Teaching PLC Program Organisation: How to Transfer PLC Best Practice Experience from Industry Experts to University Students

Ottar L. Osen
Cyber-Physical Systems Laboratory, Department of ICT and Natural Sciences (IIR), Norwegian University of Science and Technology, Postboks 1517, NO-6025, Aalesund, Norway

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Abstract: The gap between professional industry practices and academia represents a huge challenge in bringing best practices and silent knowledge from the industry to the students. Just as having a word-processor does not make you an author, knowing programming syntax does not make you a good programmer. In this paper I discuss how to transfer expert knowledge about PLC and real-time programming from the industry practitioners to the students. As a special case of interest, I investigate best practices for organising PLC programs.

1 INTRODUCTION

While teaching industrial control systems, specifically PLC (Programmable Logic Controller) programming, the author has tried to find good teaching resources on how PLCs are programmed in an efficient manner that is well suited for an industrial setting. There seems to be an abundance of resources on syntax and language specifics. However, it is very hard to find any resources that give ”best practice” advice for PLC programming based on industrial experience.

Although syntax and language specifics are necessary for a student to learn PLC programming, this is far from sufficient in order to make the student a programmer. This is analogous to knowing how to use a word processor does not make you a good author.

Whilst there are some good general resources on how to bring the practitioners experience into teaching (Schön, 2017) and about best practices for general programming (Shaw et al., 1996), they do not address how to solve PLC and other real-time programming challenges.

This calls for bringing practitioners experiences, competence and knowledge to the university. However, this is a complex task and there seem to be a lack of knowledge in the literature on how to achieve this.

This paper attempts to address this issue by presenting some advice and best practices based on the author’s own industrial experience as a case and discusses how industrial experiences can be brought into the students’ curriculum.

2 HOW TO PROGRAM PLCs

There are numerous sources on how PLCs work and descriptions of syntax and programming languages. This article focus on explaining how to utilise the PLC in an optimum way by making sensible abstraction levels for the different actors involved in engineering, construction, commissioning, maintenance and day to day use of a PLC controlled ”machine”. In this context ”machine” could be anything from a simple start-stop logic for a motor that controls your garage door to a complete control system for complex systems such as a chemical plant or an offshore oil platform. In between these extremes, you find smaller ”machines” such as elevators, cranes, robot cells, CNC (Computer Numerical Control) machines, vehicles and a wide range of standard and specially made mechatronic equipment in the processing and manufacturing industries.

Obviously, as systems grow more complex the importance of good software development standards increases. However, even for small projects adherence to the principles outlined below will have significant cost-saving benefits.

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2.1 Actors and Project Phases

In the discussion below the term ”project” is used to describe the life-cycle of a machine/plant, from engineering to decommissioning. Whether the owner actually organised it as a project or not doesn’t matter for this discussion.

In Table 1 the different project phases are outlined. For large projects one can define even more phases and for smaller ones some of the phases can merge together. The breakdown in Table 1 will suffice in order to describe the concept.

Table 1: Typical project phases.

Phase	Typical activities
Concept study	Idea development and feasibility study
Pre-engineering	Decide on important design criteria
Engineering	Detail design
Construction	Building
Commissioning	Testing and verification of sub-systems
Startup	Verifying total system performance and debugging
Operations	Day to day normal operations.
Maintenance	Scheduled repairs and modifications, and ad-hoc repairs
Decommissioning	Deconstruction at end of life.

In a project, there are typically a significant number of actors/roles. The number of actors and roles depends on the size of the project. For a simple machine, there could be a single PLC with a simple panel or GUI (Graphical User Interface), whilst on a chemical plant, there would be a large number of PLCs that are interconnected with advanced Graphical User Interfaces (GUIs) and mimic panels. These larger systems are often called SCADA systems (Supervisory Control And Data Acquisition)(Boyer, 2009). Table 2 lists some of the actors that in some way use or program the PLC / SCADA system.

In Table 2 I have assumed that levels 1–5 are personnel that the owner of the machine/plant has in-house and that levels 6–9 are personnel that are brought in to the project as needed from a PLC or system vendor but this may also vary depending on the size of the project, the company and its outsourcing philosophies. The table is meant to be indicative as to PLC programming competence and the essential part is to realise that there are different levels of competence among the actors.

With reference to the project phases outlined in Table 1 the skills and competence needed vary both with respect to project phases and machine/plant complexity/size.

In Table 3 typical PLC competence levels are outlined for different project phases and machine/plant complexity/size. In this case, I have had a fairly big project in mind and often this would be scaled down and simplified for smaller projects.

2.2 Programmatic Consequences

In order to lower development and maintenance costs, it is important to organise the code in such a manner that as little PLC knowledge is needed in order to diagnose problems, verify signals, make small modifications and extend an existing solution. Re-use of existing code is also cost-saving and requires adherence to good coding standards.

In the following, the main idea is that experts make thoroughly tested ”code templates” that less skilled personnel can use and connect to the required inputs and outputs. This often results in a graphical program that connects blocks to inputs and outputs and can be maintained without extensive PLC knowledge. The internal contents of the blocks will often be quite advanced code which must, if needed, be maintained by personnel with extensive PLC programming knowledge.

3 PLC PROGRAMS VS. OTHER PROGRAMS

In the industry and in academia there is an ongoing discussion about whether to program using a PLC, or traditional high-level languages on industrial PCs or controllers. Although this is a long discussion with many elements I will outline some of the most important aspects below.

3.1 Differences

In some ways, programming of PLCs specifically, and real-time systems generally, differ significantly from other types of program development. The most prominent difference is the ”no-wait outer loop.” A fundamental idea of real-time programs is that

Table 2: Typical actors and knowledge.

Level	Actor	Knowledge
9	Vendor expert	Expert PLC knowledge
8	Vendor senior engineer	Very good PLC knowledge
7	Vendor system engineer	Very good PLC knowledge
6	Vendor support engineer	Good PLC knowledge
5	Senior system engineer	Good PLC knowledge
4	System engineer	Basic PLC knowledge
3	Electrical tech	Electric terminations and hardware
2	Senior operator	Advanced use of GUI
1	Operator	Basic use of supplied GUI

Table 3: PLC competence matrix.

Phase	Level								
	1	2	3	4	5	6	7	8	9
Concept study					●		○		
Pre-engineering		●			●				
Engineering		○	●	○	●	○	●	○	○
Construction	○	●	●	●	●	○	○	●	○
Commissioning	●	●	●	●	●	●	●	●	●
Startup	●	●	●	●	●	●			○
Operations	●	●	●	○					
Maintenance		●	●		●	●	○	○	
Decommissioning		○	●	○					

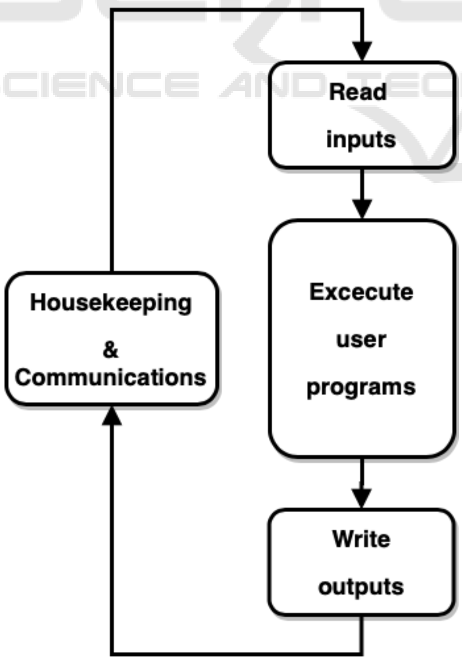


Figure 1: PLC execution loop.

the program should never wait in local loops for events/inputs to occur. The program should run as fast as possible (free-wheeling) or at a desired frequency (cyclic), and only actions whose conditions are met will be processed. Hence, the waiting time for the actions is spent on evaluating conditions and processing actions whose conditions are met. This approach ensures that no actions are starved to death and that the outer main loop is run at sufficient frequency. In addition, many systems support event triggers/interrupts and some support the use of threads.

A notable feature on most PLCs is special processing of the IO. The IO pins consist of input ports and output ports, which may be both analogue (varying from 0–10V, say) or digital (either 0 or 24V). The IO is processed in such a way that inputs (input ports) are scanned into memory (variables) at the start of the main cycle and output variables are written to the outputs (output ports) at the end of the main cycle, see Figure 1. Hence, a PLC waiting for an input to change its value in a local loop makes no sense since the input will not be updated before the next start of the outer loop. This concept is of course well known among real-time programmers and PLC programmers, but for programmers of non-real-time systems and for those who have no experience with PLCs this may be unfamiliar and cause fatal programming errors.

3.2 Why Choose PLC?

As I will discuss further in the following sections the PLC with its richness in programming languages, including graphical ones, and ease of use enables significantly reduced costs. This is because the PLC offers the possibility for doing simple modifications, error corrections and fault diagnosis. In a bigger project, the PLC approach gives reduced man-hour costs since people at different skill levels may be used for different tasks and in different stages of the project, while for traditional programming staff will need to be highly qualified to do even minor changes. This will be discussed more thoroughly in the next sections.

As an example of the PLC's ease of maintenance and diagnostics the ability to see live logic levels as coloured lines in a logic diagram is a powerful diagnostics tool (see Figure 7). A graphical representation like this which is updated live is much easier, even for experts, to debug than the tools normally available for high-level general languages. Since PLC programming languages are specially designed for writing real-time programs they lack most of the general functions that we are used to in other programming languages such as formatting of text, graphics, user input and so on. On the other side the PLC has built-in support for task scheduling (timed, free-wheeling and triggered), event prioritising, state machines, parallel and conditional execution and so on.

In addition, due to the standardised and somewhat limited instruction sets the chances of making serious design mistakes are reduced. This claim is backed by the difference in safety requirements when applying computer-controlled systems in a process/machine. According to IEC 61508 (IEC, 2010), a project that uses a PLC in a process plant will typically be allowed to follow the IEC 61511 (IEC, 2020) due to its "limited variability languages," whereas a project that uses a PC or a controller programmed in a traditional low or high-level language (variability languages) will have to adhere to the stricter IEC 61508.

There are of course many other pros and cons for both approaches but these are the most important ones with respect to the focal points for this paper. For a detailed presentation of object-oriented control design see Young et al. Young et al. (2001)

4 OVERALL STRUCTURE OF PLC PROGRAMS

In the literature, there is a lot of recommendations on how to organise computer programs in general (Shaw et al., 1996). Many of these are also valid for PLC programming. One might find that PLC programmers and programmers of high-level programming languages tend to cluster in two groups with different practices. Both groups could probably benefit from studying each other's practices.

In the following, I will address some specific recommendations for PLC programming. These are in addition to the recommendations for general programming and not meant to replace these, although one should note that some of these recommendations may be in conflict with each other. In such cases, one must inspect the reasoning behind the recommendations and weigh the advantages and disadvantages against each other.

4.1 PLC Languages

The IEC 61131-3 standard (IEC, 2013) defines 5 languages:

- IL - Instruction List
- LD - Ladder
- FBD - Function Block Diagram
- ST - Structured Text
- SFC - Sequential Function Chart

In addition, CoDeSys and other implementations of the standard may have additional language support such as CoDeSys':

- CFC - Continuous Function Chart.

Different programming languages have different advantages and limitations. Hence, it is not a good idea to choose a favourite and stick to it. One should use the language best suited for the purpose.

As an example, a 2 out of 3 (2oo3) voting scheme is implemented (with identical functionality) in IL, LD, FBD, CFC and ST for comparison as shown in Figure 2.

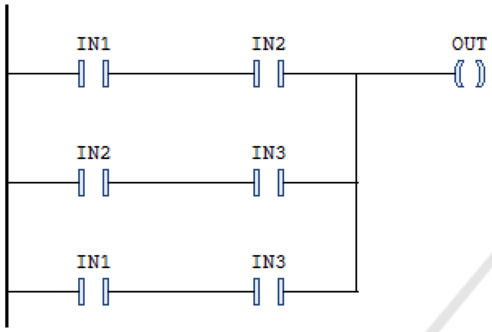
Program units are called POUs (Program Organisation Units), of which there are 3 main types:

- Programs
- Functions
- Function blocks

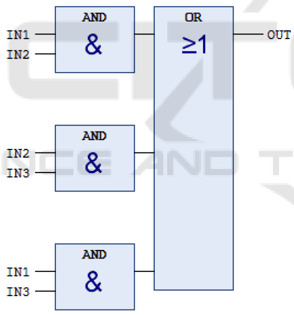
Programs are the main units, they are directly executable and are similar to programs in other languages. Functions are similar to functions in other languages and they have no persistent memory. Function blocks are similar to classes in other languages, they must be instantiated and they have persistent memory.

```
LD      IN1
AND     IN2
OR(
LD      IN2
AND     IN3
)
OR(
LD      IN1
AND     IN3
)
ST      OUT
```

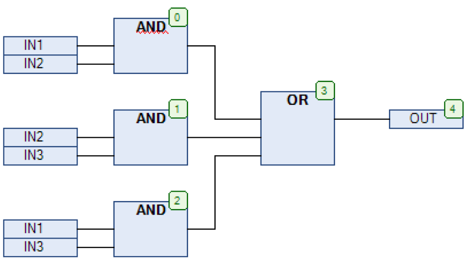
(a) Instruction List (IL).



(b) Ladder (LD).



(c) Function Block Diagram (FBD).



(d) Continuous Flow Chart (CFC).

```
OUT := (IN1 AND IN2) OR (IN2 AND IN3) OR (IN1 AND IN3);
```

(e) Structured Text (ST).

Figure 2: 2oo3 voting implemented in different PLC languages.

```
VAR
    IN1: BOOL;
    IN2: BOOL;
    IN3: BOOL;
    OUT: BOOL;
END_VAR
```

Figure 3: Variable declaration for all programs in figure 2.

A typical application setup would be programs that read inputs, connect these to functions and function blocks and connect the outputs from the function blocks to the PLC outputs and/or show results on a GUI.

The term instrument is used as a general term for equipment such as sensors and actuators. For example, an instrument could be a temperature sensor, a pressure gauge, a proximity switch, a valve, or a pump. Typically you would group similar instruments into groups and make suitable function blocks for each group. Thereafter you would instantiate copies of the needed function blocks for each individual instrument. For instance, 40 analogue sensors, 15 pushbuttons, and 20 indicator lamps, say, would typically require 3 different function blocks (one for each group of instruments), with 40, 15, and 20 instantiated copies of each, respectively. Even if the 40 analogue sensors consisted of a mix of pressure and temperature sensors and these again have different ranges, the function block should be parametric in order to handle different ranges, alarm limits, or other characteristics.

Finally, there are many cases where several instruments work together in what is often called ”a loop.” As an example, a valve is typically controlled by one output to its actuator and 2 inputs, feedbacks, indicating the valve position. For example, such a valve could be part of a tank level control loop. A tank controller would typically be connected to one level sensor and one valve (see Figure 4). Hence, we actually have one loop (the valve with feedbacks) inside another loop (the level control loop). The PLC program to control this inner and outer loop is shown in Figures 5 and 6.

4.2 Which Language to Use?

The main program(s) should be organised in a suitable number of subprograms according to the size of the machine or plant. These programs should be in a graphical language such as FBD, CFC, LD or SFC.

Since most machines or plants typically will need some kind of state machine it is advisable to employ a master Structural Flow Chart (SFC). Even a simple machine would typically benefit from some code running at startup in order to make sure the process is

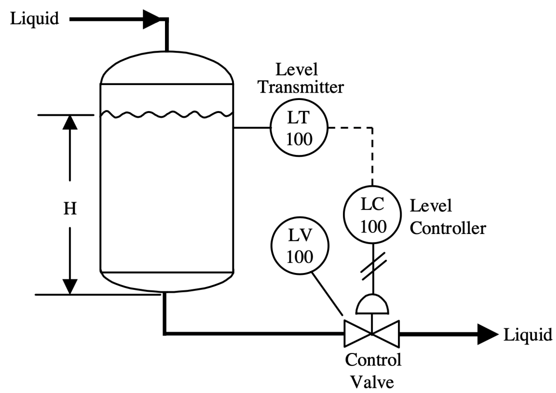


Figure 4: Tank level control example (Hughes, 2007).

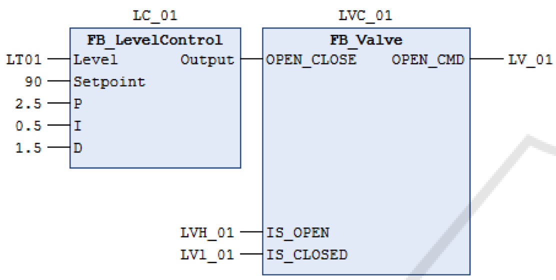


Figure 5: Tank level control programmed in FBD.

ready for normal operation (calibration, making sure mechanical parts are in the correct start position, etc.). Furthermore, after the normal operation is complete it is typically useful to bring the machine to a safe condition and ready for another start (this could also include cleaning and other operations). Hence, even a very simple machine would have at least 3 states: Startup, Operation, Shutdown. SFCs make debugging simple since it will be possible for the service engineer to see which state the machine is in. Inside an SFC, in the state blocks, one may use any of the languages and even an SFC itself.

Often, when looking for errors, the first action is to inspect the inputs and outputs of the PLC. Sometimes it is useful to measure the inputs and the outputs physically on the PLC whit a VAR meter, but often it is sufficient to inspect the signals in the program. All the graphical languages support indicating logical values with different colours etc. and variables are readily available for inspection. Hence, debugging and fault finding at the IO level becomes easy even for non-programmers since you can graphically see what is happening (see Figure 7).

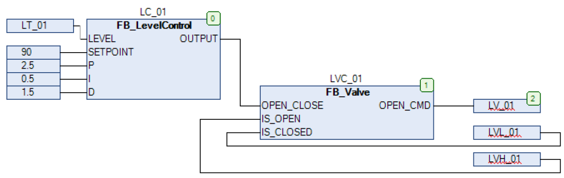


Figure 6: Tank level control programmed in CFC.

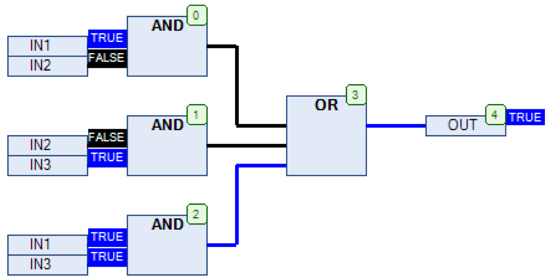


Figure 7: Debugging using CFC.

FBD and CFC are quite similar, however CFC gives more freedom when it comes to layout. Since FBD and CFC resemble logic diagrams very well this is a good way of representing logic and to show connections for engineers who have some knowledge of logic diagrams.

LD, on the other hand, resembles electrical wiring diagrams and is well suited to show relay logic. Hence, LD is suitable for electricians and made probably more sense historically when the PLC was seen as a relay replacement.

ST is the best for complex tasks. However, in order to keep the main program simple, it is good practice to move complex code into functions and function blocks and keep the main program(s) in graphical languages.

Finally, IL is an assembly-like programming language and is an unlikely candidate for anything unless execution speed or memory limitations demand the use of IL. In the case of automatically produced code Estévez et al. (2007) (from databases or similar), IL would be a preferred language since its simple syntax is easy to implement. All in all, IL is just for special use and in the latest versions of CoDeSys the user has to enable IL in the configuration settings, by default it is not available.

For functions, the choice of language depends on the problem at hand. If the problem may be easily described in logics then FBD, CFC or LD could be good candidates, but otherwise usually ST is the best choice.

For function blocks, since they normally are more complex, the most common language will be ST. However, since function blocks often will require a state machine, it could be useful to put the ST code inside SFC blocks.

5 KNOWLEDGE TRANSFER FROM INDUSTRY TO ACADEMIA

The challenge of transferring best practices from the industry to the students is at least two-fold: identifying the best practices and finding a suitable vessel for transport to the minds of students.

Schön (1987) has studied how practitioners learn. This arises interesting questions such as how educators learn, what is the differences in information versus knowledge; education versus training; learning versus teaching.

5.1 Identifying Best Practices

It is a common conception that industry and academia is two worlds with (too) few connections. So how can academics identify the best practices? Teachers taking sabbaticals in companies would help teachers to gain access to this ”hidden” knowledge. Since this knowledge is hidden or implicit (Frappaolo, 2008) it may not be easy to identify or to articulate. Some skills are hard to put into words, such as riding a bike or a swing. Berry (1987) states *”The fact that much of an expert's knowledge is implicit or tacit in nature is a major problem for those working in the area of knowledge elicitation.”*

Another possibility is for the university to recruit people with professional experience from the industry, both in temporary and permanent positions. The latter requires universities to change their job candidate evaluation procedure to include non-academic achievements.

5.2 Vessel for Knowledge Transfer

In most subjects, the methods to achieve learning goals vary depending on what the goals are. One popular system for this is constructive alignment (Biggs, 1996). Transferring best practice from industry to students is not different in this respect. However, an important keyword here is practice. Only hearing or reading about best practices will probably be insufficient and ineffective since a lot of this knowledge often is hidden/implicit/tacit and of a more practical and non-theoretic nature. Schön (1987) states *“I have come to feel that [the] only learning which significantly influences behavior is self-discovered, self-appropriated learning.”*

Guest lectures, case studies and selected industrial challenges are ways to achieve this kind of awareness with the students. Likewise, a selection of carefully crafted exercises, assignments and projects that are closely linked to an industrial setting could help illuminate the importance of the best practices. However, the scale of systems found in the industry will often be significantly bigger than what we are able to recreate in university laboratories. Thus, it can be hard to find means to scale exercises in a way fitting to the university context and at the same time bringing forward the challenges of large scale systems.

Compacting years of industrial experience into information that students can digest in a short time is very challenging. In an industrial setting, a task can be difficult either because it is technically challenging or because it has a huge volume (a lot of data, equipment, tools, etc., or a lot of connections). In a teaching setting the former can more easily be adapted to the students' competency levels through making the industrial problems the basis for exercises with sufficient guidelines etc. The latter, big volume, is harder to copy. How could we copy a big industrial setting to the classroom and achieve anything in a short time? Obviously, some scaling is needed. One idea could be to carefully design a number of closely related assignments given to groups of students that together formed a single large project.

Probably, in some cases we will have to accept that there is no shortcut to gain experience, ”you have to walk the walk”. However, in many cases, there are ways to accelerate the process. One important tool could be the use of hardware-in-the-loop (HIL) simulation equipment (Schlager, 2008). HIL enables students to gain experience from controlling equipment that is normally not possible to operate on in a university setting. The author has experimented with using HIL in PLC teaching by employing a HIL valve simulator (Osen, 2019). A similar approach has been used by De Farias et al. (2019) and Shiakolas and Piyabongkarn (2003).

6 FURTHER WORK

In order to complete this study on program structure, I am planning to write a follow-up article on how function blocks should be designed. Thereafter it could be useful to describe good practices on how to divide a large project plant into sections with a focus on programming, communications, reliability and safety.

On a more general level, it would be interesting to research in more detail different methods to transfer knowledge from the industry to the students, both from a PLC or real-time programming perspective and a more general computer science perspective.

7 CONCLUSIONS

There is a gap in the literature when it comes to best practices in PLC and real-time programming. In this paper, I have investigated the case of PLC program organisation. This illustrates the kind of information that is typically acquired at the workplace and often after a significant time. The challenge is how to relay this information to the students. Below are some take-home messages from this case.

In order to reduce development and maintenance costs, it is important to be able to re-use code and that troubleshooting and maintenance can be done without the need of experts. This can be achieved by following these guidelines:

- Divide the program into subprograms dependant of the size of the project.
- Make the main programs simple and easy to maintain.
- Use a graphical program for the main program where inputs and outputs are connected to function blocks.
- Make the main program well suited for troubleshooting.
- Use a graphical program wherever possible (simple programs and logical problems.
- Respect the real-time properties and avoid internal loops- Don't use IL unless absolutely necessary.
- Don't use LD unless the program needs to be maintained by electricians without much knowledge of logic diagrams.
- Make function blocks that have parameters to support different uses.
- Put complex code and hard to maintain code in function blocks.

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