CDIO APPLIED IN THE CONTEXT OF MATERIALS SCIENCE

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Abstract

The applicability of CDIO framework to materials science has been discussed and it is suggested by using the framework it is possible to clarify the problem solving approach in materials science for the students using a paradigm familiar to them. Suggestions are made of materials engineer activities that could correspond to conceive, design, implement and operate and examples of appropriate learning activities are discussed. Learning activities for a CDIO inspired materials science program are suggested to be active learning, integrated learning, design-implement projects, virtual assignments, labs, project courses, virtual projects, sharp assignments using materials science software, taking part in larger design project as a materials specialist, student designed labs in polymer processing or heat treatment of metals, characterization of failed materials or industry as receiver of eco-recommendations. Examples are given from a new master's program in Advanced Engineering Materials, showing cdio adaptation by for instance stressing the problem solving approach by having linked courses on failure analysis and materials selection where teams work on cases or strengthening the link to industry. Examples for improvement are also shown as well as a strategy to promote further development.

Keywords: materials science, CDIO, learning, master's program

Introduction

The CDIO model for engineering education emphasises both analysis and synthesis in education and sets the role of disciplinary knowledge in a professional engineering context. Other key elements are active learning and integrated learning of generic competencies such as communication and teamwork within the engineering science discipline. The CDIO standard 1 suggests that conceiving, designing, implementing and operating of a product or system should be the professional context for engineering education. The model was developed in aeronautical, mechanical, vehicle and electronics engineering and thus there are several examples of excellent design-build-test courses and laboratories suited for manufacturing of prototypes [1-[15][2]. For a graduate in materials science, however, future engineering practice might involve design of products, similar to that of a design or manufacturing engineer, or on the other hand it could be development and manufacture of the materials themselves. Apart from the generic benefit of CDIO as teaching support and program improvement, including a clear strategy for integrated learning of interpersonal and personal skills, as well as a template for accreditation, the question thus has to be raised in what way a program in materials science would benefit from adapting to the CDIO framework.

When applying CDIO to materials science it is also important to consider the multidisciplinary nature of the subject. At the undergraduate level it is usually taught in schools of engineering, in materials science departments or equally in departments of mechanical engineering, physics or chemistry [4]. In one university a masters' degree in materials may be taken within mechanical engineering or engineering physics while in other universities there are dedicated materials science programs. The adaptation might thus look different depending on the curricular context.

Currently many countries are adapting to the Bologna process which strives towards a common European framework for higher education based on 3 cycles; bachelor, master and doctorate (3+2+3 years). In practice this means, in the case of Chalmers, we are challenged to create a 2 year master's program where some students enter from a CDIO-based mechanical engineering program while others come from different universities throughout the world with varying background concerning competencies such as teamwork or communication. Another challenge is idiomatic; Swedish students and teachers will have to adapt to teaching in a foreign language.

The aim of this paper is to discuss conceiving-designing-implementing-operating in the context of materials science, including discussion of when it is applicable and the type of learning activities that support such a view. We will also describe how these findings can be applied to the ongoing process to create a 2-year master's program in materials science.

The applicability of CDIO framework to materials science

For a product there are strong connections between the properties, the manufacturing and the design of the product. On a smaller scale, there are equally strong connections between the properties, the structure/composition, the manufacturing/synthesis/processing and not least the performance of the material itself. (The performance is here considered to be the measurement of the materials' usefulness in actual conditions taking into account of economic and social costs and benefits) [4]. In materials science the second relationship is pictured in a tetrahedron, well known to most material scientists, see Fig.1. Ethnomethodological studies, made by Östberg, of the thinking and activities of designers and manufacturing engineers, with respect to problem solving and selection of materials, have shown that their perspective is different from that of materials scientists [5]. He found that only rarely are materials issues of first order importance in a designer's approach to a new product or the improvement of an existing one. The materials are subordinated in the design process, having a supportive role of materializing the design. The performance is of primary concern, followed by considerations of related materials properties and eventually their structure. There is hence, a difference between materials science and mechanical engineering as disciplines; materials scientists and engineers distinguish themselves from mechanical engineers by their focus on the internal structure and processing of materials, specifically at the micro- and nano-scale [4].

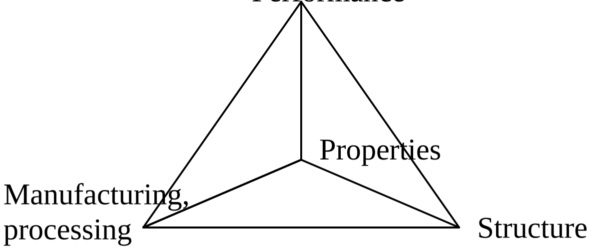

Figure 1. The tetrahedron of materials science

The implication would be that the students, future materials engineers, need to become aware of the difference in the perception of the design process to be able to communicate with design engineers and to add value to the design process, having a different focus. There are restrictions in the computerized selection of materials that a materials engineer is aware of and there are possibilities to develop materials microstructurally designed for a certain purpose such as cutting tools consisting of several layers interatomically bound through vapour deposition.

There are many descriptions of the problem solving process in engineering design process. For instance Centre for Engineering Learning and Teaching (CELT) at University of Washington use the description below derived from analysis of 7 engineering texts, see table 1 [5]. Most engineers and engineering students would probably feel comfortable with such a description, here compared to the C-D-I-O stages of a design process. In materials science, however, faculty teach most materials related subjects starting from the materials science triangle or tetrahedron, see Fig 1, although a recent textbook by Ashby which approaches materials education from the product perspective, may initiate a change in this thinking. The student might not necessarily feel familiar at all with this new materials science paradigm in the beginning, but on the other hand probably has previous training in problem solving according to CELT's approach or a similar one. It would thus be of interest to compare the problem solving approach of materials science to the one of engineering design and discuss whether similarities could be found. Deng and Edwards have suggested that the design process could be clarified in this aspect by differentiating between "materials identification" and "materials selection" [7]. They state that the design task involving materials during conceptual design is primarily related to identifying materials with specific functionalities, while at the downstream design stages the task is "merely" to select one or more materials.

Table 1. Example of a general description of the engineering design process [6] compared to engineering problem solving as defined within the CDIO Initiative [2]

Design activities	**Design stages**	**CDIO stages**
(Identification of a Need) Problem Definition Information Gathering	Problem scoping	Conceive Include defining the need and technology, considering the enterprise strategy and regulations, developing the concept, architecture, and business case.
Generation of Ideas Modeling Feasibility of analysis Evaluation	Developing alternative solutions	Design Focuses on creating the design, *i.e.*, the plans, drawings, and algorithms that describe what will be implemented.
Decision Communication (Implementation)	Project realization	Implement Refers to the transformation of the design into the product, including manufacturing, coding, test and validation.
		Operate Uses the implemented product to deliver the intended value, including maintaining, evolving and retiring the system.

Considering the differences discussed, it is not obvious that the CDIO framework would be fully applicable to materials science. On the other hand, by assuming that also the materials field of engineering could fit into a more abstract and general description, it could actually be possible to improve education by focussing on the methods of problem solving in materials science.

The c-d-i-o in materials science

The CDIO framework compares very well with a generic approach such as described above and even takes it further by highlighting *Operate* as the final stage, see Table 1. In addition Standard 1 focussing on the product and system lifecycle context is definitely applicable to materials science– with a clear lifecycle, from raw material, through process, use, scrapping and recycling. Having this in mind, the suggestions below are concentrated on discussing what is conceived, designed, implemented and operated by the materials engineer.

Conceive

"Problem scoping defining the need and technology, considering the enterprise strategy and regulations, developing the concept" or "Problem definition and information gathering". For materials science this first stage could be related to e.g.:

- materials identification or selection for instance regarding
    - new products
    - environmental adaptation of a product
    - demand for a light-weight design
- development of new materials or improvement of an existing one
- material dependent process optimisation, e.g. joining of parts or failure in service
- optimisation of processing of raw materials

The activities involved to tackle the problem sets above could be characterisation of currently used materials regarding properties, performance, structure (e.g. corrosion, fatigue, creep, wear, brittleness, failure analysis). Other activities would involve literature analysis; correlating the results of analysis to the other corners of the tetrahedron; one of the common tools during the career of a materials engineer is for instance the Handbook of Metals. It could indeed also be cooperation with other engineering disciplines for simulations or life cycle analysis. All the problem sets above could be found, with different objectives, in long term research related projects as well as in short term industrial development.

Design

"Focuses on creating the design, *i.e.*, the plans, drawings, and algorithms that describe what will be implemented" or "Generation of ideas, modeling, feasibility of analysis, evaluation" Could in the case of materials be:

- specification of materials properties/structure
- specification of environmental impact or sustainability
- definition of a change in the processing method
- design of a composite, layered material, functional thin film, structural foam or biomaterial

Activities involved in the design phase would be handling and structuring of results from the conceive phase and it could in many cases be supported by software such as for instance Cambridge Engineering Selector (CES) for materials selection, Thermocalc for simulation of phase transformations or JMatPro for prediction of materials properties.

Implement

"Refers to the transformation of the design into the product, including manufacturing, coding, test and validation" or "Decision and communication". Translated into materials:

- fabrication of the new material/product, processing routes, methods such as injection moulding, casting, forging, thin film deposition, machining etc.
- full scale test of products/materials testing
- again process optimization

This phase is very close to manufacturing, resulting in collaboration between manufacturing and materials or materials engineers specializing in manufacturing. As the third point suggests, for any kind of implementation the assignment could loop into the conceive stage.

Operate

"Uses the implemented product to deliver the intended value, including maintaining, evolving and retiring the system". Again translated into materials:

- failure in service such as for instance corrosion in a power plant, creep of turbine blades, welds fracturing due to precipitation in the heat affected zone
- development of recommendations for recyclability
- non destructive testing (NDE)
- optimization of performance

Activities in this phase would be in closely related to production. Characterization is, as for the conceive phase, a key activity including both NDE and analysis of parts failed in service. Activities could also here generate new problems pointing towards the conceive stage.

Learning activities supporting a CDIO influenced materials science program

Active learning

A vital part of introducing CDIO concepts is changing from a lecture based towards a student centred educational approach. It is well documented that students learn more effectively being fully engaged and responsible for their own learning [8][9]. There are already many examples of best practice in this area, both generic such as muddy cards [10][2] and examples more closely connected to the materials science context. Case studies are an approach that presents material to students in context, thus bridging the gap between theory and practice. At the University of Birmingham they have implemented case studies in several courses, decreasing the number of lectures, for instance by having groups of students working on specifying joining processes for specific components [10]. At the University of Liverpool the students experience "What´s it made of? (WIMO)" where student teams develop a unique materials classification scheme, which is to be applied to three unknown artefacts [12]. The teams brainstorm materials properties and have to research terminology and property value ranges. Another active learning module used at both Liverpool and Chalmers is the web-based material and process selection exercise "21st Century steel for Car Doors" developed in collaboration between International Iron and Steel Institute research and MATTER at University of Liverpool [13] The intended learning outcomes include both very specific technical understanding as well as more general transferable skills associated with industry.

Integrated learning of professional skills

Another aspect of introducing CDIO concepts concerns integrated learning of professional skills such as communication. In general materials science courses include significant amounts of experimental work in teams as well as written and oral presentations, although these aspects could be further developed by increasing students' awareness of what they learn, supporting learning and assessment of these skills. In this aspect the examples of best practice found at the cdio homepage is not disciplinarily restricted.

Design-build experiences

A third key element is design-build courses. To develop design-build courses a systematic approach could be adopted by considering learning objectives in the specific context [3], but it is not easy to develop applied design-implement courses in materials science. Experimental equipment is expensive and requires long training times. One might raise the question; maybe participating in a larger design-build project as a materials specialist doing materials identification and selection is enough? This could be supported by smaller scale projects with emphasis on conceive-design. One example from the master's program at Chalmers is failure analysis, where the students characterise a fractured part, report and give suggestions on how to avoid such a failure. Another possibility to experience implementation is case studies or projects set up in virtual settings [12]. A dedicated materials science design-implement experience could for instance be design of a given sheet material for a specific purpose. Activities would include analysis of the material regarding composition, finding parameters of mechanical properties, making detailed suggestions for a heat treatment, use of an oven and performance of final tests. Many financial and logistic problems regarding characterization and ovens would have to be overcome, though, if this is to be done in a larger scale and the idea remains thus as a challenge.

Learning activities supporting the c-d-i-o stages

It is difficult to make a distinct difference between different learning activities supporting the C, D, I and O. Active learning, a project course or a design-build experience as discussed above could support all stages. Nevertheless a few attempts are made and summarised in Table 2. In addition, returning back to Standard 1 – the life cycle of the product as a context, would result in inclusion of discharges from mining, scarcity of raw materials, life cycle analysis and recycling in material science or product centred courses [14]. Good examples could be found at the University of Delft which has sustainability issues integrated into most courses in addition to specialized courses on sustainability [15].

Conceive. Usually materials science courses already focus on characterisation of currently used materials regarding properties, performance, structure (e.g. corrosion, fatigue, creep, wear, brittleness, failure analysis) including literature analysis. Improving the cdio aspect could be to done by for instance problem based teaching, or clearly stressing the underlying need for characterization, as is described for active learning above or for the master program below. Larger project courses in cooperation with other engineering disciplines for simulation or life cycle analysis could also be a challenge.

Design. Evaluation of results from the conceive phase and development of recommendations regarding materials selection, heat treatments, designed layers could be done virtually as in the example of "21st Century steel for Car Doors" above. Again, students acting as materials specialists in a larger design project course supports learning of design. In many materials science departments students are trained in the use of software such as CES, Thermocalc and JMatPro. From a CDIO aspect it would be interesting to make the assignment sharp by adding the implement stage, either by letting the students participate in research or by having companies involved.

Implement. This is difficult for materials science, processing and manufacturing requires expensive equipment which is not necessarily easy to fit into teaching. Apart from taking part in larger design projects or cooperate with companies as described above, some processing experiences could be developed for smaller classes by for instance letting students design a process for polymer processing or heat treatment of metals and then carry it through.

Operate. Activities in this phase would be closely related to production and the enterprise. Characterization is, as for the conceive phase, a key activity including both NDE and analysis of parts failed in service. Learning activities could be labs, study visits or characterization where industry supplies parts failed in service or receives eco-friendly user recommendations for products on the market.

Table 2. Examples of learning activities that support the CDIO approach in materials science

Generic design	CDIO stages	Materials Science	Activities and examples of learning activities
Problem definition Information gathering	Conceive	• mtrls identification/ selection o new products o env. adaptation o light-weight • development of mtrls • optimize processing of (raw) mtrls	*Characterization of properties, performance, structure stressing the underlying need (e.g. corrosion, fatigue, creep, wear, brittleness, failure analysis)* E.g. problem based, virtual assignments, hands-on labs, project courses
Idea generation Modeling etc	Design	• specification of mtrls properties/ structure • specif. of env. impact • def. process change • design mtrls	*Evaluation of analysis results & recommendations for materials selection, heat treatments, designed layers* E.g virtual projects, sharp assignments using CES, Thermocalc, JMatPro.
Decision Communication	Implement	• make new mtrls/ product, processing: injection moulding, casting, forging, thin film deposition, machining etc.. • full scale test of products • optimize processing	*Close to manufacturing, cooperation or specialization* E.g. taking part in larger production/design project as a materials specialist, student designed processing labs in polymer production or heat treatment of metals.
	Operate .	• failure in service corrosion, creep, welds fracturing etc. • development of recommendations for recyclability • NDE • optimize performance	*Close to production/enterprise. Characterization is important* E.g. characterization labs. Industry supplies failed parts or as receives eco-friendly user recommendations for products on the market.

The CDIO-syllabus and materials science

The syllabus has shown to be useful in creating for instance learning objectives for the program discussed below. The terminology, especially for 4.x, “conceiving, designing, implementing and operating systems in the enterprise and societal context”, needs to some extent be “translated”. For instance build can be read as implement, product as system, material or product. Regarding more substantive conceptual changes in 4.x, or level of detail (x.x, x.x.x, x.x.x.x) for application it is an issue that needs to be addressed but is beyond the scope of this paper.

Example from the masters’ program in Advanced Engineering Materials

The program used as an example is the 2 year master’s program in Advanced Engineering Materials, starting autumn 2007 at Chalmers. The estimation of the size of the program is currently around 20 international students and 10-14 Swedish students. Most courses are possible to choose as voluntary in other programs and the total number of students attending materials science courses is thus difficult to estimate. The program, as all master’s programs at Chalmers, consists of 45 ECTS credit units (3/4 of a year or six courses) which are mandatory. The courses are: Materials Characterisation and Failure Analysis, Materials Selection and Design, Engineering Ceramics, Engineering Metals, Engineering Polymers, and a choice of Functional materials, Joining technology or Composite and Nanocomposite Materials. In addition the student may specialize in one of four areas; *Engineering materials* (Joining Technology, Composite and Nanocomposite Materials, TEM & crystal deformation, Phase Transformations), *Functional materials* (Functional Materials, Semiconductor Materials Physics, Liquid Crystals: Physics & Devices, Materials in Medicine), *Materials and manufacturing technique* (Joining technology, Environmentally adapted product development, Fundamentals of Micro- and Nanotechnology, Modern manufacturing technique) or *Materials and applied mechanics* (Composite and Nanocomposite materials, Fatigue Design, Materials Mechanics, Phase Transformations). The different themes reflect different kinds of engineering areas a material specialist may work in, in industry or in university. Alternatively the student may select an individual combination of elective courses. The program is finished by a diploma work of 30 ECTS credit units, often done in industry or at the university working with an assignment from industry.

Program goal statement

For the development of the master’s program, it was necessary to decide on which parts of CDIO process that were appropriate. Obvious ones to start with were generic program goal statement, aligned course learning objectives, elements of active and integrated learning and support for staff development. The program goals have been developed on the basis of CDIO syllabus, the Dublin descriptors and the Swedish rules for the degree “civilingenjör”. The resultant program goal statement is shown in appendix I, and is of course something that is to be renewed and improved continuously in cooperation with industry as well as faculty. Among the courses there are elements of active learning, labs, projects, case studies and integrated learning of communication abilities in addition to lectures and tutorials, of which some are new and others have been for many years.

3+2 years, what skills should be trained in a Master’s Program?

Specifically there are issues that are difficult when cutting a cdio based education in three + two year such as assignment of learning objectives and activities in BSc and MSc level. What increase level of proficiency is expected for the master’s in CDIO skills? Maybe only the ability to deal with more complex problems. The basic CDIO skills should be at the level of a graduate from a 3-year program; the problem is that not all entrants will have graduated from a CDIO program. There are differences in the training of professional skills between the Chalmers students and students coming from universities with no such training. The question then arises; how do we “fill in the skills” of the students who don’t meet input standards? This is a challenge. One alternative is by running a specific module (outside the normal credit system) for such students. This is not just a Materials problem but arises for all Masters programs, whether 3+2, 4+1 or 4+0. In the current program we are attempting to overcome this by informing the international students from the beginning, running an introductory course for all international students held by the library. In addition, in the first course, they are immediately mixed with students trained in teamwork which can act as role models or mentors.

Learning activities linked to c-d-i-o

A question that arises is: where should the two design build sequences be? For comparison, at Liverpool, there are planned 2 for both 3-year BEng and 4-year MEng. In the master’s program described here it is solved such as the students can participate in larger projects, e.g. Formula Student or other design projects, together with students from production or design. This is voluntary though. The aim of focussing on professional problem solving in materials science is reflected in the mandatory courses ”Materials characterisation and failure analysis” and “Materials selection and design” that include case studies performed in teams. The starting point is “disassembly”; how to evaluate the microstructure and the fracture of materials which has failed during operation. Students are actively implementing a method and try to find evidence from failure. From failure analysis the focus then changes to the role of materials in product development and active training in the use of professional software in materials selection. The elements of design-build have thus possibilities for improvement, maybe as described above in *Design-build experiences.*

The discipline materials science is very broad and engineers/researchers are often specialised on a group of materials. The mandatory courses (advanced level) on ceramics, metals and polymers are thus separated, each of them focussing on engineering aspects such as processing, characterization, properties, areas of application and other aspects within a products’ lifecycle for the respective material.

Integrated learning of professional skills are found in several courses for instance in the problem based voluntary course on environmental adaptation of products, developed within the CDIO Initiative. In the aim to prepare the students for a professional career there are connections to society and industry through guest lecturers in some courses and projects closely connected to industry or academic research in others. The ceramics course is taught by IVF Industrial Research and Development Corporation. To promote further interaction/networking, several of the elective or specialisation courses are shared with other master’s programmes such as Applied mechanics, Product Development, Biotechnology, Microtechnology, Industrial Ecology or Applied Physics.

Continuation of the development of the program

The program has been developed starting from an existing international master’s program in Advanced Material and also from a part of the former MSc program in Mechanical engineering that is now cut in 3+2. Some courses are new but many of them are good existing courses and attempts are made instead to encourage faculty to improve and embrace the concept of active learning and CDIO. A part of that work could be to continue the discussion on what the materials engineer conceive, design, implement and operate. In order to ensure quality, create a forum for discussion and a starting point for possible projects, a reference group is formed consisting of faculty, industry and students. The assignment is to analyse overall performance and quality issues (such as pedagogy and the program being gender and ethnicity neutral).

Concluding remarks

The applicability of CDIO framework to materials science has been discussed and it is suggested that by using the framework it is possible to clarify the problem solving approach in materials science for the students using a paradigm familiar to them. Suggestions have been made of typical materials engineer activities that could correspond to conceive, design, implement and operate activities.

Learning activities for a CDIO inspired materials science program have been discussed and incorporate active learning, integrated learning, design-implement projects and activities more closely linked to the c-d-i-o stages such as problem based learning, virtual assignments, hands-on labs, project courses, virtual projects, sharp assignments using materials science software, taking part in larger production/design project as a materials specialist, student designed labs in polymer processing or heat treatment of metals, characterization of failed materials or industry as receiver of eco-friendly user recommendations for products on the market.

Examples are given from a new master's program in Advanced Engineering materials, showing cdio adaptation by for instance stressing the problem solving approach by having two linked courses on failure analysis and materials selection where teams work on cases or strengthening the link to industry by having courses given by institutes. Design-build courses are offered by cooperation with production engineering. Examples for improvement are also shown as well as a strategy to promote further development.

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Appendix I: Program goal statement for Advanced Engineering Materials 2007

Graduates shall to be able to independently and professionally participate in and lead projects concerning aspects of materials in conceiving, designing, implementing and operating products, processes and systems. They shall also be able to independently and professionally participate in and lead materials research, industrial or academic.

1. **Knowledge and understanding:** Graduated students should be able to:
   - 1.1. attain a basis of deep disciplinary knowledge to be able to recognise and describe properties for metals and explain how these are coupled to the structure on an atomic as well as microscopic scale
   - 1.2. attain a basis of deep disciplinary knowledge to be able to recognise and describe properties for polymers and explain how these are coupled to the structure on an atomic as well as microscopic scale
   - 1.3. attain a basis of deep disciplinary knowledge to be able to recognise and describe properties for ceramics and explain how these are coupled to the structure on an atomic as well as microscopic scale
   - 1.4. evaluate and draw conclusions concerning different materials' fields of application based on knowledge of material properties
   - 1.5. explain how different processing methods can influence the structure of a material and whereby its properties
   - 1.6. describe and draw conclusions based upon the scientific foundation and proven experience of materials science as well as show insight into current research and development work
   - 1.7. demonstrate knowledge and understanding that is founded upon and extends the learning objectives for materials science, mathematics, applied mechanics, manufacturing technology and thermodynamics associated with bachelor's level
   - 1.8. *For Engineering Materials:* apply fundamental concepts concerning materials' behaviour on the microstructural scale in improving mechanical properties of the material, joints between materials or a resultant product
   - 1.9. *For Functional Material:* describe and discuss concepts concerning material's electronic, optical and magnetic properties on nano- and microscale in applications where these properties are of primary interest
   - 1.10. *For Materials and Manufacturing:* describe and choose methods for machining and joining for different materials and discuss influence of different manufacturing parameters on material's resultant behaviour on both micro- and macroscale
   - 1.11. *For Materials and Applied Mechanics:* compute and dimension for safety, perform simple simulations using constitutive models being aware of the differences in material behaviour, ageing, and failure on a mesoscopic and a macroscopic scale
2. **Skills and abilities:** Graduated students should be able to:
   - 2.1. critically, independently and creatively conceive, design, implement and operate products, processes and systems such as design of materials, materials selection, failure analysis and prediction of properties.
   - 2.2. describe, address applicability of characterisation methods and within given constraints plan and carry out qualified tests using e.g. hardness measurements, tensile testing, optical, scanning electron and transmission electron microscopy or X-ray, Auger or ESCA analysis
   - 2.3. participate in research and development to create new knowledge and develop originality in ideas.
   - 2.4. create, analyse and critically evaluate different technical solutions
   - 2.5. critically and systematically integrate knowledge and predict and evaluate material behaviour and events, also with limited or incomplete information
   - 2.6. consider relevant scientific, societal and ethical aspects fulfilling human needs and the society's goals for sustainable development in the context of materials science
   - 2.7. work with projects in a group, solving open problems while being aware of different stages in project work and group dynamics
   - 2.8. communicate, in a dialogue, their conclusions and the rationale underpinning these, to both specialists and non-specialists, nationally and internationally, based on fundamental concepts, results from material characterisations or theoretical predictions
3. **Formulation of judgements and attitudes:** Graduated students should be able to:
   - 3.1. formulate judgement concerning selections of materials or development of new materials that include reflecting on scientific, social and ethical responsibilities and to demonstrate awareness of ethical aspects on research and development work
   - 3.2. show insight concerning consequences for manufacturing, product behaviour and environmental load during the full life cycle
   - 3.3. draw conclusions showing insight into the possibilities and limitations of materials science, its role in society and the responsibility of humans for its use, applying social, environmental and ethical considerations
   - 3.4. identify their need for more knowledge, and to continuously develop their competence