COMPETENCIES-BASED LEARNING MODEL DEVELOPMENT FOR A CYBER-PHYSICAL SYSTEMS IMPLEMENTATION

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ABSTRACT

We might wonder about the professional motivations that drive students to pursue electromechanical (EM) engineer graduate studies. In this sense, we approach the notion of professionalization not only in the field of work, but also in the field of education, so that teachers and learners confront work situations and articulate work and training more closely within the framework of multiple specialisations in a dynamic environment. In this framework, a Competencies-Based Learning (CBL) approach was developed to list, prioritise, and complement competencies of the reference job repository of an EM engineer with the learning outcomes to cover the training areas through the specified curricula (Standards 1, 2). These competencies were transformed during the developing process of a learning factory established by a Cyber-Physical Systems (CPS) to meet the training needs of an EM engineer in a pedagogical environment faced with a professional situation (Standards 5, 6, 7). For an EM engineer, we study the different situations encountered and experienced by the learner and draw up a list of specific professional skills encountering different layers of the pyramid of automation and industry 4.0 by referring to our technological installations within spaces set up for this purpose. A synergistic process between the different technological layers has been set up to support the learning process to match the targeted learning outcomes through the technological aspect defined via the CPS platform in an iterative process (Standards 3, 4, 8). Thus, a modular CPS platform is adapted to an engineer work environment and fed by real industrial projects ensuring knowledge, skills, and attitudes necessary to CDIO framework implementation.

KEYWORDS

Competencies-Based Learning, Cyber-Physical Systems, Professionalization, Electromechanical Engineer, Integrated Learning, Standards: 1, 2, 3, 4, 5, 6, 7, 8

INTRODUCTION

Faced with students' preoccupation with teaching practice, we might well wonder about the professional motivations that drive them to pursue graduate studies. Are they really looking for training in scientific research when they can also be trained in work situations in their academic environment? In this context, we approach the notion of professionalization not only in the field of training, but also in the field of work, so that teachers and learners confront work situations and articulate work and training more closely within the framework of multiple specializations and in a dynamic context. This paper is structured as follows. First, we describe the CBL approach implementation for CPS education. Indeed, we follow-up pedagogical research of the EM department to integrate its CBL approach into its curricula. For a CPS model competencies are crossover for a better professional integration. The second session concerns the CPS competencies generation for a pedagogical scheme implementation. A case study session is developed to lead to a discussion of primary results. Finally, we conclude the main work and give insight into few perspectives.

CBL APPROACH FOR CPS EDUCATION

To analyse this dialogue between the different situations encountered by the teacher, it is necessary to trace the epistemological logic underlying the training system and the constituent elements of its "professionalizing" structure, studying the different situations encountered and experienced by the learner and drawing up a list of specific professional skills. In this sense, we note the aspirations of EM engineering students in relation to the skills required by the job market. In this way, a professionalization action enables the implementation of the skills in the referential through involvement in the action. To this end, we conducted a study based on a competency-based approach inspired by the work of Rezende et al., (2023) who resigned the CBL approach with the CDIO framework.

Electromechanical CBL Approach

Thanks to an international market study, we have compared the competencies of the reference job repository of an EM engineer with the learning outcomes to try and cover the training areas. To this end, the Electromechanical Monitoring and Steering Committee (MSC) conducted the study by developing a space for construction and exchange between teachers. The committee ensured the adequacy between the training and the professional profiles so that an engineer fulfills this role in an efficient way. The analysis of the results of the market survey, conducted with professionals, showed consistency between the established skills and a complementarity and continuity ensured between the different modules taught. We also took care to establish the link between skills and learning outcomes on the one hand and learning outcomes and activities on the other. A competency framework has been established. The MSC compared the skills of the generated reference system and its components with the learning achievements to try to cover the areas of training. Indeed, a work on competencies' census, crossover and integration was launched to take charge of the skills targeted in the training through the learning achievements that evoke the heart of the EM curricula. To support the competency-based approach, we have identified the micro-competencies of professional situations, through graduates' testimony and final grade students' skills profile in their work situation. Thus, we support feedback for associated training situations' generation. To align our approach with the targeted professional skills, we declined EM engineer profile throughout curricula, mainly focused on the CDIO framework for the mechanical, electrical and information sciences sectors, particularly to deal with complex and modern issues. Through this work, we have made sure to establish the articulation between skills and learning achievements on the one hand, between disciplinary fields and professional profiles and finally between learning achievements and learning activities. The proposed CBL approach delivered these skills and enables us to set up reliable and effective learning paths. In fact, the method implemented is an organizational model designed to target and evaluate professional skills while optimizing human and material potential. This method allows us to predefine our needs and to make the student aware of the relevant professional competencies while allowing to visualize the inputs of his activities, its outputs, and its multidisciplinary impact by knowledge, attitudes and acquired skills according to the project and the level of the learner throughout his studies.

Competencies crossover through a CPS model

Industrial sectors are quickly implementing the industry 4.0 vision and related technologies to capitalize on the development of intelligent cyber-physical systems and operations. Some industries, like manufacturing, have made headway in creating digitalization plans, executing pilot programs, and bringing the industry 4.0 concept to life. Although CPS engineering is an emerging field, industry and society have defined their expectations and requirements for establishing CPS education and qualifications that engineers need to have to succeed in their profession, and what knowledge and skills are not sufficiently developed after completing engineering education (Francalanza et al., 2017; Kannengiesser et al., 2021; Meng et al., 2023; Thramboulidis, 2015; Törngren et al., 2017; Wu et al., 2019). The unifying conclusion drawn from these researches is that CPS engineers require a thorough understanding of CPS, strong foundational knowledge of CPS engineering, and a strong set of social and methodological abilities. Other research of the CDIO community provide an overview of anticipated educational needs, the current state of the art in education, and an analysis of the subject of CPS to comprehend the implications for education. Indeed, recent studies highlight critical issues in curriculum design, such as balancing depth and breadth, theory and practice, academic and industrial needs, and core technical skills with complementary skills (Mäkiö et al., 2021; Meng et al., 2023; Rezende et al., 2023; Yudin et al., 2021; Zabasta et al., 2020). To acquire these skills, the engineering student must study the fundamental subjects and the engineering sciences with in-depth studies proposed for different optional specific courses starting from the first year of engineering cycle. The student accrues fundamentals and practical skills of the generated competencies as part as the developing process of the CPS pedagogical platform as part of CDIO 6th Standard (Kulkarni et al., 2020; Martseva et al., 2021; Rezende et al., 2023; Yudin et al., 2021).

Based on our CBL approach, CPS competencies throughout an EM engineer's curriculum were identified. Thus, learning paths with several level of depth were developed and implemented. In fact, Table 1 describes the evolution of skills generated when moving from one learning level to another from the first to the third grade. Each course requires a specific competencies acquisition path (Understand and master, Design and innovate, Act, manage and implement, Transversal skills). In this way, we represent a cross-reference of the main skills generated with their rate of intervention in each course of the CPS chain throughout the learning cycle. The rate of intervention is cross-referenced with the level of depth required to acquire a given competency. The "+" mark describes the importance of this cross-reference, so that "+" and "+++" represent the lowest and the highest level, respectively.

Table 1. Main courses for CPS chain implementation and Competencies crossover

Learning grade	*CPS courses /Competency*	*Understand and master*	*Design and innovate*	*Act, manage and implement*	*Transversal skills*
1st	Electrical systems	+++	++	++	+
1st	Additive manufacturing	++	+++	++	+
2nd	Quality control	++	+	++	++
2nd	Robotics	++	++	++	++
2nd & 3rd	IoT & Mobile robotics	++	+++	+++	++
2nd & 3rd	Automation & Supervision	++	+++	+++	++
3rd	Sustainable energy	+	++	+++	+++

For each course, a scenario for implementing the learning path is generated to match the targeted educational objectives through the technological aspect defined via the CPS platform in an iterative process throughout the curricula. Indeed, targeted competencies are identified for the appropriate learning situation throughout a recommended skill's level spectra for a reliable implementation. In fact, Table 2 below shows a corresponding approach for the "Electrical systems" course, described above. Learning-teaching paths are generated for a reliable technical-pedagogical CPS implementation. Moreover, to respect the distribution of technical skills and their chronological and practical aspects, we set up an integrated professional learning path with its own pedagogical implementation for an integrated learning experience (CDIO Standard 7).

Table 2. Extract of electronic learning-teaching path for a specific skills' level

A learning outcome	*Skill level*	*Learning situation*
Ability to model physical phenomena related to electrical energy production, transportation, distribution, conversion, storage, and management	Know the standards of electrical networks	Interactive course
	Understand a specific electrical diagram	Problem based Learning
	Create an electric installation based on specifications	Project
	Evaluate compliance of an electric installation standards	Peer review

This work is carried out for each learning outcome integrated into each course through the CPS learning path to align the training objective, learning situation and teaching methods.

CPS COMPETENCIES CROSSOVER FOR PEDAGOGICAL IMPLEMENTATION

At this level, the aim is no longer to start from a specialist issue, but rather to map out a learning path and the acquisition of well-defined skills based on the CDIO framework.

CDIO Standards for CPS Education

The particularity of the CDIO approach lies in the practice-oriented training of engineering students, which is the very purpose of this study, which describes the development of a method for setting up a practical CPS workshop based on a CBL approach. In fact, the main objective of modern technical education is to train students for successful professional activity, by developing their professional skills through targeted and concrete learning activities.

The implementation of the CDIO framework in the ESPRIT electromechanical workspaces through the CPS via the Siemens Tia portal presupposes the improvement of engineering education at international level, delivered in the regular context of industrialization of real systems. Through CPS, students develop skills in the design, implementation, and operationalization of processes, and apply theoretical knowledge in real engineering practice, solving educational and practical tasks for the design and creation of products and systems integrated into the curriculum. In fact, the first standard presents the concept of CDIO and assumes that what should be taught in engineering schools depends on how complicated an engineering task is as demonstrated throughout our process. Further, the standards for educational outcomes are stated in Standard 2. This component has been upgraded and changed using the CBL approach to better prepare for engineering challenges. As per Standard 3, the curriculum that has been designed is integrated, meaning that it incorporates connected disciplines and a tight plan for incorporating interpersonal and personal competencies with product, process, and system design abilities. The existence of an initial "Introduction to Engineering" course in the educational program is defined by the Standard 4, which lays the groundwork for the engineering practice's decline in a variety of pedagogical scenarios that lead to the CPS platform's pedagogical objectives.

From a practical point of view, the curriculum of a CPS educational program includes more than seven projects (Robotics, Supervision, IoT, Advanced automation, automation, 3D printing, Quality control, etc.) at the basic an advanced level (Standard 5). In fact, the CBL approach is based on integrated projects as a means of consolidating basic science and reducing the gap between theory and practice. Indeed, the requirement to provide enough workspace for students to gain practical engineering, social interaction, cooperation, and independent work skills led to aim the Standard 6. This standard serves as our final basis for building these collaborative places, as we covered in section *Pedagogical implementation through a collaborative model.* Besides, Standard 7 requires that throughout our CPS implementation to refer to instructional strategies that support the development of engineering, interpersonal, and personal capabilities in addition to skill acquisition for integrated learning strategies as well as for active and successful practice-oriented approaches (Standard 8).

Technical-Pedagogical implementation

The place given to full-scale, accompanied experiential learning regarding future professional skills. The approach is aligned with the corresponding industrial-scale processes and systems, and the respective skills required for development and operation. The approach described has been validated by application in a team project at university as part of an EM engineering robotics, automation and supervision modules. To implement the practical aspects of the CPS, hardware and software products have already been implemented in collaboration with the Siemens Automation Cooperates with Education (SCE) for a “Totally Integrated Automation” (TIA) Portal installation (Figure 1). Under this program, students and teachers have the opportunity to get “Advanced” or “Expert” Siemens certifications. To align professional required skills with workshop learning situations, a realistic model-scale process was selected from among others and enhanced to suit the dedicated learning objectives. Indeed, the CPS pedagogical implementation strategies are based on the CBL approach and pedagogical alignment already developed in section *Competencies crossover through a CPS model*. The CPS line was built around the operative part as illustrated in Figure 1 and based on four processes as shown in Table 3.

The laboratory workstation is controlled by a personal computer via a USB interface, using either off-the-shelf software tools or software created through advanced integration in the field of graphics programming. To ensure pedagogical and technological consistency, the two main parts of the cyber-physical platform have been developed. In fact, the “Cyber” part is implemented through “The Industrial Performance Starter Pack 4.0” (Figure 1.a.). It enables students to test value through use, and thus accelerate their thinking on use cases that will improve the industrial performance of the case studied. The “Physical” part of the CPS platform is the robotic cell “MITSUBISHI RV-2FR-D-S25 6-axis system” (Figure 1.b.). It is the most complex and flexible handling device in an industrial environment upgraded with RFID, Energy Meter, and a servo drive Sinamics S210 for industrial automation systems simulation. By another hand, collaboration between technological aspects has been integrated through digital twins. This technological framework has enabled a multidisciplinary approach removing the barriers between different CPS courses previously described in Table 1.

a. Cyber Part - Industrial Performance Starter Pack 4.0

b. Physical Part - Robot 6-axis System

Figure 1. The operative part of the CPS platform via the TIA Portal and the SCE for pedagogical implementation

For instance, the practice scenarios in Table 3 are based on guidelines. The illustrated learning paths involves Additive Manufacturing (3D printing technology), followed by a robotized assembly line, to parade assembled parts according to specific patterns onto a part quality control platform via a manufacturing execution system with the intervention of an autonomous robot system that manages a supply store for inventory management. Each practice session is divided into several sections. Each section is made up of several practical workshops that include theory, homework, practice, and instructions to cover the learning outcomes. Preliminary design work precedes each workshop, helping the student to better understand the operation of the elements studied. The "+" mark describes the CPS competencies fulfilment, so that "+" and "+++" represent the lowest and the highest level, respectively.

Table 3. Rating of processes regarding CPS for competencies fulfilment

Process regarding CPS components	*Physical*	*Data Acquisition*	*Cyber*	*Feedback/ Control*
Additive manufacturing (3D printing technology)	+++	+	+	++
Robotic assembly line	+++	++	+	++
Quality control of parts via a Manufacturing Execution System	++	+++	++	+++
IoT and Autonomous robots	++	+++	+++	+++
Procurement and inventory management	+	+++	++	+++

For a specific process, the proposed practical work contains guidelines that enable students to merge deeper into a relevant subject as their grade progresses. Thus, for their understanding, it is important that students have the suitable background knowledge of the main disciplines, an appropriate knowledge of the basic principles of technical analysis of mechatronic, robotic, and connected systems based on the generated competencies and their degrees of deepening to make learning paths throughout the considered learning grade. The result of this work is the last version of the guidelines, specially developed for the CPS platform.

Pedagogical implementation through a collaborative model

Although the work described in this manuscript focuses on system design, it is essential to consider all phases and requirements of the product life cycle. The different types of product integration presented below are also a source of organizational complexity. They require a high level of collaboration, which not only leads to organizational complexity, but also to the diversity of the domains involved. Thus, a multi-disciplinary collaborative integrated system for mechatronics training was designed and implemented in an evolving professional environment described below in Figure 2.

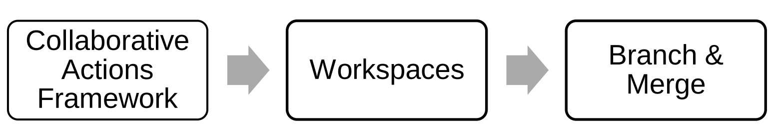

Figure 2. Agile method for multidisciplinary collaborative design

The model improve collaboration between the various disciplines by reducing the existing compartmentalization between the players involved. It is a direct response to the problem of the correlation between lack of collaboration and the resulting low level of product integration. As a result, laboratory equipment is based on an integrated approach, i.e., sequential step-by-step development and a multi-level approach to differentiating educational levels. We have taken care to balance the criteria of duality, versatility, and adaptability of the chain through modular cells that can be arranged according to the objective and level of depth of the activity. To perform this task, the teaching-learning approach (Mäkiö-Marusik et al., 2019) is adopted as a flexible and dynamic system open to the changing demands of the world of work and the specialized and/or multi-disciplinary trends all within the framework of the CBL approach performed by the project-based learning model (Meng et al., 2023) through an integrated curriculum approach (Tuselim et al., 2020). The agile method for multidisciplinary collaborative design aims to break down the barriers between disciplines by making design activities more agile, information propagation simpler and understanding of expertise phenomena clearer.

CASE STUDY

Collaborative learning path

Action 1: Collaborative action framework (CDIO Standard 5)

The collaborative actions set up during the action request creation phase are (a) Specification of a mechatronic system requiring knowledge of the disciplines of robotics, pneumatics, electrical engineering, supervision and automation (b) Sequential design of system behaviour (c) IoT data collection and analysis. The orientation phase of this approach is based on the creation of groups of students supervised by multi-disciplinary teachers who assign them different actions to achieve different learning goals. Students and expert teachers' study, discuss and, if necessary, modify the action requests to draw up precise specifications. The implementation phase is based on group work and weekly meetings to present the progress of the work and assess the learning outcomes according to their degree of depth. This step calls on the second notion of this agile method, which is the workspace to reference every modification made and every data updated. The close-out phase is defined by the completion of tests on the machines and the start-up and communication of the processes in consideration. Validation of collaborative actions considers all assessments made during implementation of the requested actions, which are weighted according to the learning outcome and its level of depth. Indeed, during the implementation stage, if validation is not achieved, the action is transferred back to the student group, with recommendations. Completion of this action is marked by passing the tests.

Action 2: Collaborative action framework (CDIO Standards 6)

In a workspace, every action in every discipline is referenced. This space makes available the work of each group and provides visibility on the different strategies deployed to solve an engineering problem. It also creates traceability and facilitates the acquisition of available and necessary data for any team involved in the workflow. Peer evaluation is thus possible to bless students to benefit from the knowledge and vision of others on their work and thus learn with a different approach.

Action 3: Branch and merge (CDIO Standard 7)

The branch creation and merge operation are essentially based on the parallel contribution of several participants in the same share for integrated learning. This enables us to achieve better results in less time. This concept is ensured by the synchronous work of different parties and disciplines making the data available. There is no longer a privileged contact for a better design or for a possible modification. An action can be refined and improved. Interactions between engineering activities or between disciplines could thus be facilitated. Thus, students can analyze productions, considering the economic and environmental sustainability aspects of the solutions established as part of the same learning experience.

Preliminary survey and discussion

To analyze feedback on post-installation pedagogical activities, a qualitative method was used. This involved direct or participative observations (professional or formative situations), explanatory or comprehensive interviews with learners or their tutors, and documentary analysis of written traces (learners' productions). Throughout our model development, we were able to observe that decision-making in a design project is facilitated by more frequent and regular feedback of precise operational information. This information may concern tasks in progress, requirements considered, difficulties encountered by the various design teams or a certification result. We also noted the traceability between the changes made to the system definition data and the decisions taken throughout the development project. The aim of this traceability is not only to improve design project management but also to be able to draw lessons from design projects to better anticipate future projects. Thus, a pilot class of 30 students was chosen to evaluate the cognitive integration of the platform, throughout the pedagogical process around specific workshops. The predefined learning elements were supported by milestones for groups of students. Through the CPS implementation the student acquires a comprehensive understanding not only of the core disciplines, but also of related disciplines. The student's interest increases as clear interdisciplinary links emerge. In addition to analyzing the student's motivation, a study of the skills acquired in terms of employability was carried out. The main employability skills acquired were teamwork, problem identification, research, time management, organization, leadership, analysis, entrepreneurship, innovation, and project management. Skills such as negotiation, persuasion, flexibility, and proactivity did not score well, which is common among students adapting to the university environment. Moreover, a Tia Portal Siemens certification process was also set up during the same year of implementation, with a larger sample covering the entire graduating classes. 63% of students wished to take the certification, relying on the learning outcomes achieved in the dedicated workshops. The success rate was 85% for Siemens TIA portal “Advanced” certification. The next step will be to set up an appropriate scientific method for student assessment, to generate results from the training process and program content, in line with norms 11 and 12 of the CDIO Standards.

CONCLUSION

The modular cyber-physics technology platform was adapted to work situations and fed by real industrial projects as part of a skills-based approach. The pedagogical model implemented enabled students to develop skills in the field of electromechanical systems. Introducing this practice into the educational process gave students the opportunity to apply theoretical knowledge in a practical environment, namely the development of CPS. By another hand, application of CDIO Standards in the teaching of CPS was a solid example of the practical implementation of international engineering training standards within electromechanical department workshops. The scientific analysis of educational situations as part of the professionalization of trainee teachers cannot be limited to the study of results at the level of immediate knowledge alone; it must be carried out on an ongoing basis at the various levels and phases of the study, in accordance with Standard 10 of the CDIO framework. It is essential to consider the various cognitive, cultural, and economic aspects involved in the search for relevant interpretations of the observations made.

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