ADAPTING CDIO TO CIVIL ENGINEERING: INVESTIGATE – PLAN – DESIGN – CONSTRUCT – OPERATE AND MAINTAIN

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ABSTRACT

The aim of this paper is to propose an alternative expression for engineering practice in the context of the civil engineering and built environment sector. Our first objective is to demonstrate that the CDIO approach can, with these modifications, be applied in developing civil engineering and built environment programs. Our second objective is to showcase the adaptability of the CDIO approach, thereby encouraging other thoughtful modifications and transformations. We outline the ideas underpinning the original expression, and identify the role it plays in the CDIO methodology for curriculum development. Taking these factors into account, a modified expression is proposed to describe the engineering process in civil engineering and built environment. We divide the process into '*investigation – planning – design – construction – operation and management*'. Further, to '*products, processes and systems*', we propose the addition of '*environments*'.

KEYWORDS

Civil engineering, built environment, conceive-design-implement-operate, adaptations of CDIO, Standard 1.

BACKGROUND

The fundamental aim of the CDIO Initiative is to strengthen the ways in which graduates prepare for engineering practice in their education. The CDIO approach refers to an image of engineering practice as "*conceiving, designing, implementing and operating products, processes and systems*"; hence the acronym CDIO. The words were carefully chosen to be as inclusive as possible, as the intention was in fact to broaden the conception of engineering practice. When the CDIO Syllabus was first published (Crawley, 2001) it was claimed to be "*universal, in that it has deliberately been written to be applicable to all engineering disciplines*" (p. ii). However, Crawley recognises a possible bias on the detailed levels of the Syllabus, and recommends customization "*to the needs and objectives of the specific local program and disciplinary field*" (p. 13).

Despite the clear ambition to achieve universal appeal, engineering programs have to various degrees felt included in the phrasing, and this has been a challenge in promoting the CDIO approach as suitable for programs in all fields of engineering. When trying to explain the essence of CDIO in its most succinct form to engineering faculty, the message is basically that the aim is to strengthen the professional side of engineering education (not at the expense of disciplinary understanding but through a purposeful integration of these two sides of education). However, it is easy to get stuck in explaining the actual acronym and its components, and this can take most of the time in an “elevator pitch’” situation. Our impression is that the terms do not possess immediate face validity in relation to programs such as civil engineering, chemical engineering, engineering physics etc.

In January 2015, Luleå University of Technology (LTU) became a CDIO Collaborator and a pilot project is currently underway implementing CDIO in four programs, one of which is the five-year Master of Science in Civil Engineering. The implementation project takes its starting point in a self-evaluation in relation to the CDIO Standards with rubrics (CDIO, 2010). In the process of joining CDIO, and in the early phases of program analysis and development, we find that the terminology is different to the language normally used by the faculty in civil engineering and built environment. The expression “*conceiving, designing, implementing and operating products, processes and systems*” was seen as unfamiliar, and reminded more of fields closer to mechanical engineering. This led us to search for an alternative expression more appropriate for civil engineering.

We note that both the open architecture of CDIO as a concept and the inclusiveness of the CDIO Initiative, serve as excellent strategies for maximising dissemination for the sake of engineering education stakeholders worldwide. Since the essential aim of CDIO is to promote educational reform to strengthen the professional aspects of engineering education, it is important that programs are developed based on a good understanding of its own professional context. The dialogue around the program will benefit from using language that can resonate with internal and external stakeholders.

In this paper, we begin by investigating whether earlier CDIO implementers in civil engineering have reported any similar experiences. Then, before we start discussing possible alternative phrasings, we must consider whether such customization is acceptable and reasonable. CDIO is certainly open for adaption to the particular contexts. However, what we are contemplating could be seen as a reformulation of *the fundamental idea* underpinning the whole CDIO approach – and is that something that can actually be changed? To analyse possible consequences of our proposed adaptation, we will therefore identify the functions fulfilled by the expression in the core definitions of CDIO, i.e. in the *CDIO Syllabus*, in the *CDIO Standards*, and in the name of the *CDIO Initiative*. Finally, we discuss the terminology normally used in the context of civil engineering practice, and end by proposing a new expression.

PREVIOUS IMPLEMENTATIONS OF CDIO IN CIVIL ENGINEERING PROGRAMS

Literature in CDIO conferences

The issue of adapting CDIO to civil engineering is mentioned already in the first CDIO Conference. In the 2005 Swedish national evaluation of MSc engineering programs, a self-evaluation according to the CDIO Standards was mandated as a component in the national scheme. Summing up the experiences, Malmqvist, Edström, Gunnarsson, and Östlund (2005) note that Standard 1, The Context, “*caused problems concerning interpretation and relevance*”. Anticipating this, programs had been encouraged to modify Standard 1 to define their particular context. One civil engineering program had decided on the wording: “*The principle is to educate engineers to meet the needs of the construction industry, i.e. for planning, design, engineering, production, operations and maintenance*” (p.10). We have not, however, found any documentation of continued discussions on this issue within the CDIO community.

The lack of discussion should not be taken to suggest that there are few CDIO implementers within civil engineering. The CDIO status survey (Malmqvist, Hugo, & Kjellberg, 2015) was sent to approximately 120 Universities all around the world in order to map in what disciplines CDIO is applied and further on to evaluate the effects on implementing CDIO and to identify the needs for the future. The survey had 47 responses from 22 countries and the results showed that 31.9% of the institutions applied CDIO to civil engineering programs. Despite this widespread participation of civil engineering programs, the remarks by Xiong and Lu (2007) still seem valid. They found that little material on using the CDIO initiative is available for civil engineering programs and point out that the suggested CDIO standards are not fully applicable for the building environment, such as large bridges, long tunnels and skyscrapers.

In the CDIO literature we find descriptions of courses featuring design-implement experiences, such as small-scale versions of houses, or material courses using bars or cubes, exists as good examples within civil engineering (Li, Yang, & Xiong, 2009; Millard & Jones, 2009; Rode, Christensen, & Simonsen, 2011). However, the enormous complexity of full-scale railways, nuclear waste power plants, water infrastructure and large infrastructure projects such as moving a whole town will not be reflected in small-scale versions. Other useful contributions address the issue of traditionally “pure” basic courses, and lacking examples related to the civil engineering area. This is a common situation also for many other engineering programmes, regarding e.g. mathematics, physics and mechanics. There are well-described experiences in courses those have been transferred into CDIO courses for civil engineers (Loyer, 2013; Ulfkjaer & Bundgaard Nielsen, 2012).

Hence, single courses and their content have been successfully developed drawing on the CDIO methodology, but there is little documentation of how a whole MSc program in Civil Engineering has considered its particular context more deeply, especially of implementing and operating products.

THE FUNCTIONS OF THE C-D-I-O EXPRESSION

It symbolises what engineers do

The expression “*conceiving, designing, implementing and operating products, processes and systems*” was formulated to capture *what engineers do*. The verbs were deliberately chosen to be generic terms that could appear inclusive to all branches of engineering. For instance, instead of *manufacturing*, which was first considered, the more general term *implementing* was chosen (Crawley, 2015). The object of engineering was also described in inclusive terms. Crawley, Malmqvist, Östlund, and Brodeur (2007) explain that “*to simplify and standardize the terminology, the terms product, process and system are consistently used for the object the engineer designs and implements, which depending on the sector, is called a product, process, system, device, network, code, plant, facility, or project*” (p.9).

It is represented in the CDIO Syllabus

The CDIO Syllabus is a list of topics that can be used to formulate the intended learning outcomes of an engineering program, addressing the fundamental question: “*What is the full set of knowledge, skills and attitudes that engineering students should possess as they leave the university, and at what level of proficiency?*” (Crawley, Malmqvist, Östlund, Brodeur, &

Edström, 2014, p. 34). The Syllabus is not prescriptive, but intended to serve as inspiration for a broad understanding of the competences needed for engineering practice. Section 4 of the CDIO Syllabus, relates to *conceiving* (4.3), *designing* (4.4), *implementing* (4.5) and *operating* (4.6).

It is present in the CDIO Standards

The phrase "*conceiving, designing, implementing and operating products, processes and systems*" is used throughout the CDIO Standards. It is at the core of the first portal standard expressing the main idea, i.e. that we educate students to become engineers who can actually engineer. Standard 1 reads: "*The Context: Adoption of the principle that product, process, and system lifecycle development and deployment – Conceiving, Designing, Implementing and Operating – are the context for engineering education*."

To achieve this aim, Standards 2, 3, 7, 9, and 11 use the expression "*personal and interpersonal skills, and product, process, and system building skills*" to denote all the intended learning outcomes that relate to skills, abilities, approaches and judgement. We like to think of it as *engineering skills* in a very wide sense, i.e. everything that graduates need from their program in addition to the disciplinary fundamentals, to be prepared for life and working life.

Standards 4, 5 and 6 refer to particular forms of learning activities for "*product, process, and system building*". Standard 4 concerns an introductory course where students should first be exposed to engineering practice, and Standard 5 refers to a sequence of more advanced learning activities, called "*design-implement experiences*". Standard 6 is about environments to support such learning activities.

It gave the CDIO Initiative its acronym

The acronym formed from the expression "*conceiving, designing, implementing and operating*", the working definition of engineering practice, came to name the whole CDIO Initiative. It serves as a reminder that the aim of the endeavour is to strengthen the professional side of engineering programs. On the positive side, it has achieved some symbolic status and become something of a brand. At the same time, the acronym can also be a burden, if some engineering programs feel excluded.

WHAT ENGINEERS DO IN CIVIL ENGINEERING

The civil engineering process

A typical construction project can be divided into the stages of investigation, planning, design, construction, and operation and maintenance. The division of the construction process is not typical for all cases but gives an understanding and outline of the stages leading to, for instance, a building.

Just like in the conceive-design-implement-operate, we do not imply that there is only a straight linear process, but it is rather to be seen as the holistic background to any specific activity. For many situations the investigation and planning stages go back and forth due to for instance risk assessment and social development in infrastructure underground projects.

The process can also look differently depending how the project is organised. The typical construction phases can be seen in Figure 1.

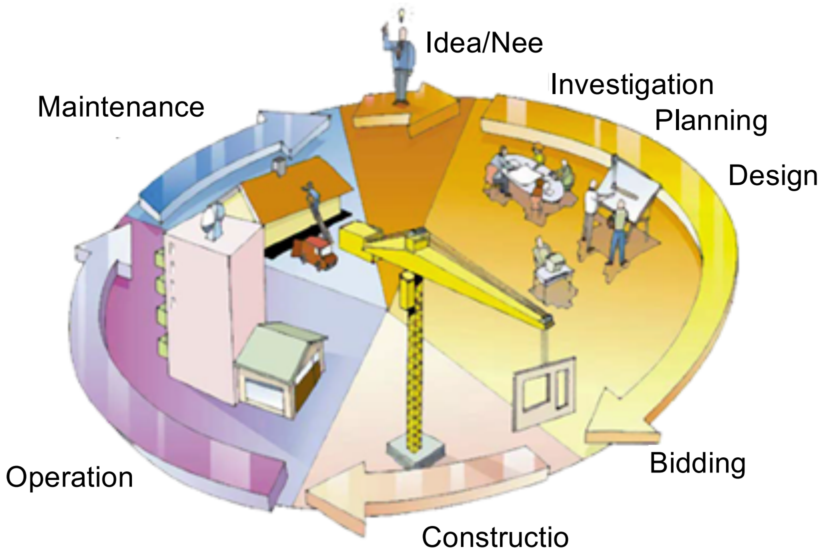

Figure 1. The construction phase that follows after an idea: investigation and planning – design – construction – operation and maintenance. The bidding is when contractors bid for the construction part of the project. Modified from Byggfakta (2016).

In each stage of the process, it is important to simultaneously be aware of all the other stages, and understand how the whole construction process is linked together and how the stages depend on one another. This is one of the most important learning outcomes for civil engineering students, to be able to work in this complex situation, simultaneously seeing the whole and the details. The interdependencies throughout the process add a considerable complexity, which can take much time and effort to learn. For instance, a civil engineer designing the reinforcement in a concrete beam must know in what type of structure the beam should be used in – which determines the loads, environment and other requirements – and must simultaneously also think about the construction workers who shall build the beam – it must be practically possible to place the reinforcement in the formwork and to cast the concrete. When issues such as aesthetic possibilities, cost, environmental impact and risk assessments are added, the task is even more complex.

Investigation

A construction project starts when someone has a need of a building, bridge, tunnel, airfield etc. To start the process aiming for the need, clients who have the need do (or commission) investigations and establish feasibilities on what type of construction they aim for and how big or small the object should be. They also make schematics, preliminary budget and schedule, form a project team, arrange for financing, and identify risks. A first proposal is presented. This stage can also be referred to as the concept stage.
For underground and geotechnical constructions a pre-investigation takes place aiming at defining location for the construction based on environmental effects, function, purpose and economy.

Planning

Based on the result of the investigation a planning phase is settled. The planning includes location of the object, its basic measures, dimensions, type of construction regarding materials and general shape leading to sketches and outline drawings. It also means development of plans, selection of equipment, suggestions of technical solutions, reconfirming of the economics in terms of budget, cash flow, financing and schedule. The risks and alternatives are re-assessed. A more detailed proposal is presented.
For underground and geo constructions a detailed investigation takes place in the planning phase at the selected location. Compared to other engineering fields where the material often is selected in the planning or design stage, the soil or rock mass that will be used as construction material cannot be replaced for underground constructions. Hence, for geo constructions, there is a comprehensive investigation and evaluation of different alternatives performed.

Design

After the planning, and in the design phase, all details are determined and digital drawings are made, (i.e. architectural, construction, electrical, ventilation, water and waste water) and specification documents are written. All calculations for the construction are done and details about ventilation, fire safety, climate etc. are solved. The drawings and specifications should meet all requirements from the client, environment and the society (building regulations, laws etc.). Still at this stage, some specific detailed investigations might be performed for underground constructions.

Construction

With help of the drawings and specification documents contractors are set to construct the object. The finalization of the projects needs many contractors including building, electricity, plumbing, ventilation, fire proofing etc. The final product is inspected in order to see if it fulfills the construction and specification documents. The construction phase often needs planning and design in further detail in order to finalize the construction. Most civil engineers work in the design and construction stages. However, they are involved in different roles also in the other stages.

Operation and maintenance

When the project is finished it goes into the operation and maintenance phase. The built construction should be used during its intended life, which for buildings could mean 20, 50 or 100 years and for bridges 60 or 120 years while for underground tunnels it is often more than 100 years (and some all eternity, such as nuclear power plants). This of course implies that the object must be maintained and kept in good condition. A new building process might take place if the construction needs to be repaired or changed.

Comparing the civil engineering process with C-D-I-O

Side-by-side with conceiving – designing – implementing – operating, the stages of the civil engineering process do not cover exactly the same conceptual phases. A tentative mapping is seen in Table 1.

Table 1. Comparing C-D-I-O and the civil engineering process.

C, D, I and O	The Civil Engineering Process
Conceive	Investigation
Design	Planning Design
Implement	Construction
Operate	Operation and maintenance

Widening “products, processes and systems”

When it comes to civil engineering, “*products, processes and systems*” do not sufficiently describe the object of engineering. In addition to these, civil or built environment engineers also create residential areas, highways, power plants, industries, landscapes, harbours, dams, airfields etc. To some extent these objects could also be referred to as products or systems, but we propose the addition of *environments* to better capture their quality as human-built spaces (Hughes, 2004).

To summarise, for civil and built environment engineering the phrase corresponding to “*conceiving, designing, implementing and operating products, processes and systems*” would read in full: “*investigating, planning, designing, constructing, operating and maintaining products, processes, systems and environments*”.

FURTHER DEVELOPMENT

Sustainable development

Nowhere in our proposed description of the process, nor in the original C-D-I-O phrasing, is there any explicit mention of end-of-life considerations. This is peculiar, as the intention is precisely to describe a *cycle*. In our field, structures are traditionally demolished after they reach their intended life. In the past, materials and parts were mostly crushed and just dumped, but now society, and thereby the construction industry, is developing a more circular view on materials and land usage. For instance, sometimes parts and materials can be re-used, i.e. steel is melted to produce new steel, and crushed concrete can be used as ballast in new concrete or as road fill. To enable sustainability we may now need to plan for several cycles of use. This implies a possible new stage in the construction phase after the end of the operation and maintenance stage, a stage that might be called re-usage. However, we do not propose adding it to the expression as a separate stage. We find it more important to *keep end-of-life considerations in mind during the whole process*. Sustainability can be purposefully *designed in*, if it is taken into careful consideration during every stage of the process. This is an area where more work is needed, including how it is implemented in the learning experiences throughout the education.

CONCLUSIONS

This proposal for an alternative expression does not in any way alter the underlying ideas and arguments of the CDIO approach to engineering education reform. When developing the Civil engineering program at LTU, we still call ourselves a CDIO program. But internally, we needed to deeply consider the fit between the fundamental ideas of CDIO and our subject area. By translating some key phrases into our own language, the same ideas are expressed for the civil engineering and built environment field. We have merely taken the essential conception of engineering in CDIO and dressed them in our own clothes.

Finally, we recommend other programs to make the same exercise of adaptation. Because we could, without too much trouble, translate the key phrases in a way that makes full sense to us, it is an indication that the fundamental concepts of CDIO are valid also in our field.

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