginative immersion	3	3	4	3	4	3	3	4	26
	Fluency	2	2	3	1	3	3	2	2	17
	Annoyance/Tension	0	0	1	2	0	0	0	1	4
	Challenge	1	1	2	2	2	1	2	2	13
	Negative Effect	0	0	1	2	1	0	1	1	5
	Positive Effect	3	2	4	3	4	3	3	2	24
In-game Module	Aptitude	2	3	3	3	3	3	3	2	21
	Sensory and imaginative immersion	4	3	4	3	4	4	3	4	27
	Fluency	2	1	3	2	2	3	1	3	14
	Tension	0	0	0	1	0	0	1	1	3
	Challenge	2	1	4	3	3	2	3	4	21
	Negative Effect	0	0	0	2	0	0	1	1	4
	Positive Effect	3	2	3	3	3	3	3	2	21
Post-game Module	Positive Experience	3	2	3	2	2	3	3	2	19
	Negative Experience	0	0	0	1	0	1	2	1	4
	Fatigue	0	1	1	1	1	1	2	1	6
	Back to reality	0	1	2	1	0	2	1	2	10

Figure 14. GEQ Results

According to the GEQ results in a first approach there are high scores for the Positive Experience features in the three GEQ modules. In the Core and In-game modules the Sensory and imaginative immersion feature had the highest results followed by the Fluency, Aptitude and Ability features. The GEQ shows, with the difference in the Core and In-game modules, that as the user remains more time in the simulation the Challenge feature is conceived with a lower score. These results show a positive experience regarding the simulation integrated with the VR environment. A more experienced user may interact with the simulation for a better learning with less challenging features.

This pilot test was also useful to calculate a correct sample size for the real test based on the SUS results. Using a statistical software, a calculated mean of 63 and a standard deviation of 10.92 was obtained. Because the SUS has a trust of 0.911 according to Bangor, A., Kortum, P. T., & Miller, J. T. (2008), with the Equation 1. for the calculation of a sample size based on cuantitative variables, an adequate sample size was calculated.

Equation 1. Sample size calculation

$$n = \left(\frac{Z_{1-\frac{\alpha}{2}} * \sigma_x}{e_m}\right)^2 = \left(\frac{Z_{1-\frac{0.911}{2}} * 10.92}{10}\right)^2 = 3.4462 \approx 4$$

In the previous expression n stands for adequate sample size; $Z_{1-\alpha/2}$ stands for the value of a standardized normal distribution with a probability of $1-\alpha/2$; α is the employed trust; e_m is the mean error of the measure which translates in the precision of the estimations; and σ_x is the standard deviation of the results. For this validation the chosen error was 10 percental units because of the limited available persons to make the test. After replacing the values in the Equation 1 the result was 3.4 for an approximation of 4 persons. This result stands for the minimum required sample to generate valid and trustful results.

b. Focus group test

For the focus group test the same considerations were taken from the pilot test, both the SUS and the GEQ questionnaires were applied to a total of 5 persons that, unlike the assessed persons in the previous test, had more experience with real industrial processes as they took the class of “flexible manufacturing” or “industrial processes” at the Pontificia Universidad Javeriana where they managed the use of a PLC. The results were as follows:

Question	Assessed person				
	1	**2**	**3**	**4**	**5**
1	1	1	1	2	2
2	5	4	5	5	5
3	4	2	1	2	1
4	3	4	4	4	5
5	1	1	1	1	1
6	1	4	4	4	5
7	1	2	2	2	2
8	5	5	5	5	5
9	2	1	2	2	2
10	1	3	5	4	3
Total	25	29	33	35	36
Average	32				

	Positive Response - Agree or Strongly Agree for positive questions (even), Disagree or Strongly Disagree for negative
	Neutral - neither Agree nor Disagree
	Negative Response - Agree or Strongly Agree for positive questions (odd), Disagree or Strongly Disagree for positive

Question	Ponderation				
	Assessed person				
	1	**2**	**3**	**4**	**5**
1	4	4	4	3	3
2	4	3	4	4	4
3	1	3	4	3	4
4	2	3	3	3	4
5	4	4	4	4	4
6	0	3	3	3	4
7	4	3	3	3	3
8	4	4	4	4	4
9	3	4	3	3	3
10	0	2	4	3	2
Total	65	83	90	83	88
Average	82				

Assessed person	**1**	**2**	**3**	**4**	**5**	**Average**
Recomendation	10	10	10	9	9	10

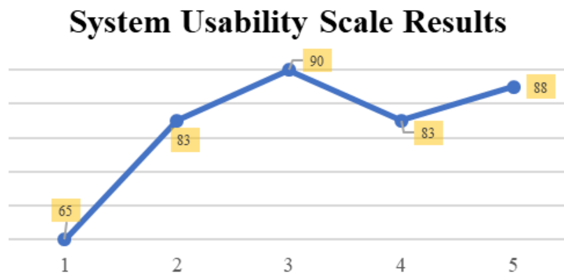

Figure 15. SUS Results, Pondered Results and Recommendation

In the SUS results the assessed persons got a higher score in comparison to the pilot test, being 65 the lowest and 90 the highest score. Because the subjects in the focus group test had more knowledge regarding PLC programming and industrial processes, these results may show a more certain approach to the validation of the simulation tool given that they have a similar criterion. Also, Figure 15. shows a more consistent data compared to the pilot test results, making the average score classify the simulation tool as excellent according to the scale proposed by Bangor, A., Kortum, P. T., & Miller, J. T. (2008). For this test the observations from the pilot test were considered, clarifying some statements from both questionnaires so that the answers were well oriented. Finally, the tool recommendation score increased to a rounded average of 10.

In comparison with the pilot test, the focus group test results show a big improvement with the atypical data of assessed person number 1 as the standard deviation went down to 9.78 and obtained a variance of 95.63. If the atypical result from individual number 1 is excluded the deviation and variance dropped to a 3.75 and 14.06 respectively. This shows that the data is not so scattered around the mean.

In conclusion, it can be said that the performed tests show truthful data to validate the performance of the simulation tool. These results may be due to the scope and interest that the evaluated people on the focus group test had in relation to their knowledge about PLC and the facilities that the simulation tool grants. Given that for both tests the evaluated people was asked to perform the same task of searching for a glitch inside the PLC routine, because the second test sample had previous work regarding PLC management and programming, they explored in a deeper and more detailed way how the different satations inside the simulation interacted and followed the proposed PLC routine.

Module	Features	Assessed person 1	2	3	4	5	Total
Post-game Module	Back to reality	1	2	2	2	1	9
	Fatigue	0	1	1	0	0	2
	Negative Experience	0	1	1	0	0	2
	Positive Experience	3	3	3	3	3	14
In-game Module	Positive Effect	4	3	3	3	3	15
	Negative Effect	0	0	0	0	0	0
	Challenge	3	3	2	3	2	13
	Tension	0	1	0	0	0	1
	Fluency	4	2	2	3	2	11
	Sensory and imaginative immersion	4	4	4	4	3	18
	Aptitude	4	3	4	3	3	17
Core Module	Positive Effect	4	3	3	3	3	16
	Negative Effect	1	1	1	0	0	3
	Challenge	2	2	1	1	1	7
	Annoyance/Tension	1	0	0	0	0	2
	Fluency	4	3	2	2	1	12
	Sensory and imaginative immersion	4	4	4	4	3	19
	Ability	3	3	3	3	3	15

Figure 16. GEQ Results

Similarly to the pilot test, the GEQ results in Figure 17. for the focus group test show high scores for the Positive Experience features in the three GEQ modules. The negative effect in the In-game module stands out as the five test subjects answered that the simulation had no negative effect when executing it. From these results it is evident an improvement in the evaluated aspects from both the SUS and GEQ questionnaires. Also, there's a relation between the high scores and the recommendation given to the use of the simulation tool as the assessed persons expressed a better and dynamic understanding of how the system and the PLC routine worked.

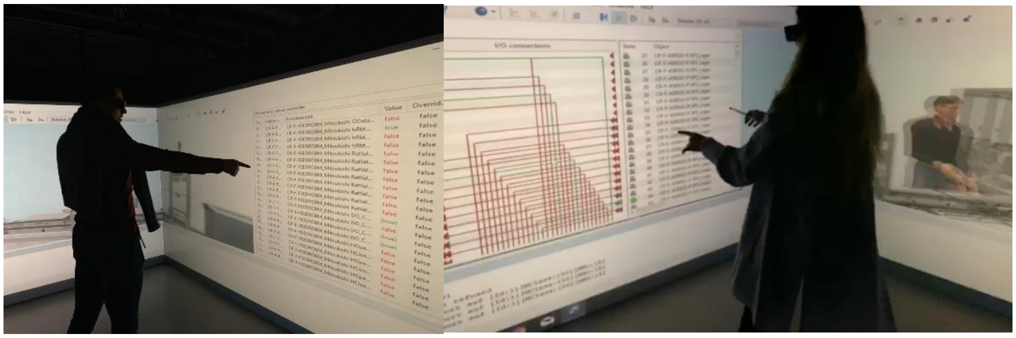

Figure 17. Assessed persons in the CAVE room
Source: Own authorship, 2019.

Regarding the system as a whole, including the software and the CAVE room, in both the pilot and final test the assessed persons expressed an interest in the possibilities and lack of limitations for the training and practice of the PLC verification and other tasks. Thanks to the CIROS Studio configuration for 3D environments, the 3D visualization inside the CAVE room had no problems during the tests and had a good performance at the moment of wanting to explore in detail each component within the simulation together with its development inside the PLC routine in the Inputs/Outputs tab.

5.5. Design restrictions (Feasibility)

- Available hardware: since the simulation requires a specialized hardware to run without problems, the tool must be programmed so that it operates in the best way possible with the available VR space at the Pontificia Universidad Javeriana.
- Size of the experiment: once the rendering of the tool is done, it is possible to test it with 5 to 10 users. Due to the availability and ease of access, it is only possible to check the tool with industrial engineering students familiar with the CTAI laboratory (subjects: industrial processes or flexible manufacturing).
- Plc integration with graphic engine: it may happen that some PLCs are not compatible with the tool used to program the simulation, therefore the design of the tool must be adapted to compatible platforms that allow the integration of the available hardware and software.

5.6. Fulfillment of the standards

The project is worked under the IEC 61131 standard for international PLC (IEC, 2006), focused on the specifications and testing of the equipment, programming languages, user guides, communications and diffuse control. For access to information (data access) OPC 2.0 Foundation Standard will be handled focused on the way in which automation applications can exchange information in real time, historical information and other applications in a safe and reliable manner. Because CODESYS complies with the IEC 61131 standard, OPC-Server V2.0 and it was used for the PLC programming, it is guaranteed that the final simulation tool fulfills the proposed standards.

In addition, the VR at IEEE, in its Augmented World expo event in 2017, has established projects composed by a work team to define the standards in VR and AR projects, so they will be used as a guide throughout the development of the current project (Yuan, 2018).

The IEEE P2048 standard focuses on different areas, including:

- IEEE P2048.1 ™: Taxonomy of devices and definitions
- IEEE P2048.2 ™: Immersive video taxonomy and quality metrics
- IEEE P2048.3 ™: Transmission formats and immersive video files
- IEEE P2048.4 ™: Personal identity
- IEEE P2048.5 ™: Safety of the development environment
- IEEE P2048.6 ™: Immersive user interface
- IEEE P2048.7 ™: Virtual objects in the real world
- IEEE P2048.8 ™: Operability between virtual worlds and the real world
- IEEE P2048.9 ™: Immersive audio taxonomy and quality metrics
- IEEE P2048.10 ™: Immersive audio files and streaming formats
- IEEE P2048.11 ™: Augmented reality inside vehicles
- IEEE P2048.12 ™: Classification and content descriptors

Because this regulation is currently under development, they do not have defined standards, however, the main topics were considered when developing this project.

6. Results

6.1. Objectives fulfillment

This project satisfies each specific objective as they are required to reach the main goal. In first place, specific objectives A and B are achieved through chapter 4 and 5 with the selection of software that allowed the design and implementation of the simulation described in chapter 4.1 and that permitted the integration of a PLC routine to later validate the simulation tool in chapter 5.4. This validation sought to comply specific objective C with both quantitative and qualitative justification with the use of SUS and GEQ as standard validation tools. After realizing a programming routine for a productive system´s PLC in a software that allows its visualization in a VR environment, the user can verify the system performance. With the use of the SUS and GEQ questionnaires, the acceptance and usability of the system is verified with a pilot and later a more qualified sample. The results conclude an overall classification of "excellent". The proposed simulation tool accomplishes the goal of verifying the programming routine of the designed industrial process. Finally, for specific objective D the performance of this tool can be verified under the aspects showed in Figure 8. from chapter 4. This Baremo shows how well does a 4.0 industry tool such as CIROS Studio performs in terms of costs, time, risk and energy consumption compared to the currently used assets in the CIM CTAI.

6.2. Impact measurement

To measure the impact of this project Figure 7. is recalled as a reference of the past and future changes of the tools that make up the 4.0 industry such as CIROS Studio. In an economic aspect this type of projects tend to have a positive impact as the use and maintenance of new assets is reduce because, as shown in chapter 5.4, simulations and VR spaces are much flexible and can be adapted to almost any need. Environmentally the proposed tool generates savings in terms of the used material and energy, especially for tests, because it does not generate waste nor requires large amounts of energy.

Socially, the industry 4.0 generally has different opinions and implications due to its characteristic of transforming products and processes, but it also seeks to generate value for the end user and the industry. For the tested people in both tests, this type of tool is considered as innovative and creative and with possible uses in other faculties. In this way, the impact of this type of simulations in the society is not yet determined due to the continuous changes and needs in the industry. The operational impact of this project is given by the ease and dynamism to train an individual for a given job in comparison to the most commonly used methods.

7. Conclusions and Recommendations

This project submits a proposal for the verification of a PLC programming routine of an industrial process with the use of a virtual reality tool. In first place, the software to be used was selected through a Baremo after comparing it with different options for the design and modeling of the stations and functions to be simulated that were in accordance with the performance requirements and the current conditions of the CIM CTAI together with its current process of entering the 4.0 industry. With the use of CIROS Studio the simulation was designed from the ground with the use of the available models included in the software´s libraries. Every connection was tested and verified to be certain that the simulation tool was properly made.

In second place, as progress was made in the design of the simulation and it was been guaranteed that the proposed simulation tool meets the stablished standards for PLC and OPC while remaining within the limitations of the project, the visualization inside the CAVE room was being prepared so that the existing CIROS Studio license was available for the time the validation was going to be made. With the help of Centro Atico in the Pontifical Xaverian University, the CAVE room was properly configurated to run the simulation.

Then, the validation methodology of the tool was chosen and executed given its characteristics and limitations with the use of a standardized SUS and GEQ questionnaires. After applying a pilot test with random people, making the correct corrections and applying a final test in the CAVE room to people with a proper background for this project, an overall average score of 82 with a mean of 9.78 was obtained. In this way, it was concluded that the simulation tool, composed by a designed layout in CIROS Studio and a PLC routine connected via OPC with CODESYS, classifies as an excellent product/system for the verification of PLC for the proposed simulation.

After making the analysis to verify the performance of the tool it is emphasized that this investigation work searched to evaluate the tool´s performance under certain indicators and not the real advantages that it may have with real students, for which raises the recommendation of using CIROS Studio, hopefully in CAVE related environments, as an alternative for the currently used methods of evaluation and learning in classes like Industrial Processes and Flexible Manufacturing so that the students may have more options and a better visualization of real industrial processes. Having the proposed layout configuration, the students can add or modify the work stations to make more or less complex simulations. With the proper guidance for the PLC routine programming, the students can use the stablished OPC server-client connection to take their models and execute them in the CAVE room and in the future engineering building.

It is recommended the continuation of this degree work given the scope that this has as a first step towards machine learning based on the data generated after modeling production lines in CIROS Studio with the purpose of generating an ERP (Enterprise Resource Planning) that is fed by the simulated data after being processed in a statistical software. A second recommendation refers to encourage the use of this type of tools in educational environments due to the potential and advantages the simulation has. Also, it is suggested to verify different layout configuration for the evaluated model given that the proposed one may have included less or more work stations. Finally, it is proposed to evaluate the simulation tool for the complete layout of the future engineering faculty building at the Pontificia Universidad Javeriana.

8. Glossary

Virtual Reality: A space defined by a machine or programmable interface that generates environments which recreates behaviors, objects, and relationships to establish a world with programming-set rules. (Deloitte, 2018)
Immersive virtual reality: A method linked to a three-dimensional environment generated by a computer where virtual objects can be manipulated using gloves, helmets or other devices that project the position and movements of the user. (Quiteria, 2008)
Virtual Simulator: Software and hardware tool designed to simulate a programmed virtual reality. (Deloitte, 2018).

PLC: Programmable Logic Controller. Computer used in industrial automation to automate electromechanical processes. (IEEE, 2012)
Simulation: Model of a real system with the purpose of studying the behavior of the system under alterations imposed by one or several criteria for its operation. (Cellary, 2013)
Production Line: Set of sequential operations in a factory to go through a process to produce a product. (Fukuda, 2006)
CAVE: Cave Assisted Virtual Environment is an immersive virtual reality environment. It consists of screens with projectors oriented towards the walls and ceiling. Special glasses are required for the user to see the generated graphics. (Deloitte, 2018)
Training: Activities or procedures aimed at preparing an individual in attitudes, knowledge, skills or behaviors. (García, 2017)
Interactivity: Participatory relationship between the user and the computer systems. (Deloitte, 2018)
OPC: Open Platform Communications. Communication standard in the control and supervision of industrial processes. (IEEE, 2012)
Baremo: Set of standards established conventionally to evaluate something. (Cruz-Neira, 1999)
Likert scale: type of rating scale used to measure attitudes or opinions. (Cruz-Neira, 1999)
Industry 4.0: developmental process in the management of manufacturing and chain production. (Deloitte, 2018)

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