

# A Chemical Process Automation Virtual Laboratory to Teach PLC Programming\*

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*This paper introduces a chemical process automation virtual laboratory to teach programmable logic component (PLC) programming to chemical engineering students. The virtual laboratory was used in the practice part of an electrical engineering course and focuses on the basic automation of chemical processes. The students have been provided with the open CoDeSys software and the initial program (containing the virtual process simulation) created by the instructors. The students developed their own applications both in local practices and at home. In the local classes they can exchange doubts and ideas with the other students and the instructors. Based on students' course completion surveys, the experience has proved to be positive.*

**Keywords:** project-based learning; PLC programming; chemical engineering; virtual laboratory

## INTRODUCTION

THE HIGH DEGREE OF AUTOMATION developed in the chemical industries in the last decades is raising the need for process engineers to have a certain knowledge of automation. At the same time, there has been an important growth in remote and virtual laboratories, which has enabled distance learning of automation disciplines. While some systems allow the use of real remote laboratories (automatic control laboratory [1], flexible manufacturing cells [2], robot control [3], domotic systems [4]), chemical processes may involve a more complex treatment and, hence, the use of virtual laboratories becomes especially interesting.

Regarding the teaching of PLC programming, in Gomis *et al.* [2] commercial PLCs are used to automate a manufacturing cell and communicate with other systems. In Persin *et al.* [5], an OPC is introduced to exchange data between MATLAB and a PLC-controlled system. In Hshieh *et al.* [6] a tutoring system for PLCs is presented. Other authors [7, 8] have proposed courses to teach control to chemical engineering students, focusing on PID controllers, and automatic control concepts. In Jiménez *et al.* [9], the control of a distillation column is addressed, as well as dealing with the tuning of PID controllers.

The present paper introduces a virtual laboratory to teach process automation using PLCs. Hence, not only the controller, but also the overall process is considered, and all the elements involved in a real installation are discussed: valves, sensors, pumps, agitators, PLCs, etc. A simulator is integrated in the PLC software CoDeSys [10] and the course students are allowed to program the PLC in order to control the virtual process.

This virtual laboratory has been used in the Electrical Engineering course of the Chemical Engineering degree and it is a mandatory component in the students' curriculum. The course described in this paper covers only the practical part of the course; in the theoretic part, general analysis of electrical circuits, transformers and machines are discussed.

The pedagogical issues addressed by using the virtual laboratory described above include:

- Introduction of common automation elements of chemical processes
- Learning how to plan an automation project
- Implementation of easy PLC programs using the different available IEC61131-3 languages
- Learning how to supervise automated processes
- Debugging and editing performed programs
- Grasping PLC automation concepts and noticing the importance of standards
- Understanding how a process simulator works.

Although the remote laboratory was devised to teach chemical engineers, it could also be used for electrical and control engineers. In some cases, the instructors will introduce some chemical and process engineering concepts, if they are not included in the curriculum of the students.

The paper is structured as follows. In the next section, the course with its corresponding sessions is explained. The virtual laboratory is then introduced. The results are discussed and, finally, the conclusions are summarized.

## COURSE STRUCTURE

The described course is the practice part of an Electrical Engineering course that has been taught

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to Chemical Engineering students. The authors consider that it is very important to include industrial automation content in the course, since chemical engineers frequently have to deal with process automation problems, and a basic knowledge in the field can be very useful. The practical part of the course is structured in six sessions: half with real systems and PLCs and the other half with simulation of chemical processes, using the virtual laboratory introduced in this paper.

#### Real-laboratory practices

In the first three sessions with real PLCs the students familiarize themselves with the PLCs and address several PLC hardware and software issues. They begin to work with the common IEC61131-3 languages: LD ladder logic, SFC Sequential Function Chart, IL Instruction List, FBD Function Block Diagrams and ST Structured Language.

The sessions have been devised to provide enough tools for the students to allow them to develop the automation of a chemical process in the following three sessions (sessions 4–6). The first three sessions are structured as follows:

- Session 1: General automation concepts are taught, including the most common elements found in automation systems: PLCs, drives, SCADA systems, communications, etc. The purpose is not to delve into such issues, but to present them briefly to the students. The students are introduced to the hardware and software of the PLCs. This is a demonstration session where the students do not perform any programming.
- Session 2: The students program a real PLC. They have to control a garage door using LD language. They can try with other languages once they have made the door work correctly.

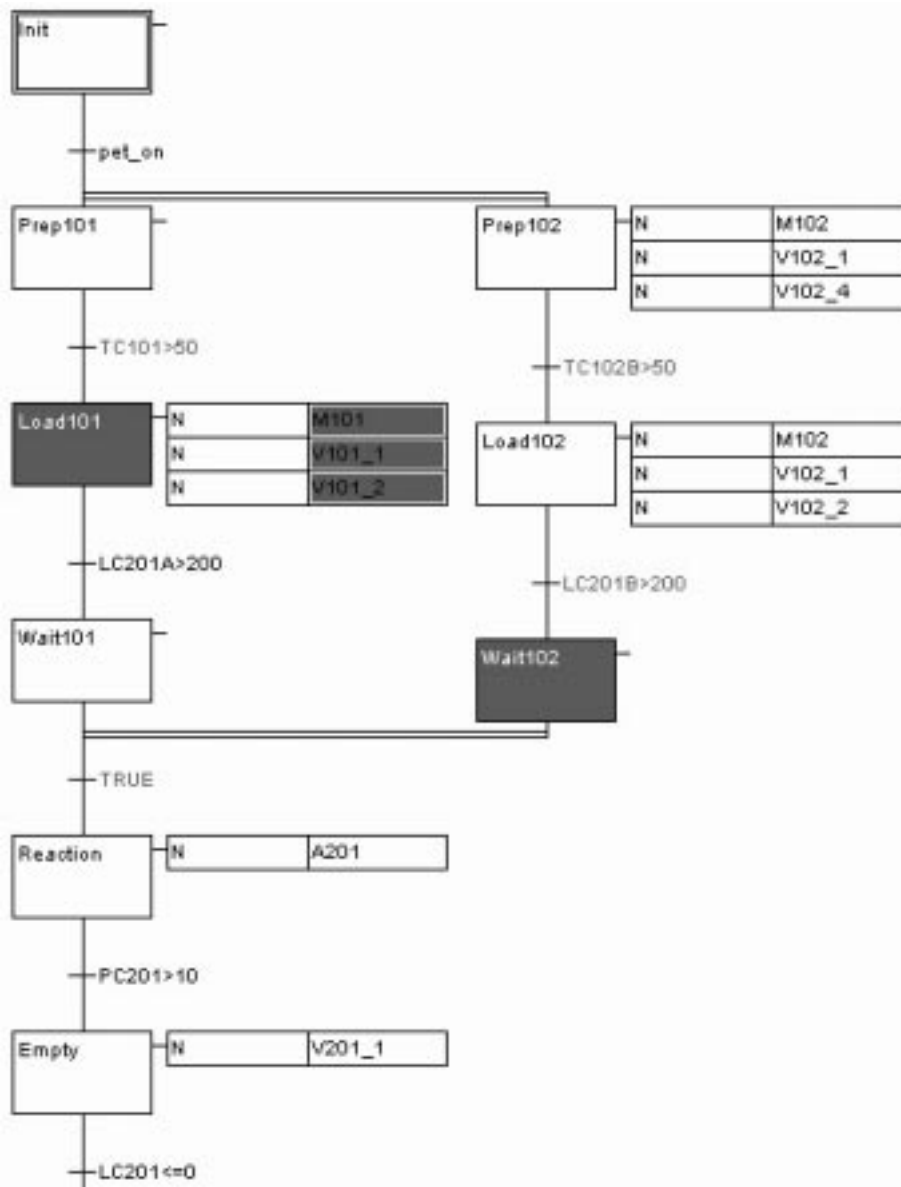


Fig. 1. Example solution program.

- Session 3: They have to automate a traffic light crossing employing SFC language.

#### Virtual-laboratory practices

In the three virtual laboratory sessions, the students become familiar with the virtual platform, but an important part of the work is to be done at home. The problem given to the students is the general automation of the chemical process. The students have to propose algorithms to control such a process. They are absolutely free to choose the language and the way to approach the solution; however they will have to defend their choice to the other students and the instructor. The three sessions are structured as follows:

- Sessions 4 and 5: Development of the chemical process control programs. The students can solve the problems that appeared while they were working at home and discuss their ideas with the instructor.
- Session 6: Oral presentations and debate.

The laboratory sessions are both developing and discussion sessions, where the students can bring up the problems they have encountered when working at home. A final project report has to be prepared by the students, to include the following parts:

- Specification of the necessary digital and analogue inputs and outputs of the PLC
- PLC Configuration
- PLC programming
- Test and simulation of the program
- Discussion of the results.

The students must prepare an oral presentation (session 6), where they put forward the points described. A discussion between students giving different strategies to solve the same problems is encouraged.

An example solution was put forward by the instructors. After submitting their own projects, the students can compare their solutions with the example. The proposed program is based on SFC (Fig. 1); however, as has been explained, the students are free to choose their programming language.

### VIRTUAL LABORATORY SETUP

#### Process

The virtual laboratory is based on the batch process shown in Fig. 2. The process consists of mixing two different products stored respectively in tanks 101 and 102. A certain quantity of each

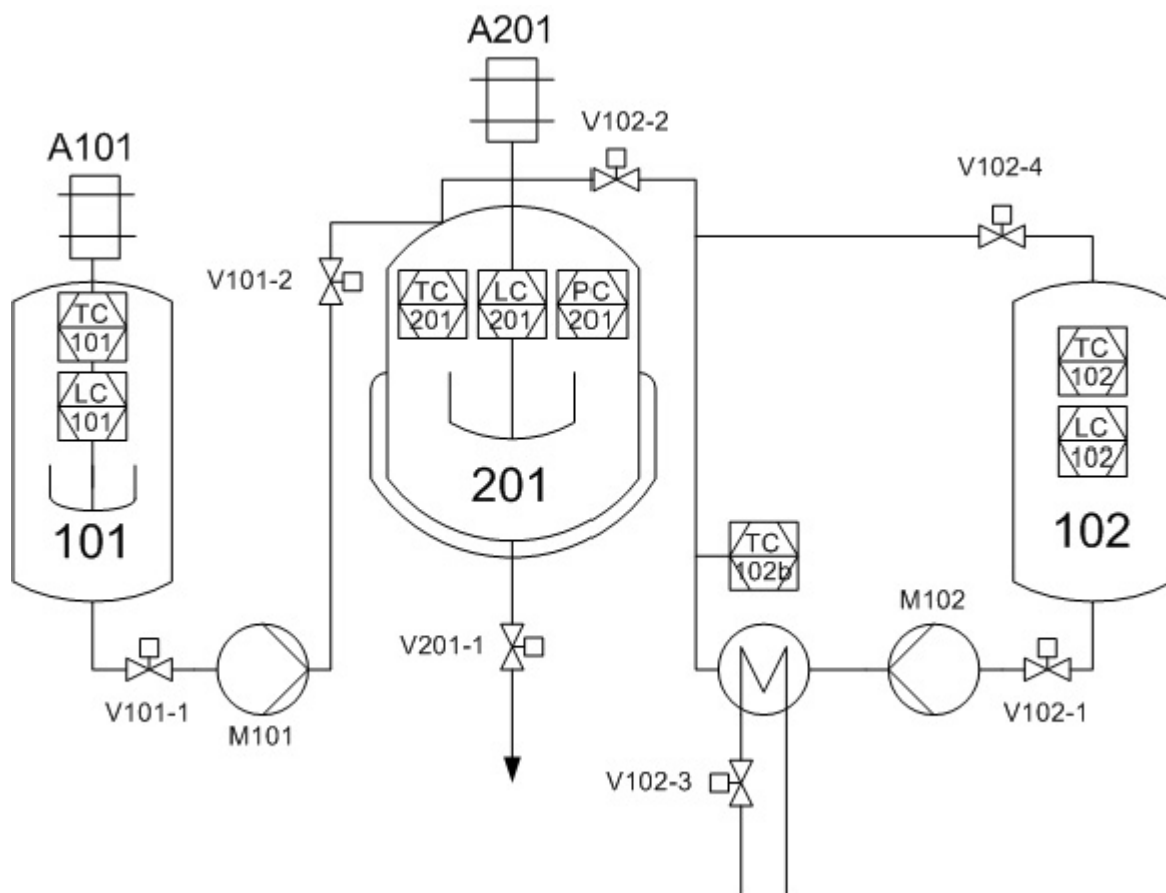


Fig. 2. General scheme of the chemical batch process to be controlled.

Table 1. Motors and valves employed

Element	Description
M101	Pump to transfer product from 101 to 201
M102	Pump to transfer product from 102 to 201
A101	Agitator of tank 101
A201	Agitator of reactor 201
V101-1	Valve between output tank 101 and input pump M101
V101-2	Valve between output pump M101 and reactor 201
V102-1	Valve between output tank 102 and input pump M102
V102-2	Valve between output pump M102 and reactor 201
V102-3	Steam valve to heat product from tank 102
V102-4	Tank 102 recirculation valve
V201-1	Reactor 201 emptying valve

product has to be introduced into the reactor 201. The products have to be introduced at a certain temperature in order to aid the chemical reaction. To this end, two different heating strategies are used. In tank 101 heat is produced by means of agitation. In tank 102 heating is achieved by means of a heat exchanger, once the product has been pumped into the reactor. Preheating is achieved by recirculating the product with a recirculation valve. When reactor 201 has been filled, the chemical reaction is started by running agitator A201; it is run until the pressure is greater than a certain threshold value. At this point, the reaction has ended and the resulting product can be delivered. The motors and valves that are used are defined in Table 1. The different sensors used to control the process are shown in Table 2. Note that the first character indicates the quantity (L Level, T Temperature, etc.) and the second character the function (C Control, I Indication, etc.).

#### PLC software

In order to control such a chemical process, a PLC is proposed to the students. PLCs are the most widely used form of control technology used in the chemical industry to control such processes, due to their flexibility, robustness and ease of modification and debugging by maintenance and engineering staff.

The CoDeSys [10] software was chosen to develop all the programs. CoDeSys is a free IEC 61131-3 [11] programming software for PLCs and industrial controllers. It is used by more than 100

Table 2. Sensors employed

Element	Description	Units
PC201	Pressure reactor 201	Bar
TC101	Temperature tank 101	°C
TC102	Temperature tank 102	°C
TC102b	Temperature after heating tank 102	°C
TC201	Temperature reactor 201	°C
LC101	Level tank 101	1
LC102	Level tank 102	1
LC201	Level reactor 201	1

manufacturers. It features programming in the different IEC 61131-3 languages, HMI (Human Machine Interface) capability and simulator.

#### Simulation

The simulation capability of the CoDeSys software allows virtual laboratories to be built without the need for any other external software or hardware. The students download the program from the course Website. The program already has a virtual process section (created by the instructors), where the real system is simulated. Hence, in the new program sections created by the students, they can read the sensors' information from the memory and write the actuation of the motors and valves. Changes in the states of the motors and valves make the sensor information change (as programmed by the instructor in the original virtual process section). The sensor, motor and valve states are defined as global variables, and hence they can be used anywhere in the program without any problem. The inputs and outputs are configured for a Wago 750-841 PLC, with the syntax `Variable AT Address : Type := InitValue;`. The configuration of inputs and outputs reinforces the feeling of reality, which is very important where virtual facilities are concerned. Part of the variable definition can be listed as:

```
VAR_GLOBAL
  EMER AT %IX12.0 :BOOL;
  (* DIGITAL INPUTS *)
  M101 AT %QX2.2 :BOOL:=0;
  (* DIGITAL OUTPUTS *)
  PC201: REAL := 1.0;
  (* ANALOG VALUES *)
  . . .
END_VAR;
```

The process simulation is executed periodically each 100 ms in order to actualize the process variables. The process variables  $x$  are computed with expressions as:

$$\dot{x} \equiv \frac{\Delta x}{\Delta t} = \frac{x_{k+1} - x_k}{t_{k+1} - t_k} = \begin{cases} k_{inc}(x_{max} - x_k) & \text{State S1} \\ k_{dec}(x_{min} - x_k) & \text{State S2} \end{cases}$$

$$x_{k+1} = x_k + \Delta x \quad (0.1)$$

where  $x_{max}$  and  $x_{min}$  are the maximum and minimum values and  $k_{inc}$  and  $k_{dec}$  are the increasing and decreasing variable rates in the presence of states S1 or S2. (S1 corresponds to an agitator that is turned on, and S2 to it turned off, for instance). A brief example of the performed virtual process programming is listed below:

```
(* Pulse generation *)
TON1 (IN:= NOT(ton1.Q) ,
      PT:=t#100MS );
IF ton1.Q THEN
  (* Temperature in 101 *)
  IF LC101 > 100 THEN
  IF A101 THEN
```

```

TC101 := TC101
+ (TC101_max-tc101)*K1_TC101;
ELSE
TC101 := TC101
+ (TC101_min-tc101)*K2_TC101;
END_IF;
END_IF;
(* Transfer from 101 to 201 *)
IF M101 AND V101_1 AND V101_2 AND
LC101 > Q101 THEN
(* Level of 101 decrease *)
LC101 := LC101 -Q101;
(* Temperature in 201 computation *)
TC201 := (TC201 * LC201+ TC101
* Q101) / (LC201+Q101);
(* Level of 201 increase *)
LC201 := LC201 + Q101;
END_IF;
END_IF;

```

The process parameters  $x_{max}$ ,  $x_{min}$ ,  $k_{inc}$  and  $k_{dec}$ , etc. are defined as constants in the program and can be modified by the user, however changing them is not recommended in order to prevent too fast or too slow variable evolution. In the initial classes, until the students have acquired a reasonable programming level, such a parameter modification is forbidden.

It is important to note that the code listed above has been performed by the instructors. The students are not required to write the simulation

code, they are required to develop the programming of the simulated process in separated sections, created by them in the chosen languages.

### Supervision

The process evolution can be supervised by the HMI utility included in the CoDeSys software. All the involved motors, valves, sensors, buttons, etc. have been placed in a single screen (Fig. 3) where the evolution of the process variables can also be noted.

## RESULTS DISCUSSION

Eighteen students, divided in two groups of nine, completed the course. The students were requested to answer (with marks 1–5) an anonymous questionnaire. The survey questions and results are shown in Table 3 and Fig. 4.

The survey results elicited some relevant facts:

- The students mainly agreed that the course was challenging and interesting and that they had learnt useful things during the course.
- They were mainly indifferent to the quality of the material and the Website employed. This will motivate an effort to improve this material.
- The students were not content with the number of practices with the real laboratory. It obeys the number of hours assigned to the practices.

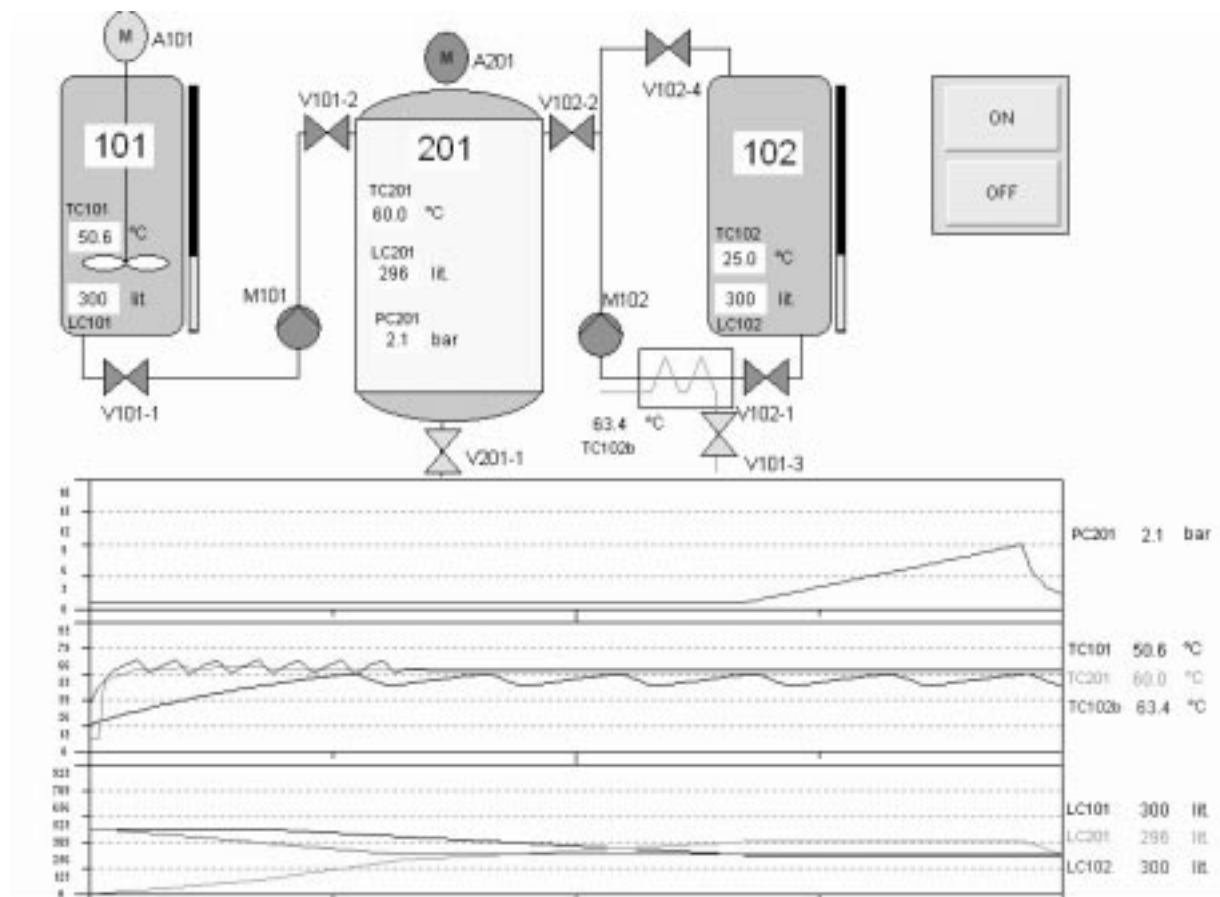


Fig. 3. CoDeSys Supervision screen.

Table 3. Survey results

Question	The marks correspond to 1 = Strongly disagree, 2 = Disagree, 3 = Unsure, 4 = Agree, 5 = Strongly agree	Response					Av.
		1	2	3	4	5	
<b>General questions</b>							
Q1	Was the course challenging and interesting?	0	0	1	15	2	4.1
Q2	Have you learned with this course?	0	0	0	12	6	4.3
Q3	Do you think you will apply the learned concepts in the future?	0	1	4	11	2	3.8
Q4	Are course materials of high quality and easy to understand?	0	2	7	8	1	3.4
Q5	Was the course Website appropriate?	0	2	11	4	1	3.2
Q6	Would you recommend this course to other students?	0	2	10	6	0	3.2
Q7	Has the practices division been appropriate? (3 with real PLCs, 3 with virtual laboratory)	0	2	2	12	2	3.8
Q8	How would you rate this course?	0	1	5	12	0	3.6
<b>Real Laboratory</b>							
Q9	There have been enough practices.	0	6	1	11	0	3.3
Q10	I have acquired the basic concepts.	0	1	0	17	0	3.9
Q11	How would you rate this practices part?	0	2	6	9	1	3.5
<b>Virtual Laboratory</b>							
Q12	It has been easy to work from home.	1	1	3	9	4	3.8
Q13	The virtual process may resemble a real industrial process.	0	0	2	14	2	4.0
Q14	The virtual process has worked appropriately.	0	0	1	13	4	4.2
Q15	The comparison with other students work has been useful.	0	1	1	10	6	4.2
Q16	How would you rate this practices part?	0	0	2	8	8	4.3

- The general opinion is that students found they could work from home without problems. Only one student disagreed absolutely with this statement, probably because of some problems with his/her computer or Internet connection.
- Students valued the virtual process performance and thought that it resembles a real industrial chemical process.
- Students enjoyed the way that the classes had been devised. They valued the fact that participation was encouraged.
- The students' marks of the overall course and

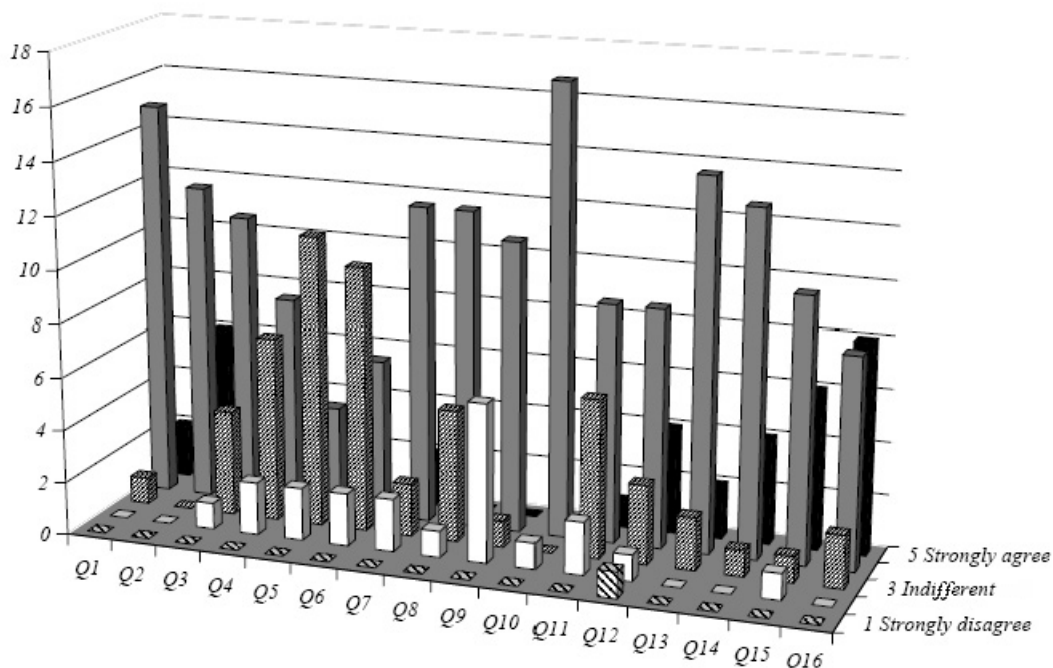


Fig. 4. Survey results.

the real laboratory were around 3.5, while the virtual practice part was rated at 4.3.

After evaluating the results, the instructors believe that the virtual laboratory had significantly improved the quality of the course. The course methodology also proved satisfactory.

The students gave an oral presentation, explaining the program they had devised and comparing it with the other students' programs. Some issues were debated, focusing on:

- Security. The different types of emergency stops were discussed.
- Process operation. Different operation modes were proposed; the concept of automatic and manual was understood differently by the different groups. The issue of stopping and restarting the process, once the operator has pressed the stop button, was thoroughly discussed.
- Refilling of the tanks. Once the batch process had ended, different ideas about refilling the tanks were proposed. Some students added elements (valves and pumps), while others assumed manual refilling.
- Resemblance to a real process. What the students can expect when confronted with a real industrial process was discussed as well as the key differences and things to take into account when automating real processes.

The debate proved to be very useful in enforcing the work undertaken by the students. They could hear the positive ideas put forward by their fellow students and agreed that if they had to program the process again they might do it differently.

## CONCLUSIONS

The present paper presented a virtual laboratory to teach chemical process automation with PLCs. A simulator was integrated in the open and free PLC software CoDeSys. The students were allowed to use the software during classes and at home, to control the virtual process.

They also learned the basic automation concepts that will be helpful in their professional careers. They not only learned how to program a PLC, but also how to plan and structure a general automation project. The opinion of the instructors, along with the survey results shows that the students' motivation was increased by the challenge to control a chemical plant, instead of a conventional process.

The authors feel that the balance between real and virtual laboratory has proved to be successful. A complete virtual laboratory would have introduced a feeling of non-reality in the students. They could grasp the advantages of a virtual laboratory, once they knew what they were doing and which devices they were dealing with.

The use of a virtual laboratory allowed the instructors to change the conventional course structure. The students could develop their programs at home and come up with implementation problems and doubts. So, classes turned into discussion sessions where the students could compare and contrast the solutions adopted. In conclusion, the experience proved to be very positive and will be repeated in the coming years.

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