Design and Development of CDIO Student Workspaces – Lessons Learned

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Introduction

Project courses in which students design, build and test a device on their own are increasingly being used in engineering education. The reasons include that such projects do not only train students skills in design and implementation but can also be exploited in order to increase student motivation, to give an improved understanding of engineering science knowledge and to practice non-technical skills such as teamwork and communication. However, design-build-test (DBT) experiences may also be costly, time-consuming, require new learning environments and different specialized faculty competence (Malmqvist et al. 1).

In particular, design-build-test experiences play a critical role in the education strategy developed in the CDIO project (Berggren et al.2; CDIO Initiative Homepage3), an international initiative that aims to develop a new model for engineering education, characterized by using the process of conceiving-designing-implementing-operating, i.e. the product lifecycle, as the educational context. A prominent attribute of the CDIO initiative has been the design and implementation of a new class of student workspaces (design studios, classrooms, study areas, laboratories) that enable student teams to design, build and test in project-based courses. This is in contrast to traditional student labs that are heavily oriented towards demonstrations (Gunnarsson et al.4; Wallin & Östlund5).

The proper set-up of a student workspace that supports design-build-test education experiences requires consideration of a large number of factors – such as ownership, functionality, staff competence, costs, safety, security, sustainability and so on - that differ from those in classical student workspaces. A set of CDIO workspaces also needs to be designed holistically with the entire curriculum in view rather than an individual course or subject.
However, existing research into student workspaces tends to focus on the setup of particular workspaces such as LabView-supported environments (Ertugrul), project studios (Kuhn; Thompson), CAD/CAM/CAE labs connected to workshops (Dutta et al.) and multimedia environments (McCarthy et al.) rather than an integrated set of workspaces. We therefore see a need for a better general understanding of CDIO student workspaces, along with guidelines for their design. Thus, the objectives of the paper are to:

- Describe the concept of CDIO student workspaces and its implementations at MIT, Chalmers University of Technology, KTH, Linköping University, and Queen’s University Belfast
- Identify objectives, requirements, benefits, limitations, critical issues and challenges related to design, implementation and operation of CDIO student workspaces
- Summarize and generalize experiences with the design, implementation and operation of CDIO student workspaces
- State guidelines for the design, implementation and operation of CDIO student workspaces

In the paper, we first describe the concept of a CDIO student workspace, including its basic components: Concept forum, Design Center, Implementation Lab and Operations Center. We then describe a number of CDIO student workspaces with emphasis on the systematic development of the top-level requirements – the workspace usage modes: System development and implementation, knowledge discovery, disciplinary learning and community-building - that directly shaped the physical layouts, equipping, operations, and usage of the CDIO workspaces developed at the universities who have been engaged in CDIO since 1997. Key attributes of the workspaces at each CDIO partner school are described to illustrate how CDIO’s pedagogical objectives were integrated into workspace design, and enable benchmarking of CDIO student workspaces. Discussions and analyses focus on the original design intent as well as on the actual usage. A collection of lessons learned, and experiences gained to date by students, faculty, and staff as the workspaces have reached operational status are included. Insights are shared on how effectively the workspaces have satisfied original design intentions. Benefits, limitations, critical issues and challenges in the area are identified. Finally, a set of guidelines for the design, instrumentation and operation of CDIO student workspaces are proposed.

**CDIO Workspaces Concept**

CDIO workspaces are a new type of learning environment that supports conceive-design-implement-operate for a scope of simple to complex problems, and individual as well as group-based projects (Crawley et al.). CDIO workspaces thus need to support learning which is related to various phases of a product’s lifecycle. It follows that the facilities need to be multi-functional, with support for information searches as well as hardware manufacturing. Thus, CDIO workspaces can typically be divided into four different categories of workspaces, as illustrated in figure 1.
In the Conceive stage of a CDIO project, students are encouraged to exchange ideas using disciplinary knowledge plus their interpersonal skills in order to develop solutions to engineering problems in the presence of stated requirements and constraints. From a workspace perspective, several physical attributes have been found to facilitate this initial phase of the CDIO sequence. Access to reference material through the internet is a powerful means to gather background information to establish the context of possible future solutions to the students’ problems. Another aspect is the physical arrangement of the discussion area to facilitate both face-to-face discussions as well as presentations of information through electronic display equipment – LCD or overhead viewgraph projectors. While not claimed to be totally unique to the CDIO process, all the partnering CDIO schools have facilities designed to facilitate these interpersonal discussions. Features include readily configurable furniture, and electronic displays that support displays of graphical information.

The Design stage, the second segment of the CDIO sequence, encompasses the engineering and educational processes where chosen concepts are rigorously developed and defined using disciplinary knowledge, Computer Aided Design (CAD) programs, and other design tools. From a CDIO workspace perspective, workspaces can provide design-centric work areas where the students can conduct more detailed design studies using CAD tools as well as other analytical means of performing trade studies via parametric variations. The attributes of typical CDIO Design workspaces include access to computers, printers, and graphic devices, as well as discussion areas where results can be presented to other students, to faculty and staff, and to outside reviewers. The Physical Prototype Laboratory at Chalmers University of Technology, Göteborg, Sweden is a good example of a CDIO workspace that provides undergraduates from programs in Mechanical, Automation & Mechatronics and Industrial Design Engineering with the resources needed to design, create CAD models, to manufacture prototypes, and to test functional models of various mechanical and mechatronic products to meet exacting design requirements.
Implementation, the third stage of the CDIO sequence, describes the processes and practices that result in the manufacturing, assembly, and testing of engineering projects. Working from engineering sketches, digital models, or blueprints, students typically produce engineering devices that challenge the students’ abilities to use manufacturing equipment ranging in complexity from simple hand tools to CNC machine shop equipment. Project complexity can range from fairly simple first-year introductory projects to large-scale multi-disciplinary projects such as the Solar Powered Aircraft or the Waterbike projects (Figure 2) undertaken at KTH, Stockholm, Sweden. From a workspace perspective, the Implementation phase places a premium on preparatory planning for efficient use, adequate construction space to support a multi-disciplinary curriculum, and tools and manufacturing machinery that are good matches to engineering students’ talents and their developing skills. Technical staff support is an essential ingredient to provide instruction in the use of equipment, for supervision and safety, and for providing technical knowledge to resolve specific technical problems.

![Human Powered “Waterbike” designed at the Royal Institute of Technology (KTH), Stockholm, Sweden](image)

Figure 2. Human Powered “Waterbike” designed at the Royal Institute of Technology (KTH), Stockholm, Sweden

Operation, the fourth and final stage in the CDIO sequence, describes the spectrum of activities where an engineering project undergoes assembly, pre-use testing and calibrations, and functional operations are verified. Creating electro-mechanical devices that actually operate in some manner has proven to be highly motivating for engineering students. In a CDIO-designed course, the Operation stage is where the students are forced to confront the realities of devices that may not function as intended for a wide variety of reasons, and to use their observation and analysis skills to evaluate the effectiveness of their solutions. Thus is often a true test for young engineering students. The variety of projects undertaken by the CDIO university collaborators ranges from introductory first-year courses which usually do not require significant amounts of space to test and operate; to 3rd and 4th year courses that may require significant workspace for the final testing and checking prior to full operations at a suitable test site. From a workspace perspective, the Operations’ stage places large demands on the sizes and availability of work area, electronic and mechanical equipment for checking and verification, and in some cases, room to do limited functional tests. Considerable planning needs to take place between Workspace technical staff, course instructors, and teaching assistants to ensure that the
Operations’ activities can be adequately handled in conjunction with other planned commitments of the facilities. A good example is the Formula SAE® competition in which several of the CDIO universities have taken part. This competition entails the design, construction, and testing of a small single-seat racing automobile (figure 3) according to stringent technical specifications. This particular project requires space for assembly of the race car, engine check test stands to measure motor torque and horsepower, and additional equipment to verify that the final automobile configuration properly meets the team’s design specifications. Equipment storage, safety precautions, and proper care of flammable materials are significant issues that are best handled by early discussion and coordination between key personnel.

![Formula SAE® racing car designed at Chalmers University of Technology, Göteborg, Sweden](image)

**Figure 3.** Formula SAE® racing car designed at Chalmers University of Technology, Göteborg, Sweden

**Examples of CDIO workspaces**

The development of workspaces at each of the primary CDIO collaborating schools has taken several routes prior to reaching full operational status. The Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (USA) created their Gelb and Seamans Laboratories through extensive renovation of their Department building first built in the 1930s. The Mechanical Engineering Department at Chalmers University of Technology reclaimed and refurbished existing university space to create a 2000 m² facility that is now used to support their mechanical, automation, and industrial design engineering programs. KTH took a similar approach to create the Poolen, a capstone engineering work center that has supported three multidisciplinary projects run by the Department of Aeronautics and Vehicle Engineering – a Solar Powered Aircraft, a Human-Powered “Waterbike” vehicle, and a sub-surface craft that converts to a high speed surface craft.

A common theme in each of the workspace developments described above was the advance planning to establish the requirements for workspaces, teaching and learning modes, equipment, computer support, storage, and other essential infrastructure. In addition, ready access to facilities has been an important element in each university’s use of the workspaces. This has been balanced by the need for occupational safety and the desire to provide leeway, if at
all possible for a wide variety of engineering experiences including meaningful extra-curricular ones. Various usage and layout concepts and approaches were proposed, evaluated, and refined in order to achieve a good balance between desired attributes, space, and installation costs.

A key planning instrument was the definition of the desired learning modes that each institution’s workspaces would be required to support. These modes include curricular, research, extra-curricular, and other applications. A complete listing and description of the 21 established modes can be found in [11]. For ease of assimilation, these 21 modes have been condensed into the four major categories as follows:

1. **System development and implementation** refers to design-build-test projects that are usually team-based, highly multi-disciplinary, and collaborative in nature. Variants of this usage mode include Large Student Projects, Large Systems, Operations, Linked Projects, Research Design Support, External Income Generating, Paper Design/Competitions.

2. **Disciplinary learning** denotes workspace usage modes that support the teaching and learning of engineering material that directly links to established curricula. Educational activities of this usage mode include Lectures/Presentations, Class Lab/Experiment, Teaching in Labs, Interactive Electronic Class.

3. **Knowledge discovery** represents workspace activities where research, experimentation, and synthesis are the primary characteristics for students’ activities. Examples include Design Projects, Experimental Projects, Graduate Theses.

4. **Community building** describes the activities where the workspaces provide meeting places for faculty, staff, and visitors to socialize in either curricular or extra-curricular modes to promote a larger sense of community spirit in the academic population. This usage mode spans Educational Outreach, Tinkering, Self-Directed Learning, Paper/Conference, Collaborative Projects, Site Learning/Teaching, Distance Learning/Teaching.

Tables 1 and 2 summarize data for the different workspaces designed and built in the CDIO project. It is apparent that the dimensions and costs can vary significantly, from 60 m$^2$ to 2200 m$^2$, and from USD 1,000 to 15,000,000, depending on the number of students and courses and available resources. Large spaces are needed if the workspaces are to support the whole curriculum, while smaller areas can be used for capstone projects in specialized areas.
### Table 1: Summary of CDIO workspace characteristics (part 1 of 2)

<table>
<thead>
<tr>
<th>Name</th>
<th>MIT</th>
<th>KTH</th>
<th>US NA</th>
<th>LIU</th>
<th>QUB</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDIO Workspaces</td>
<td>CDIO</td>
<td>CDIO</td>
<td>CDIO</td>
<td>CDIO</td>
<td>CDIO</td>
</tr>
<tr>
<td>Basic description</td>
<td>The study environment in the M-building consists of traditional classrooms, a study hall, computer facilities, the Prototyping lab and the Engineering science lab.</td>
<td>A multipurpose workspace for meetings, workshops, studies and lighter manufacturing and assembly.</td>
<td>Workshop spaces to support Senior Aircraft Design/Build/Fly activities</td>
<td>Muxen is a lab for projects in electrical engineering. Muxen consists of four labs, a common area with a “discussion corner”, a conference room, a component room and a server room.</td>
<td>The innovation lab is used by 4th year students on the mechanical engineering program. New product development projects are undertaken by students teams, which include engineering, innovation and entrepreneurial activity.</td>
</tr>
<tr>
<td>Conceive spaces</td>
<td>The Study Hall is a 1000 sq m open study area. Break-out rooms.</td>
<td>The workspace is designed with configurable furniture to suit different meeting objectives. A comprehensive audio-video system allow remote conferencing and distance learning meetings to be conducted. Open study area equipped with PCs. Library.</td>
<td>The space provides access to furniture, whiteboards, billboards, books, computers, scanner, printer, wireless LAN, video projector, digital camera, video camera, tools and material for model manufacturing.</td>
<td>Space serves functionally as a central meeting place for all teams and houses.</td>
<td>Each team is allocated a specific area with a table and chairs to facilitate meetings and a white-board for idea generation and general communication.</td>
</tr>
<tr>
<td>Design spaces</td>
<td>Computer facilities with ca 150 PCs and state-of-the-art software and related equipment.</td>
<td>The main workspace is a large room, approximately 150 sq meters, with 25 PCs, and related equipment.</td>
<td>The space supports the design phase by providing means for model building and analysis, partly involving the hardware mentioned above but also through dedicated software for math, CAD and FE modelling &amp; simulation.</td>
<td>Each team has access to a computer and printer. Files are stored centrally on a server to provide flexible access. Office, design and project planning software is available on the computers.</td>
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</tr>
<tr>
<td>Implementation spaces</td>
<td>Metal Machining, Woodworking and foam, Paper, Paint, Plastics, Material joining, Assembly, Test, Rapid Prototyping, Electronics manufacturing, Software coding. Ca 30 machines/equipment types.</td>
<td>Metal machining, water jet cutting, wood working, rapid prototyping equipment (3D solid printer, CNC hot wire foam cutter, composite layers). Ca 20 machine/equipment types.</td>
<td>All but Rapid Prototyping, including hand and table tools for work on different materials. Access to electronics, metal and composites shops and space and equipment for larger assembly are not included but provided when necessary.</td>
<td>Limited metal/woodworking machines, small hand tools and aircraft parts/supplies. Not used for major assemblies, but used for storage and electronics buildup and flight test preparations. Ca 10 machines/equipment types.</td>
<td>Assembly, Test, Rapid Prototyping, Electronics manufacturing, Software coding, Meetings, Discussions, Component storage, Server room. Ca 10 machines/equipment types.</td>
</tr>
<tr>
<td>Operation spaces</td>
<td>Open area for building and testing prototypes.</td>
<td>Appr. 500 sq m open workspace floor area. 30+ work tables for individual projects, electronics laboratory with workbenches and Quanser digital control test beds.</td>
<td>The space is used for operation and verification of smaller products or subsystems of larger products. Final testing often takes place outdoors due to the nature of the products. The space is then used for modifications, re-design or repair.</td>
<td>None</td>
<td>Workbenches and hand tools are available to enable basic prototypes to be developed. More complex prototypes are manufactured by the department's machine shop.</td>
</tr>
</tbody>
</table>

**Notes:**
- **QUB**: Innovation Lab
- **KTH**: Poolen
- **US NA**: Senior Aircraft Design/Build/Fly Workspaces
- **LIU**: MUXEN
<table>
<thead>
<tr>
<th>Name</th>
<th>Chalmers</th>
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<th>USNA</th>
<th>LiU</th>
<th>QUB</th>
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<tr>
<td>Programs</td>
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<td>Complex Systens Laboratory</td>
<td>Poolen</td>
<td>Senior Aircraft Design/Build/Fly Workspaces</td>
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<td>Innovation Lab</td>
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<td>Courses/subject</td>
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<td>1</td>
<td>6</td>
<td>2</td>
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<tr>
<td>Program years</td>
<td>1-4</td>
<td>1-4, graduate</td>
<td>3-4</td>
<td>4</td>
<td>1-4</td>
<td>4</td>
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<tr>
<td>Learning objectives</td>
<td>System design &amp; implementation</td>
<td>System design &amp; implementation</td>
<td>System design &amp; implementation</td>
<td>System design &amp; implementation</td>
<td>System design &amp; implementation</td>
<td>System design &amp; implementation</td>
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<tr>
<td></td>
<td>1-4</td>
<td>1-4, graduate</td>
<td>3-4</td>
<td>4</td>
<td>1-4</td>
<td>4</td>
</tr>
<tr>
<td>Space [m²]</td>
<td>2000</td>
<td>2200</td>
<td>60</td>
<td>100</td>
<td>450</td>
<td>115</td>
</tr>
<tr>
<td>Initial investment cost</td>
<td>3</td>
<td>15</td>
<td>0.02</td>
<td>0.003</td>
<td>0.4</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 2: Summary of CDIO workspace characteristics (part 2 of 2)
Discussion: Usage, Benefits and Challenges

As can be gleaned from an examination of the Workspace characteristics depicted in Tables 1 and 2, each of the participating CDIO collaborator schools has integrated, in varying degrees of intensity, the four stages of the Conceive-Design-Implement-Operate sequence in their teaching and learning facilities as well as in their undergraduate programs ranging from first-year through to fourth- and fifth-year courses. A general theme at all the schools has been to initially introduce first- and second-year students to engineering fundamentals through laboratory projects centered around D and I (Design and Implement) elements and subsequently to challenge the more sophisticated senior students with engineering projects that also contain substantial portions of C and O (Conceive and Operations) – and that thus address the whole CDIO sequence. This approach has worked well and has proven to be a good match to the “learning curve” of undergraduate engineering students.

Table 2 further shows the usage modes of the workspaces. As might be expected, systems design and implementation is featured in all cases. Other frequently cited learning objectives to be supported include learning of disciplinary knowledge, knowledge discovery, communications, teamwork and community-building. This indicates the multi-purpose nature of CDIO workspaces and the central role that such workspaces can play throughout the curriculum. In particular, it is apparent from our experience with building and operating CDIO workspaces that the workspaces play a central role for building communities amongst students. In addition to working on their particular design-build project or experiment, students also use the workspaces to study disciplinary courses and for social functions. The workspaces can also provide facilities for student clubs devoted to tinkering, model-building and other extracurricular projects. In return, these students can be involved in the operations of the workspaces, as tutors and as “lead users” (von Hippel, Reference 12) to inspire further workspace development.

The initial expectations for the first CDIO workspaces implemented by the original collaborators (MIT, KTH, Chalmers, Linköping University) were relatively modest, in retrospect. One particular attribute, reached after conducting student surveys, was to allow 24/7 after-hours access by students with entry controlled by internal security measures such as ID card controls and keys. Although usage of clearly hazardous equipment is kept to office hours under staff supervision, the CDIO workspaces were deliberately designed to provide an environment for group study, socialization, and mixing of students and faculty in both curricular and extra-curricular settings. Other key considerations include emphasizing flexibility when designing and building the workspaces. Workspaces need to be easily re-arrangeable to suit the needs of different projects, and to facilitate the upgrading of equipment based on operational experiences. Perceived limitations of the workspaces studied typically involve available floor or storage space rather than missing equipment.

Students’ response to these workspace initiatives has been uniformly positive at all the participating schools. Survey data taken at MIT, in particular, shows that the Aero-Astro graduating students feel that the redesigned workspaces have not only increased their ability to learn disciplinary material but has also increased their positive feelings towards their classmates and their chosen profession (Brodeur, Reference 13).
Substantial challenges have been identified in the operations of these CDIO workspaces. Scheduling during the school terms is a continuing challenge to prevent overcrowding and gridlock during highly congested periods of work that emerge at mid-term and end-of-term periods. Acquiring technical staff proficient in a wide number of professional areas who are willing to work closely with numerous students throughout the year is a key ingredient for successful acceptance by the students. Close coordination with academic instructors to pre-plan upcoming workspace projects, as well as to manage ongoing projects, requires diligent effort from all parties. Financial resources, needless to say, are vital to being able to provide the required facilities, equipment, and staffing. Each participating CDIO school has used a variety of means, including internal funding from their Engineering Departments, donations from alumni organizations, and from industry.
CDIO Workspace design and operations guidelines

Based on the experiences from designing, building and operating CDIO workspaces, a number of guidelines have been developed by the CDIO collaborators. The intent is to provide some assistance for future developments. The guidelines are categorized into guidelines for overall workspace design, guidelines for equipment and guidelines for operations. Additional information is available in the Workspace section of the CDIO Initiative website (Reference 3).

Table 3: CDIO Workspace design and operations guidelines.

<table>
<thead>
<tr>
<th>Overall workspace design</th>
<th>Map out learning modes most likely to be employed for both curricular and extra-curricular activities. Develop operational philosophies that meet objectives for pedagogy, community building, and skills development. Communicate to the faculty what the workspace capabilities are that can be linked to curriculum materials and initiatives. The ability to reconfigure a study area or meeting place, to suit different meeting modes, is very essential to having effective meeting venues that are flexible in terms of equipment and activities. Avoid over-designing the workspace from the start, let space evolve. Provide room for group meetings and discussions. Involve students in the designing, building and later operating and developing the workspace. Allow for management and control by students.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>Within funding constraints, install equipments that have clear relevance to professional as well to curricular applications. Include exhibits that reflect the education’s content. The workspace should be totally wired, or wireless. Integrate with other assets. Establish collaborations with external workshops for specialized manufacturing processes, such as SLS (Selective Laser Sintering). Provide access to internet, word-processing, CAD, simulation tools, etc.</td>
</tr>
<tr>
<td>Operations</td>
<td>Stress safety! Provide 24/7 access to workspaces once all safety concerns have been addressed. Be sensitive to differing levels of supervision required for students with varying skill and learning attributes. Have backup systems for hardware and software implementation. Be alert for ways to improve efficiency, productivity, usage, training, and safety. Work with course instructors to pre-order needed supplies. For new course projects, do prototyping and risk reduction as much in advance as possible. Installation and maintenance of computerized design tools requires significant and specialized effort – having an IT-cognizant person quickly available is often crucial for classes to start on schedule. Pre-coordination of new application programs, and early installation and testing, should be done as early as possible before first use. Maintaining control of operating budgets is a continuing challenge. Budget for replacement of raw materials, supplies, expendable equipment (drills, bits, adhesives, machining stock). Instill into users a sense of responsibility for equipment and materials. Insure all necessary tools and supplies are provided up-front to insure all teams have adequate stocks before beginning operations. Provide dedicated workspaces for each team with inventoried tools/supplies that are their responsibility to maintain and track.</td>
</tr>
</tbody>
</table>
Conclusions

The experience to date of the CDIO collaborating schools has reinforced the initial assumptions that an integrated learning space can provide significant augmentation of the education of engineering students. Mid-course and post-course surveys and assessments have shown that students respond positively to workshop environments where they experience the four key stages (Conceive, Design, Implementation, and Operations) of the product lifecycle through engineering projects, both curricular as well as extra-curricular.

The examples of CDIO workspaces discussed in the paper show that costs and formats can vary significantly, depending on goals, numbers of students and available financial resources. However, some design issues stand out regardless of scope: the need for a curriculum/usage mode-driven workspace design, planning for flexibility in usage modes and for enabling the workspace to evolve over time, safety concerns and 24/7 access. In order to take these issues into consideration, the paper suggests a set of guidelines for workspace design and operation. The benefits identified include enabling a new mode of engineering education, the strengthening of student motivation and improved student-teacher interaction. The workspaces studied have also been shown to play a new role, as community-building spaces for students, that goes beyond their initially planned purposes.

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3. CDIO Website, www.cdio.org


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