IMPLEMENTING ENGINEERING EDUCATION FOR ENVIRONMENTAL SUSTAINABILITY INTO CDIO PROGRAMS

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Abstract
This paper aims to bridge education for sustainable development (ESD) and integrated learning of generic competencies applying the CDIO model, by describing how ESD can be implemented into an existing CDIO-based program. It was found that the CDIO syllabus is exhaustive regarding sustainability though not under a separate headline; this would be beneficial to be clarified for adopters of the approach. A process developed for integrating learning for sustainable development is described. The process model is a bottom-up and top-down approach involving stating program-level goals and curriculum design but also support given to faculty such as a program workshop, followed by individual dialogue between resource group and lecturers. In the application of this model to the CDIO-based Mechanical Engineering program at Chalmers it was found that the previous adoption to CDIO facilitated the process in several aspects. First, there exists experience in adopting program-level goals and turn it into course learning objectives integrated in a successive manner into the program design matrix. Second, the programs' teachers have become more used to and prone to appreciate generic skills, have become experienced in formulating learning objectives and accepting a partly top-down approach. Finally, there exists already learning modules centred around the product/system/process realization process, where sustainability issues are ideal to incorporate.

Keywords: CDIO, sustainability, ESD, education for sustainable development

1. Background

Sustainable development has become a more known and accepted concept in society since it was introduced and defined within the United Nations activities in the 1980s. In education, stakeholders such as government and industry as well as students are expecting engineering programs to include learning experiences aiming at developing knowledge, skills and attitudes related to sustainability. There exist several definitions for the concept of sustainable development. One definition was created by ICLEI: "Sustainable development is development that delivers basic environmental, social and economic services to all residents of a community without threatening the viability of the natural, built and social systems upon which the delivery of these services depend" [1]. According to the World Commission for Environment and Development (also called Brundtland Commission) [2] it was said "Humanity has the ability to make development sustainable - to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits - not absolute limits, but limitations imposed by the present state of technology and social organization, on environmental resources and by the ability of the biosphere to absorb the effect of human activities." The Brundtland report highlighted three fundamental components to sustainable development: environmental protection, economic growth and social equity. It is possible to see a similar line of thoughts in the following excerpts from the current Swedish national degree requirements for the "Civilingenjör" degree (Master of Science in Engineering) (translated from Swedish):

"To be awarded the Civilingenjör degree the student should be able to demonstrate
- the ability to formulate judgements considering relevant scientific, societal and ethical aspects, and demonstrate an awareness of ethical aspects on research and development work,
- insight into the possibilities and limitations of technology, its role in society and the responsibility of humans for its use, including social, economic as well as environmental and occupational health aspects"

However, integrating learning experiences addressing these goals in engineering programs involves many challenges, including stating operational learning outcomes for sustainability knowledge, skills and attitudes for a particular program, making a contextualized interpretation of the concept, curriculum design issues such as creating separate courses on sustainability and/or integrating such topics in other courses, planning progression etc. In Sweden, educational initiatives aiming at developing sustainability learning experiences have evolved to train also "generic" engineering skills such as communication, creative problem-solving, ability to formulate judgements and to make decisions. Depending on the curriculum design, sustainability learning experiences may then both interplay with and compete with existing courses. Thus, careful planning of sustainability learning experiences in a curriculum is essential. CDIO is an approach to engineering education that uses the product/system/process/service as the context of the education. This context is a natural environment for addressing issues and topics related to sustainability. CDIO also features a toolbox for curriculum and course development that can help faculty deal with the challenges mentioned above.

There are many published examples of SD courses and also some descriptions and examples of integrated learning, "embedding", of the sustainability knowledge and skills [3, 4, 5]. Some of the well-known examples of education for sustainable development are from Delft University of Technology, University of Barcelona or Chalmers University of Technology [6, 7]. In a comparison of the three universities it was concluded that there were five common factors for successful embedding of education for sustainable development (ESD) within the curriculum [7]:
- *Legitimacy*: It is beneficial if it is seen as legitimate for lecturers to focus on environment and ESD in research and in education.
- *Commitment in university management*: It is of vital importance that university management is determined to integrate ESD in the educational programs.
- *Responsibility spread throughout organization*: The responsibility to work with ESD should be spread between different departments and individuals – ideally a responsibility of all teachers.
- *Skilled teachers*: It is an advantage if there are many lecturers in the organization that have a long experience of working with ESD.
- *Effective structure of organization*: The educational organization can be structured in such a way that it enables or facilitates ESD integration efforts.

CDIO has been a successful initiative facilitating the integration of generic competencies. However, it has also been criticized for the low visibility of sustainability-related learning objectives in the CDIO syllabus; they are considered in the program-specific part (category 1) and on x.x.x and x.x.x.x levels. Some critics have interpreted this as a down-prioritization. There is also a lack of examples describing sustainability learning experiences in CDIO-based programs.

This paper aims to bridge the two domains of education for sustainable development (ESD) and of integrated learning of generic competencies applying the CDIO model by describing how ESD can be implemented into an existing CDIO-based program. More specifically we aim to

- Clarify the relationship between the concept of sustainable development and the CDIO approach, in particular the CDIO syllabus
- Describe a process for integrating learning for sustainable development for engineers in CDIO programs. The description accounts for process steps such as stating program-level goals and curriculum design but also for support given to faculty from (sustainability) subject experts in the development process
- Exemplify the use of this process in Chalmers' Mechanical engineering program.

2. Consideration of sustainability issues in a CDIO-based education

Let us now discuss how sustainability can be considered when designing a CDIO-based education, in particular with respect to the CDIO syllabus and the curriculum design process.

There are few explicit references to sustainability in the CDIO syllabus. In fact, it is only included under the heading 4.4.6 Multi-objective design, where it is stated that graduating engineers should be able to design for implementation, verification, test and environmental sustainability. Environmental sustainability is here considered in the context of engineering design-making: the development team is faced with a decision situation characterized by the need to make trade-offs between multiple objectives. Environmental sustainability may in some cases be the most important objective but must in almost all practical situations also be weighed against other objectives, such as performance, cost and reliability. Ultimately, it is up to the customer's willingness to pay for improved environmental friendliness. In some cases, environmental sustainability requirements act as constraints rather than objectives.

However, it can also be argued that CDIO is fundamentally very strongly aligned with the ideas of sustainability: Engineers are said to conceive, design, implement and operate complex technical systems with the entire product/process/system lifecycle in mind. The product lifecycle is claimed to be the proper context for engineering education. The systematic exploration of all lifecycle phases in the education provides a multitude of realistic situations where engineering problem-solving situations, in which sustainability is an issue, can be trained and reflected upon.

The role of sustainability in the CDIO syllabus can also be viewed from the perspective that sustainability has become a wide concept, which rather might be characterized as a framework or an umbrella which not only covers economic, social and environmental sustainability, but also the engineer's professional role, ethics, globalization ect. A number of links between sustainability principles and CDIO syllabus topics can be identified [8], and are further developed in Figure 1. There are also many places in the CDIO syllabus where the lifecycle perspective is emphasized. It is argued that requirements should cover all lifecycles, further that analyses should be made of the lifecycle value and costs, and that product retirement should be planned ahead and so on. Adapting this perspective, we can argue that there are major overlaps between CDIO syllabus topics and concepts included in the sustainability framework. These appear in the CDIO syllabus categories 1, 2, 3 and 4 as indicated in Figure 1.

1 TECHNICAL KNOWLEDGE AND REASONING
1.1. KNOWLEDGE OF UNDERLYING SCIENCES
< Basic science sustainability knowledge >
1.2. CORE ENGINEERING FUNDAMENTAL KNOWLEDGE
< Program-specific sustainability knowledge >
1.3. ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE
< Specialized sustainability knowledge >

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES
2.3. SYSTEM THINKING
2.3.1. Thinking Holistically
2.3.2. Emergence and Interactions in Systems
2.3.3. Prioritization and Focus
2.3.4. Tradeoffs, Judgment and Balance in Resolution

2.4 PERSONAL SKILLS AND ATTITUDES
2.4.3. Creative Thinking
2.4.4. Critical Thinking

2.5. PROFESSIONAL SKILLS AND ATTITUDES
2.5.1. Professional Ethics, Integrity, Responsibility and Accountability

4 CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT
4.1. EXTERNAL AND SOCIETAL CONTEXT
4.1.1. Roles and Responsibility of Engineers
4.1.2. The Impact of Engineering on Society
4.1.3. Society's Regulation of Engineering
4.1.4. The Historical and Cultural Context
4.1.5. Contemporary Issues and Values
4.1.6. Developing a Global Perspective

4.3. CONCEIVING AND ENGINEERING SYSTEMS
4.3.1. Setting System Goals and Requirements
Factors that set the context of the requirements: Ethical, social, environmental, legal and regulatory influences
Requirement completeness and consistency
4.3.3. Modeling of System and Ensuring Goals Can Be Met
Life cycle value and costs (design, implementation, operations, opportunity, etc.)
4.4.5. Multidisciplinary Design
4.4.6. Multi-Objective Design (DFX)
Design for:
Performance, life cycle cost and value
Implementation, verification, test and environmental sustainability
Robustness, evolution, product improvement and retirement

4.6 OPERATING
4.6.3. Supporting the System Lifecycle
4.6.5. Disposal and Life-End Issues

Figure 1. Sustainability-related CDIO syllabus topics.

When relating CDIO and sustainability is must also be understood that the CDIO syllabus does not include any detailing of the technical knowledge and reasoning included in category 1. This is intentional, as the technical knowledge is highly program-specific. CDIO does not address the program-specific parts of curriculum design, it only aims to support the common parts. It is therefore a task for the program developers to identify and write learning outcomes for the

Table 1. CDIO curriculum design steps and sustainability considerations

Perform stakeholder survey	Identify national degree requirements related to sustainability Identify other stakeholders sustainability requirements
Analyze pre-existing conditions	Identify university requirements
Create program goal statement	Write learning outcomes related to sustainability
Benchmark curriculum	Evaluate how the current curriculum meets the sustainability learning outcomes Identify need for changes
Design basic curriculum structure	Identify courses with a major emphasis on sustainability
Design integrated curriculum	Identify unassigned sustainability learning outcomes Identify opportunities for integrated learning experiences focusing on sustainability Assign responsibility for sustainability learning outcomes to disciplinary knowledges courses and projects Develop planned learned sequences in order to assure progression

specific technical knowledge that the program aims to develop amongst its students. In contrast, the knowledge, skills and attributes listed in section 2-4 are stated to be common for all engineering disciplines, and are therefore worked out in detail in the CDIO syllabus. However, specifically for sustainability, there exists a common, program-independent, core of science knowledge that all engineers need to know, eg to be able to define the concept of sustainable development, and to be able to describe possibilities and limitations of the use of different natural resources from a sustainability point of view. In addition, there is also program-specific sustainability knowledge: A mechanical engineering program might emphasize energy conversion aspects, a chemical engineering program might emphasize ecology and toxicity aspects, and a civil engineering program might emphasize geological issues, just to mention a few possible variations. In a CDIO curriculum design process, it is up to the program developers to identify both common and program-specific sustainability knowledge. However, university requirements might help in identifying the common parts. Other common sustainability-related learning outcomes emanate from national degree requirements (see section 1) or the Dublin descriptors.

In conclusion, the baseline form of the CDIO syllabus provides a structure for writing a program goal statement where some of the generic sustainability skills and attitudes are present. It needs to be complemented with common and program-specific sustainability knowledge. As a result, the program goal statement will reflect a holistic view on engineering, where the product/process/system lifecycle is the basic context for any engineering activity.

Finally, let us consider the main steps of a CDIO curriculum design process, and discuss how sustainability aspects are considered there. The steps are summarized in table 1. The process starts with the collection of stakeholder expectations on future engineers. Some of the competences that are expected from the graduated engineers will be related to sustainability. These stakeholders include governmental agencies, accreditors and industry. In addition, many universities are stating their own strategies for sustainability. These may include specific credit requirements related to sustainability. The next step is to evaluate the current curriculum and to identify needs for changes. In the first version of the re-newed curriculum, certain courses that can take on sustainability knowledge learning outcomes such as energy conversion or ecology may be identified. In a second step, sustainability learning outcomes of more general character such as ethics or multi-objective may be analyzed. These may suitably be integrated in disciplinary courses or projects. This is a process that may take some time and require support from sustainability experts that coach engineering faculty when searching for sustainability issues that may be taught in the context of their course. In section 4, the application of such a process for Chalmers' Mechanical engineering program will be discussed.

3. Implementing sustainability in curriculum design

The program goals concerning sustainable development discussed in section 2 could be implemented or interpreted differently for different programs. During 2006-2009 a reform project is pursued within all programs at Chalmers University of Technology regarding ESD [9]. The project comprises many different aspects of ESD, among those are:

1. Guarantee and enhance quality in basic courses in SD.
2. Guarantee and enhance quality of SD content in other courses.
3. Give effective support to those who order SD courses.

At Chalmers, the topic of sustainable development is required to amount to at least 7.5 ECTS in the curriculum. The 7.5 ECTS credits include common as well as program-specific elements. By a survey involving faculty at Chalmers teaching in the field of sustainability, it was concluded that the mandatory "core" common sustainability knowledge, skills and attitudes could be visualised as in Figure 2 [9, 10]. The main components include:

A. A definition of sustainable development concerns societal changes on a global level and affects the framework for technical development. The content thus concerns technology, natural sciences as well as social sciences and needs to be tackled in a multidisciplinary approach.
B. A description of critical problems should include global problems of today, regarding population, human needs, resources, technical systems and environmental problems, and specifically issues regarding engineering and sustainability. Engineering conveys meeting human needs by identifying and solving problems within certain limitations. The students need to become familiar with models and tools to analyse the chain of causes and effects from societal activities that results in environmental damage as well as the effect of countermeasures.
C. A discussion on the professional role of engineers. It is important that students identify their professional role in societal change and are capable of reflecting on ethical values, uncertainty or built-in opposite requirements.

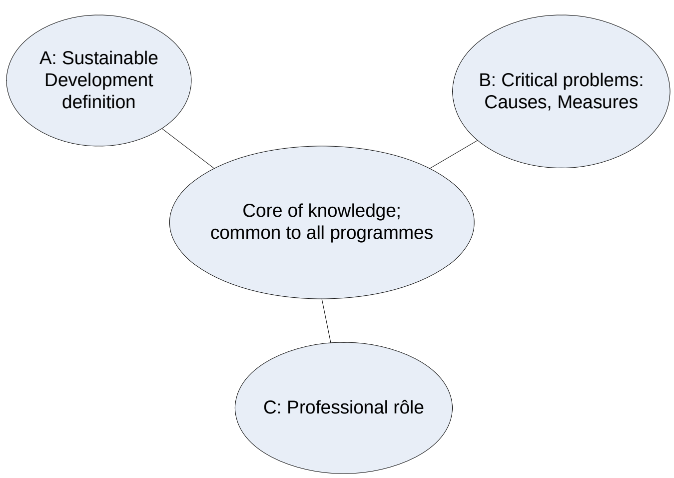

Figure 2. Three aspects of sustainability seen as important parts of a common base of knowledge. From the work of Svanström and Lundquist [9, 10].

As a part of task number one above, a subsequent mapping on how the three issues (A, B, C) in Figure 2 were implemented in different programs resulted in a diversified image. Some programs included a specific course of 7.5 ECTS credits while others had the content shared between courses. There was also a difference in focus; many of the compulsory courses had a focus on A and B. It was recognized that further integration could enhance the students' proficiency regarding their ability to work for "greening" of products, processes and systems within their specific discipline. A resource group was formed to address task two and three above, with members from different disciplines.

The resource group was inspired by the successful work done at Delft. There, it was found that in the case of ESD, a pure top-down approach was not successful. Faculty needed to find the sustainability knowledge, skills and attitudes important for the individual discipline in order to be able to see the possibilities for teaching "greening" within the specific context of their course. Individual dialogue between resource group members and faculty, where faculty described their subject and how it relates to sustainability was found to be a key activity. Based on those meetings, faculty and resource persons could come up with different learning activities that would contribute to fulfil the program goals seen in the context of a specific course. At Chalmers, a working model for the implementation of the process was developed which combines top-down and bottom-up elements. The process, described in Figure 3 and in more detail below, is based on the participation of program directors, fine tuning of program-level goals, faculty workshops and discussions, followed by individual dialogue between resource group and lecturers.

By a formal decision from the Vice President with responsibility for education, the program directors are responsible for the embedding of ESD in their respective programs. The resource group was allocated to be of support in the process. It was found for some of the programs that a one-day workshop aimed to give support for the lecturers in the program could be a key activity. It was prepared by the program director and secretary of education having support from the resource group. Preparations included to benchmark the curriculum, see Table 1, regarding sustainability and to invite selected lecturers to make presentations. They were asked to describe their courses in general, if they incorporated sustainability to some extent or if there were connections to the field but not yet visible in the course. The aim was to cooperatively improve the design of an integrated curriculum, see Table 1.

The participants in the workshop were lecturers, student representatives, study counsellors, secretary of education, program director and members of the resource group. The schedule was the following:

- Program director presented the program goals and discussed how they are fulfilled.
- A speaker well acquainted with sustainability issues gave an introductory talk on the subject.
- Lecturers from 4-5 courses presented their courses, how it is connected to sustainability issues and how it is or could be integrated in the course. One of the courses was the compulsory sustainability course mentioned previously, if it exists.
- Discussions in small groups between everyone on how disciplinary subjects could be regarded from a sustainability aspect. Discussions were supported by the resource group.
- Report from the groups. Program director identifies possibilities for improved learning goals or courses that might integrate some of them.

During the discussion new ideas regarding sustainability in the context of the specific courses were usually found. As a follow-up activity, dialogue between interested lecturers and members of the resource group could further strengthen the lecturer in finding suitable learning activities.

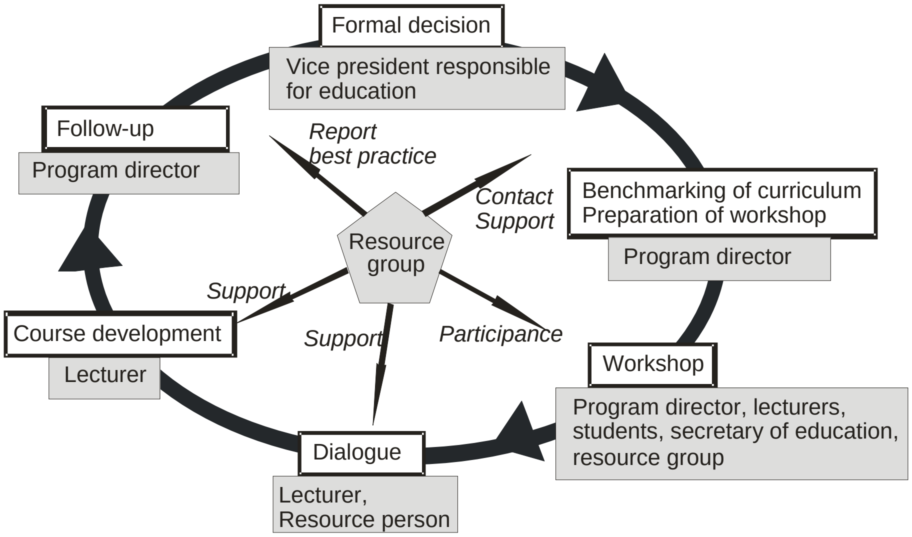

Figure 3. The top-down and bottom-up approach for integration of ESD, developed at Chalmers

4. Implementation of ESD within the mechanical engineering program

It was found that the CDIO approach was highly beneficial in several aspects when integrating ESD. There was previous experience to reflect on generic skills as program goals. The existing structure with a program design matrix made it clear that it would be feasible to integrate goals based on sustainability in the same manner as, for instance, teamwork, which also raises many interdisciplinary questions but still needs to be taught in the context of mechanical engineering. The current program goals regarding sustainability are described in Table 2. It was found that the compulsory SD course Energy and Environment (7.5 ECTS credit units) covered some of the A, B and C parts of the "core sustainability knowledge" described above but there were possibilities for improvement in integrating sustainability in other courses, for instance regarding environmental impact from the product/process/system during the full C-D-I-O cycle.

Table 2. Program goal statements connected to sustainability (translated from Swedish)

2	Be able to lead and participate in development of new products, processes and systems with a holistic view from conceive, design and manufacturing to operate and end-of-life, following a systematic development process adapted to current needs. In more detail this concerns for instance:
2.1	to be able to make material selection being aware of the consequences for manufacturing process, product performance and environmental load during the complete product lifecycle,
2.2	to be able to compare and evaluate different product regarding function, environmental load, production and economy,
2.3	to be able to analyse, design and choose production system and machining process taking into consideration efficiency, motivation, safety and working environment
2.4	to be able to understand and estimate financial, societal and environmental consequences from product development,
3	Be able to understand and estimate human impact on earth climate and ecosystem. To be able to describe existing energy resources (renewable and non-renewable), describe how these can be transformed to other kind of energy sources and understand their limitation and environmental impact.

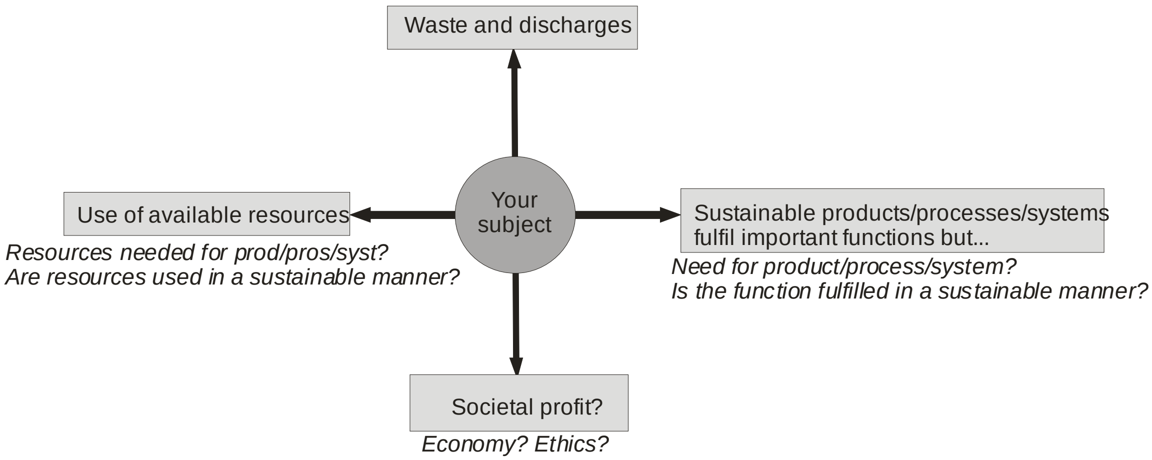

Figure 4. An overview of the material handed out as a basis for discussion in the workshop for mechanical engineering

Discussions were lively during the workshop. A basis for the discussions was handed out to everyone, see Figure 4. Faculty in a CDIO-based program seems in general have become more used to and prone to appreciate generic skills, but of course there were many opposing opinions on the subject. The faculty have also become experienced in formulating learning objectives and accepting a top-down approach combined with support for the benefit of the students. The discussions were mainly about the skills, if they were the right to attain and whether it was the program's responsibility to make sure they were integrated. The presenting lecturers had developed ideas for integration and the dialogue between lecturers was fruitful.

Integrated learning activities on environmental sustainability were possible to develop after the workshop. Since the program is CDIO-based there exists already learning modules centred on the product/process realization process, where sustainability issues were ideal to incorporate. In the introductory design-build course an interactive lecture was incorporated to present possible tools to evaluate a product from the aspect of environmental sustainability. This is to be assessed as a short evaluating text in the final report. In the second project course, "Integrated design and manufacturing", this is further enhanced. The students apply a project model stressing the value for all customers for the whole lifecycle of the product. By applying a wider view on potential customers it was feasible to introduce environmental considerations. In the third project course, "Machine design", the students make a simplified Life Cycle Analysis (LCA) as a part of evaluating a product for a re-engineering purpose.

Finally we would like to remark that even though some integrated learning activities on SD were found and integrated, much more can be done. For instance, integrating environmental evaluation of a product, eg a mobile phone, is difficult as well as valuable but discussing sustainable solutions for solving the function of personal communication is far more complex. The work described here is only a part of a long ongoing process at Chalmers to improve ESD.

Concluding remarks

It was found that the CDIO syllabus is exhaustive regarding sustainability. However, this is not stated under a separate headline and possibly would be beneficial to be clarified for adopters of the CDIO-approach.

A top-down and bottom-up approach for integrating sustainability has been developed and described. It involves stating program-level goals and curriculum design but also support given to faculty such as a program workshop, followed by individual dialogue between resource group and lecturers.

It was found that the previous adoption to CDIO facilitated the process in several aspects. First, there exists experience in adopting program goals and turn it into course learning objectives integrated in a successive manner into the goal matrix. Second, faculty in general have become more used to and prone to appreciate generic skills, have become experienced in formulating learning objectives and to a larger extent accept a top-down approach combined with support. Finally, there exists already learning modules centred on the product/process, where sustainability issues were ideal to incorporate. Some integration of ESD is reported, as a part of a long ongoing process to be continued.

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Marie Arehag is currently Coordinator for the 3-year ESD (Education for Sustainable Development) reform project, pursued within the scope of Chalmers' UNESCO chair in ESD. Since the mid 1980-ies she has worked with curriculum development within Chalmers University of Technology aiming at the inclusion of environmental sciences, humanities and social sciences in engineering education, and recently with pedagogical development reform work. She chaired roundtables on "Learning for Sustainable Development" at the 2d and 3rd International CDIO Conferences.

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