CDIO BASED ENGINEERING DESIGN AND OPTIMIZATION COURSE

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ABSTRACT

In order to design competitive products that meet today's challenges, future engineers need knowledge and experience in applying and integrating optimization theory in the engineering design process. The Chalmers course Engineering Design and Optimization addresses this need and was developed and first offered in the fall semester of 2013. This paper provides a detailed account of the course development experiences, teaching methods and course evaluations using CDIO Standards. It also includes a discussion of the learning objectives, required resources, instructional processes and student assessments. The course is analyzed to see to what extent the course aim is satisfied and highlight areas of improvement. Three projects are carried out in groups of two students. The projects are a cantilever design-build-test exercise, a redesign project that involves material selection, and a multi-disciplinary design project of an engine component using multi-physics software. The assignments are assessed with respect to both engineering criteria as well as reporting and communication. The course is believed to be novel in the way optimization theory and tools are taught as an integrated learning experience with engineering design and physical prototyping. The course has had a great impact on the students' choice of master's thesis project. The number of optimization-focused master thesis projects has increased from two or three to around 15 annually. Several of these projects are multidisciplinary and joint projects between departments of Applied Mechanics and Product & Production Development. The course has also initiated a valuable partnership with industry on optimization that now has grown to a network with 20 industrial and academic members.

KEYWORDS
Optimization, Engineering Design, Design-Build-Test, CDIO Standards: 2,5,6,8

INTRODUCTION

Optimization has been used in industry for decades to cope with the increasing needs to design and develop competitive products that offer profitable business propositions. As the engineering systems in sectors such as the automotive and aerospace industries become increasingly sophisticated and intra- and inter-connected, multidisciplinary design optimization (MDO) has emerged as the engineering design support tool for managing, and eventually exploiting, these complicated interactions to cope with more and more stringent, and typically

competing, requirements, see, e.g., (Brophy F., 2009; Haar & Brezillon, 2012; Lagloire, 2014; Piperni, DeBlois, & Henderson, 2013). Moreover, the societal challenges in the next few decades are huge, e.g., the growing population requires more efficient use of material and other resource. It is the responsibility of engineers to find optimal solutions to use resources more efficiently. While research in optimization has made significant advances in theory and algorithms to address different types of optimal design problems, optimization is still not a ubiquitous part of engineering curricula. Teaching and employing optimization theories, methods and techniques to help future engineers learn how to weigh constraints and criteria against one another and select best possible design solution should be a vital part of any engineering education.

Since the five-year program in mechanical engineering (ME) at Chalmers University of Technology is a CDIO program (CDIO, 2017; Crawley, 2007), there already existed several design-build-test product development projects in which the students realize a product from the need to a functional model or prototype. However, until a few years ago the program lacked an educational event in which students trained and learned to use algorithms, methods and software to optimize a product/system. This was true despite the fact that there existed several elective courses on optimization given by the mathematical sciences department, possibly because those courses focused on theories and algorithms, rather than methods and applications, and very few ME students took those courses. Consequently, the students have mostly practiced trial-and-error methods in combination with simulations to find "good enough" solutions before going to prototyping. A more up-to-date strategy would be to use a more systematic approach based on analysis, simulations and optimization to find optimal solutions. To address this gap the ME program has, for the bachelor part, designed its own simulation-based math education including basic optimization theory and algorithms (Enelund, 2011) and applied optimization in basic mechanics. While for the master's level a new interdisciplinary course was developed called Engineering Design and Optimization, which for three years has been an elective for students studying Applied Mechanics, Automotive Engineering, Engineering Materials and Product Development. This course teaches practical approaches to design optimization, guiding the students through different ways to apply algorithms and tools to find the best possible solution to a design problem with some objective or set of objectives, highlighting hands-on experience with addressing different types of problems, along with specific ways that economic, environmental, and social sustainability needs can be accounted for in a design optimization context.

This paper aims to bring forward experiences from the development, teaching and evaluation of the Engineering Design and Optimization course. In particular, the paper aims to

- provide a detailed account for course development experiences involving faculty from different departments, teaching methods and course evaluations,
- provide a discussion of the learning objectives, pedagogy, resources and instructional processes, as well as assessments and course evaluation,
- analyze the results to see to what extent the course aims and goals are satisfied and to discuss whether the intentions of the course have been realized?, and
- discuss in what way the students are better prepared to find optimal solutions in the development of products and systems?

The content of the paper is structured as follows: First we describe the course including the intended learning outcomes, course aim, teaching activities and assessment. The three project assignments are then further on described in some detail and discussed. Student course evaluations together with input from employees and alumni are used to determine to what

degree the course goals have been achieved. Finally, the findings from this analysis together with a summary of the experiences from the course including challenges and success factors are discussed.

COURSE DESCRIPTION

The Engineering Design and Optimization course is given jointly for the master's programs Applied Mechanics, Automotive Engineering, Product Development and Materials Engineering at Chalmers University of Technology. These master's programs are all independent programs and integrated parts of the five-year program in mechanical engineering. This means that the course has a mix of students from different backgrounds at Chalmers along with additional students joining from different universities world-wide. The size of the course is 7.5 ECTS (European Credit Transfer System, where 1.5 ECTS corresponds to 40 working hours) and runs over a nine week period.

Approximately five years ago the need for an engineering design course in combination with optimization was identified by the dean of education and the program faculty. Key elements were discussed, identified and agreed upon, such as that the course should be built around several integrated design-build-test projects with elements of multidisciplinary, simulation-driven design and optimization. The program advisory board with representatives from industry as well as the Chalmers educational managements welcomed the initiative and supported it. A working group with engaged and committed faculty from three departments (Applied Mechanics, Materials & Manufacturing Technology and Product & Production Development) was assembled. The working group was led by the head of the ME program and a development budget was given by the Dean of Education. The budget made it possible for the faculty to put a significant number (about 200) of working hours in the development. The guiding principles of the course development were CDIO (e.g., Standard *2 Specific, detailed learning outcomes for personal and interpersonal skills, and product, process, and system building skills, as well as disciplinary knowledge, consistent with program goals and validated by program stakeholders,* Standard 5 *Design-Implement Experiences,* Standard 6 *Engineering Workspaces* and Standard 8 *Active Learning*) and constructive alignment, i.e., aligning intended learning, teaching activities and assessment (Biggs, 2007).

The working group began by formulating the course aim and entry requirements. The entry requirements were chosen to be broad, advanced and active within product development, programming, simulations, materials and mechanics. Next, intended learning outcomes (ILOs) were formulated based on the aim of the course, entry requirements and input from students, faculty and industry. The learning outcomes were then presented and scrutinized at program faculty meetings and links between the course and the programs were discussed and established. After about six months of development work, the course was launched and delivered to around 40 master's students in quarter one of the fall semester of 2013. Since then the course has been annually reviewed and refined with respect to learning outcomes, teaching activities and assessments.

Course aim

The course aims at integrating traditional design methodologies with concepts and techniques of modern optimization theory and practice. With this approach the students are expected to learn to create design solutions that are creative and have better performance (e.g., lighter, stiffer, more reliable etc.) compared to traditional methods.
Specifically, the course aims to:

- Demonstrate a selection of different tools and methods for optimization of mechanical products and structures,
- Demonstrate a design process for improvement of components in products and mechanical systems,
- Demonstrate the iterative nature of the development chain including modeling-analysis-test,
- Use and familiarize students with modern CAE tools, and
- Demonstrate how to incorporate material selection as a part of the product development process

Intended Learning Outcomes

The intended learning outcomes (ILOs) describe students expected knowledge, skills, and attitudes after completing the course as shown in Table 1.

Table 1. Intended learning outcomes

ILO1	Show ability to master the complete development chain including modeling-analyses-test-evaluation
ILO2	Identify areas for improvement in a new or an existing product design
ILO3	Identify and choose appropriate material alternatives for a product
ILO4	Apply previously-learned design methods and tools to practical problems
ILO5	Create appropriate simulation models of the design problem
ILO6	Use Computer Aided Engineering (CAE) tools to design and simulate product performance
ILO7	Formulate design optimization problems based on project or product requirements
ILO8	Apply numerical optimization techniques and computer tools to solve optimization problems
ILO9	Interpret optimization results for design decision making (e.g., material selection, geometry, manufacturing)
ILO10	Create CAE drawings for use with three-dimensional printing tools
ILO11	Iterate on design solutions to continually improve a product's design and performance
ILO12	Communicate design solutions, including rationales for a given choice, advantages, and disadvantages over alternatives

The Conceive, Design and Implement Stages of CDIO are explicitly formulated in the ILOs. The Operate Stage is manifested in project assignments one and two and included in ILO1 and ILO2. In project assignment one the students manufacture and test their design solutions while project assignment two starts with scrutinizing the failure of an existing consumer product.

Course structure

The course contains lectures, exercises, project assignments (PAs), workshops, a written midterm and a final exam, see Table 2. The course emphasizes on teaching the students about optimization and how it can be integrated in the design and product development process. This is realized through mixing theory lectures together with specific workshops where software and optimization applications are exercised. The course involves an introduction and training in optimization software, where the students are introduced into the topic via traditional lectures, guest lectures and workshops. There are additional recorded video lectures which are both theoretical and training videos on how to operate certain software. These videos are uploaded on Chalmers' learning platform to be easily accessible for the students. The course has intentionally placed a majority of the lectures early in the course in order to support the students' progress with the three project assignments, see Table 2.

Table 2. Number of teaching activities per type for each study week

	Study Week								
Teaching Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Lectures	3	3	2	4	1	3	1	1	
PAs sessions	2		1		1			1	
Workshops		1	1		2	1	3		
Midterm and Final Exam				1					1

Teaching and Learning Activities

The course structure is divided into a number of activities which are carried out during the nine -week schedule. The activities include: traditional classroom lectures, industrial guest lectures, project assignment instructions, and workshops. The traditional lectures begin with an introduction to the engineering design process and iterative design-build-test loops.

Next, optimization is introduced with a focus on how to formulate optimization problems and the principle concept of different algorithms. The lectures that follow present deeper dives into optimization in the context of applied mechanics, materials selection, multi-objective problems (MOO), design for quality, design for sustainability, and multi-disciplinary systems design. Efforts have been made to align the lectures to the project assignments and workshops so that the student can quickly move from working with theoretical concepts to hands on implementation and practice. The Industrial guest lectures are used to give a broader view of optimization in industrial contexts and also to highlight the current state of art implementations in industry.

The main course literature is the textbook “Principles of Optimal Design - Modelling and Computation” by P.Y. Papalambros and D.J Wilde (2000) accompanied by texts on topology- and structural optimization (Bendsoe & Sigmund, 2003; Christensen, 2009). The engineering design processes and aspects are mainly inspired from (Pahl, 1996; Ulrich, 2008)

Learning Assessments

The course contains three mandatory design projects, midterm and final exam which together constitute the assessment and build up to the final course grade. The links between intended learning outcomes, teaching activities and the assessment are illustrated by the Course design matrix in Table 3. A closer look at the matrix reveals that the project assignments may be regarded as the corner stones of the course as they cover the full spectrum of the ILOs.

Table 3. Course design matrix. L=lecture, GL=guest lecture, W=workshop and PA = project assignment.

		Intended learning outcome											
	Teaching and Learning Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
L1	Introduction & general engineering approach	X	X										
L2	Introduction to optimization		X			X		X	X			X	
L3	Applied mech. structural dynamics, FEM	X	X		X	X	X				X		
L4	Modelling	X	X			X							
L5	Optimization algorithms & tools								X	X			
L6	Material selection & evaluation		X	X									
L7	Concept & Embodiment Design	X	X		X							X	
L8	Applied mech. Structural design optimization	X				X	X	X	X				
L9	MOO & trade-off analysis							X	X			X	X
L10	Fatigue and age-based failure	X	X	X		X							
L11	TRIZ					X							
L12	Applied mech. Topology opt. applications	X				X	X	X	X				
L13	Quality & uncertainty management					X			X				
GL1	Applied Optimization- ANSYS					X		X	X				
GL2	Topology optimization in automotive							X		X			
GL3	Optimization in practice (Aerospace)							X		X			
PA1	PA1 Introduction and tutoring	X	X		X	X	X	X	X	X	X	X	
PA1	PA1 Cantilever Challenge Live Competition	X											X
PA2	PA2 Introduction and tutoring	X	X	X	X	X	X	X	X	X		X	
PA2	PA2 group presentation	X											X
PA3	PA3 Introduction and tutoring	X			X	X	X	X	X	X		X	
PA3	PA3 Simulated engineering briefing meeting	X											X
W1	Optimization Using MATLAB								X				
W2	Material Selection with CES Edupack		X										
W3	Metamodeling-Design of Experiments					X							
W4	Reverse Engineering	X	X										
W5	Multi-objective optimization in MATLAB								X	X			
W6	COMSOL Workshop						X		X				
W7	Mathematical Exercise Workshop					X	X	X	X				
	Learning Assessments												
	PA1	X	X		X	X	X	X	X	X	X	X	X
	PA2	X	X	X	X	X	X	X	X	X		X	X
	PA3	X			X	X	X	X	X	X		X	X
	Mid-Term Exam				X			X					
	Final Exam	X			X			X	X				

PROJECT ASSIGNMENTS

In the early development of the course it was decided to have a strong emphasis on fast design iterations and to focus design activities on embodiment design and detail design phases rather than conceptual design. In other project-based courses in the mechanical engineering curriculum it is common to run projects with a broad design scope usually positioned in the early phases of the design cycle. Commonly the students are well introduced to the conceptual design phase, however, a frequent experience is that there is not enough time to work with the embodiment design and detail design phases where the system boundary and architecture have already been predefined. Still the backbone of the assignments is the full design-build-test process based on the CDIO standard 5.

The three projects in the course are:

1. Cantilever challenge - Introduction to design-build-test cycle and topology optimization
2. Redesign, material selection and optimization of a failed product
3. Multi-objective optimization
    a. of a vehicle suspension system in MSc Adams (course rounds 1 and 2)
    b. of an engine encapsulation component (course rounds 3 and 4)

In the following sub-sections the details of the assignments will be described in more detail.

PA1 - The Cantilever Challenge

In the first assignment the students are introduced to the design-build-test design cycle as well as topology (TO) and shape optimization. The specific design task is to create the lightest and stiffest cantilever beam possible given a specific design domain and load condition. The assignment is presented to the students after the first lecture on Monday morning the first study week. The ambition is to get the students involved early on in the course, however, this leads to a dilemma since almost no course material have been presented yet the first day. This is handled by separating the first project into two main design iterations. In the first part of the project, see Figure 1, the students are given the design domain, performance objective function, constraints and material properties. They are further on asked to, together with a peer student, design the best possible cantilever beam they are capable of based on their previously gained knowledge and experience. The deadline for the first iteration is on the Wednesday the same week, hence they have to complete the task in two days. A high level of instructive process guidance is given including suggestions on how much time to spend on each sub-task in the design loop. The design loop is defined as five main steps; Requirements evaluation, design sketch, CAD model, FE analysis and finally performance evaluation. The delivery for the first iteration is a one page PowerPoint slide including the initial design sketch, CAD model, FE analysis and the resulting performance number.

After completing the first iteration the students are given a lecture and one workshop tutorial on topology optimization. Essentially they are handed a new and more powerful tool to apply in the second part of the project. Due to the limitation in time it is not possible to provide tutorials and lectures in order to conduct topology optimization in 3D. Hence more simple 2D software are presented. The first is the BESO2D topology optimization software developed by RMIT University in Melbourne (2017). The second is the 2D version of ANSYS Mechanical Optimization tool (ANSYS, 2016). The students are also encouraged to download the TO app TopOpt developed by DTU (2017).

One of the key perspectives that is emphasized during the project is that design optimization essentially is an automated version of the design-build-test cycle that the students performed manually in the first part of the project. Most students perform more than 10 iterations, and possible due to the competition, compare performance results with other groups. Five days before the competition the students submit the final beam design. The models are checked for CAD modelling errors and gets 3D printed in a solid acrylic polymer. For the competition an experimental test device have been developed in order to easily mount each cantilever beam and apply the 100 N load. The mass of the beam is measured using a laboratory scale and the deflection is measured using a dial indicator. The data is inserted into an excel score board displayed via a projector so that all the students can track who is leading the competition. The test results are discussed in class with regards to simulation validation based on their predicted deflection and performance from the FE simulations. In some cases the students have not considered elastic (local) buckling leading to beams not being able to withstand the load.

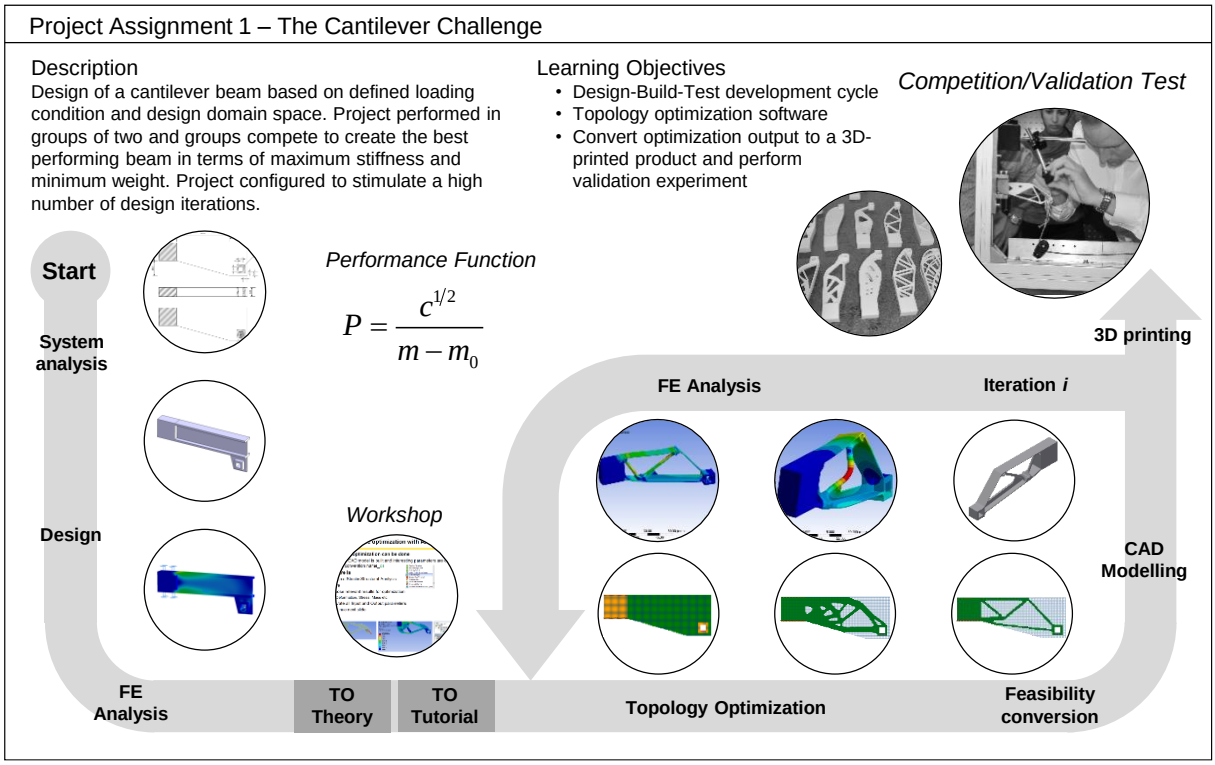

Figure 1. Illustration of the two-stage iterative design process in the first assignment.

PA 2 - Redesign, material selection and optimization of a failed product

The second assignment begins from the standpoint of the “Operate” area of the syllabus. In the early development of the course there was an idea to integrate questions regarding product and component failures. Failures both related to our everyday life as well as in industry. The fourth stage Operate in the syllabus incorporates sub-areas such as recycling, upgrading and system improvement. The PA2 assignment hence begins with asking the students a few days before the official start of the project to come up with their own example of a product or component that has failed. The students then make suggestions and the problem is discussed with the supervisor in order to judge if the problem is solvable and suitable to fit the objectives of the assignment in terms of, most importantly, modelling feasibility with respect to the project time frame.

For the students who are unable to find an example, the supervisor has two-three predefined examples at hand. The examples have been a bike lock, fridge door handle, lawnmower bracket and an oven heat adjustment knob. In some cases the student’s own examples turned out to be either too difficult or too simple to solve. However, for the most part the diversity of problems solved in the class has been a very good attribute in itself. A condensed illustration of the proposed design process can be seen in Figure 2. As an example, the bike lock product is illustrated in the images starting with a close-up image of the fractured bike lock attachment in the first image. Since the project has a time constraint of about 14 days the students are given a relatively detailed and instructive design process proposal. The process is based on the reverse engineering design process proposed by Otto and Wood (1998).

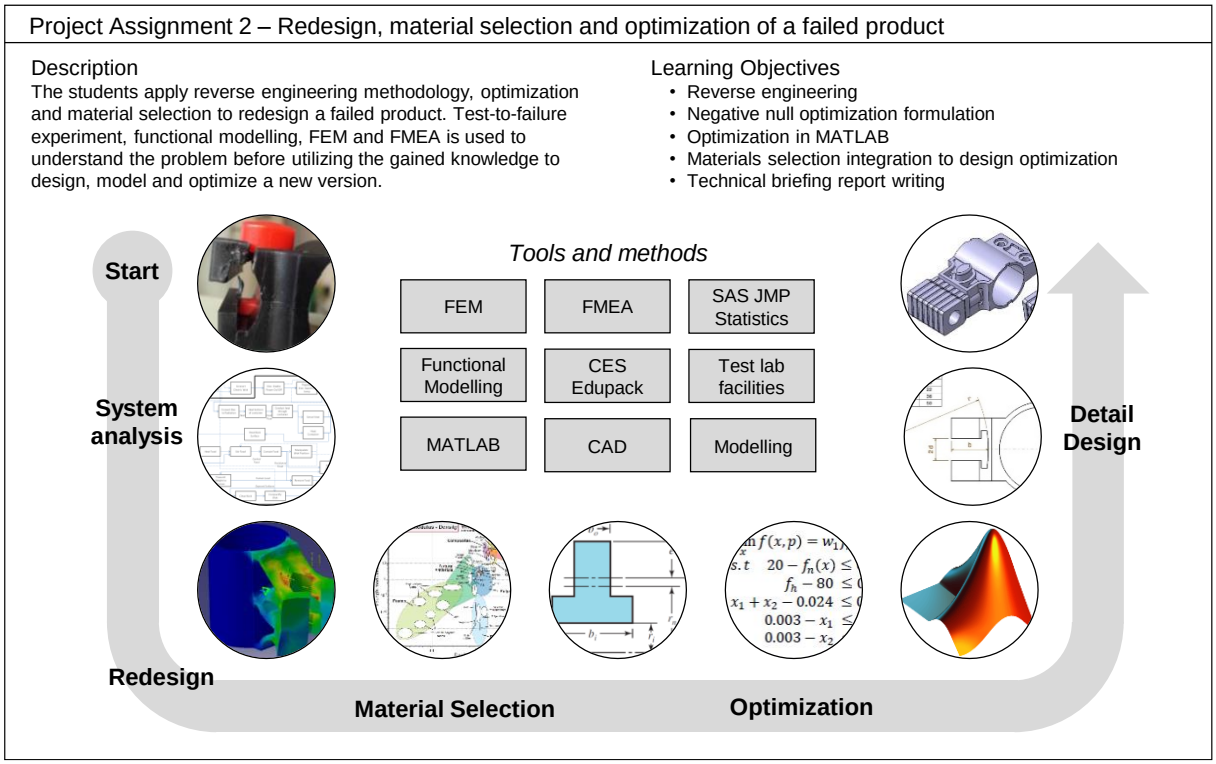

Figure 2. Illustration of the proposed design process used in the project including the main methods and tools utilized at various stages in the development.

In order to make a transition from the Operate (CDIO Syllabus 4.6.4 - System Improvement and Evolution (Crawley, 2007)) to the Conceive stage the first part of the assignment is to analyze the failure. The CDIO process is hence here interpreted as a cyclic and iterative process meaning that it may start with the Operate Stage preceding the Conceive Stage. For example when studying and testing failed existing consumer products in order to gather information for the Conceive Stage. If possible the students are encouraged to perform a breakage test and measure for instance the load necessary to break the component. This breakage test will further on provide input to the second part of the project where the student build a CAD model and perform an FE analysis in order to reproduce the stress condition leading to the failure. The students also perform an FMEA (Failure Modular Error Analysis) in order to find probably causes of failure.

During this process the students have normally asked several questions and learnt significantly about the component which provides a good basis for defining functions and requirements. The assignment continues with development of mechanical modelling and/or response modelling followed by optimization. The optimization results are used as input to the final design. Finally the new design is validated using FE analysis in order to verify improved performance.

PA 3 - Multi-objective optimization of an engine encapsulation component

This assignment targets learning objectives related to multidisciplinary problem solving and multi-objective optimization. The case is based on a real industrial problem concerning an engine encapsulation component with complex geometry and two layers of different materials.

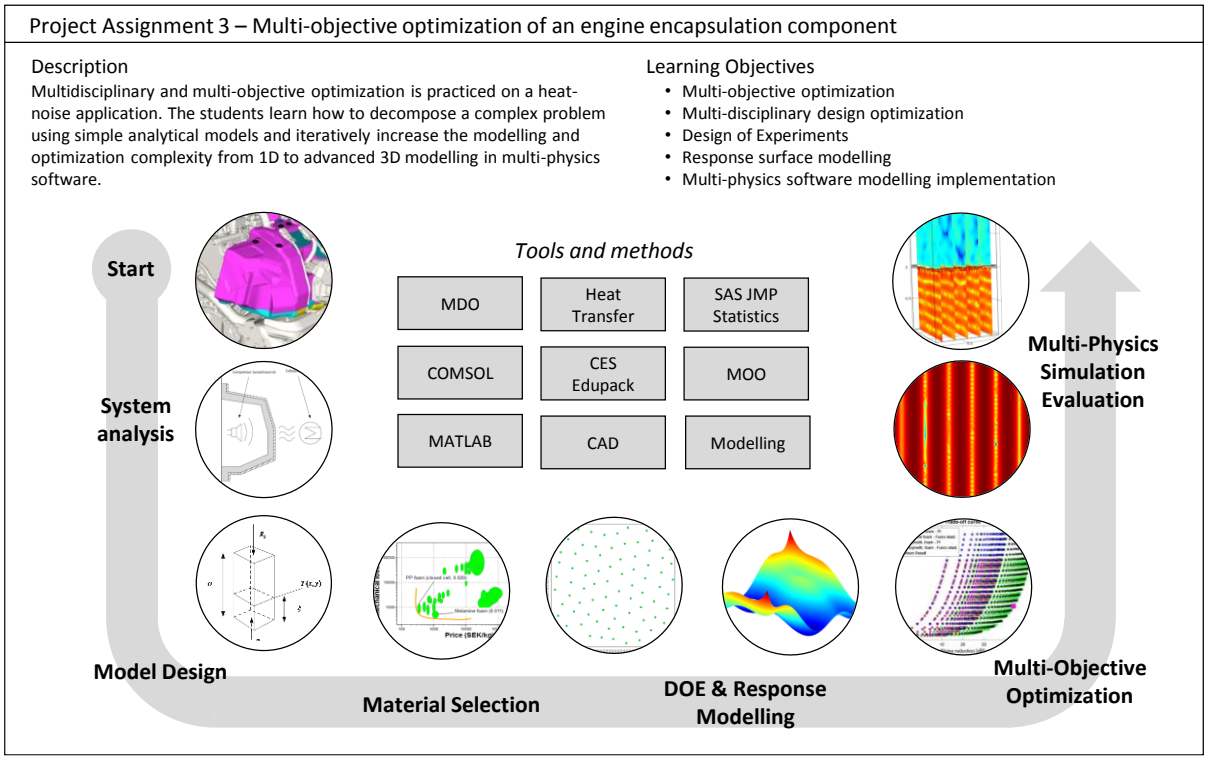

Figure 3. Illustration of the design process in the third assignment.

The component should both act as a heat insulator and a noise absorber but still have a minimum mass. The students learn how to decompose a complex problem using simple analytical models and iteratively increase the modelling and optimization complexity from 1D to advanced 3D modelling in multi-physics software, see Figure 3. The iterative nature of the assignment allows for active learning and self-assessment by, for instance, discussing and comparing the accuracy and sufficiency of different modelling approaches.

COURSE EVALUATION RESULTS

The course evaluation is carried using Chalmers' standard method. A reference group of three to six students is appointed. The reference group and the teachers have three meetings. A first introductory meeting to learn to know each other and to discuss changes from previous course round and a second mid-course meeting to discuss the course so far and to implement possible minor improvements. The third meeting is the course evaluation meeting. At this meeting teachers, student reference group and program managements attend. The basis for the meeting is a web questionnaire and the impressions from students and teachers. Meeting notes including compiled questionnaire results are published and linked to the course description on the Chalmers course-web. The response rates for the questionnaires have varied from 58% to 70% (25-31 respondents).

In Figure 4, the student overall impression from the course questionnaires 2013-2016 are displayed. As can be seen, the first course round in 2013 was very well received by the students. The course was new and both student and teaching staff were enthusiastic and overlooked most issues related to novelty of the approach as well as planning difficulties. In 2014, the course had a new teaching staff and new administration which led to problems related to course administration and assessment.

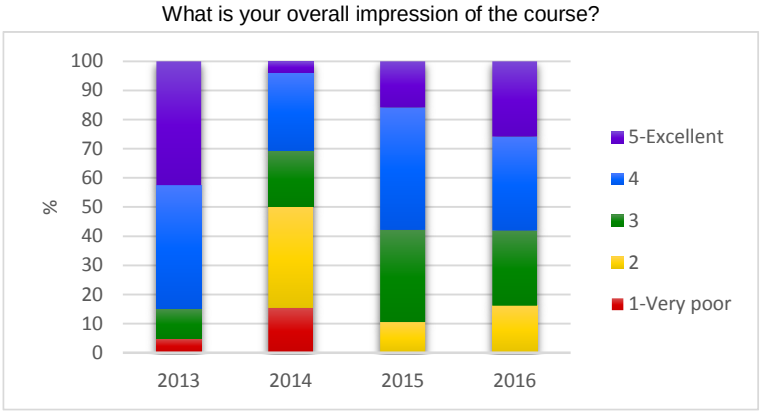

Figure 4. Course evaluation - Overall impression

The course delivery did not meet the high expectations from the previous course round. In the following years the course has generally improved from a mean of 2.69 in 2014 to 3.74 and 3.68 in 2015 and 2016, respectively. Chalmers changed the standard method for course evaluation in 2014 leading to a discrepancy in terms of the questions in the course questionnaire except for the question regarding course overall impression. This limits the possibility to include year 2013 for detailed comparison.

A set of questions and corresponding results from the course evaluation from the years 2014-2016 are presented in Figure 5. Questions regarding course prerequisites, course structure, intended learning outcomes, assessments, workload and course administration are displayed above each sub-figure. Figure 5(a) represents student's feedback on the prerequisites to the course. The participating students are form different specializations in the mechanical engineering programme such as Product Development, Applied Mechanics and Automotive Engineering which brings variability and diversity in students' prior knowledge. The course contents have been annually updated with improvements for lecturing material, workshops and supporting material. Figure 5(b) represents student's opinion on course learning which consists of structure, teaching and course materials which shows an improvement through three years in terms of the mean satisfaction (3.1 to 3.6). This is gradually achieved by improving planning of the course; better alignment of lectures with learning outcomes; scheduling of lectures, workshops according to the need in assignments, removing certain topics from the course scope, etc. Consequently, the reflection on learning outcomes has been gradually improved although we have maintained it similar over four years, see Figure 5(c). Figure 5(d) represents an improvement in opinion on assessment activities in the course although some comments were made to improve the evaluations, such as improvement in criteria for grading the assignments. There has been an inclination that the student's grade is driven by the project assignment grade as they get higher grade in assignments compared to the final exam. Students pointed out that the mid-term exam was helpful to keep track on the progress of learning although they did not find the final exam to be challenging. The workload on the student's side is comparative higher than other courses at Chalmers due to time intensive assignments in the course and other activities, which is also evident from Figure 5(e). Also, some students' commented that it was too high work load and some said it was too low which seems to have been influenced by the motivation of students. To manage the excessive time demand, some of the workshops have been replaced by video lectures. The student impression of the course administration is displayed in Figure 5(f). The trend is somewhat typical for a new course with a continuous improvement to a well-established high level. The general lesson learned is to put a lot of effort in administrative issues and to be very clear in communication with the students both prior to and during the course.

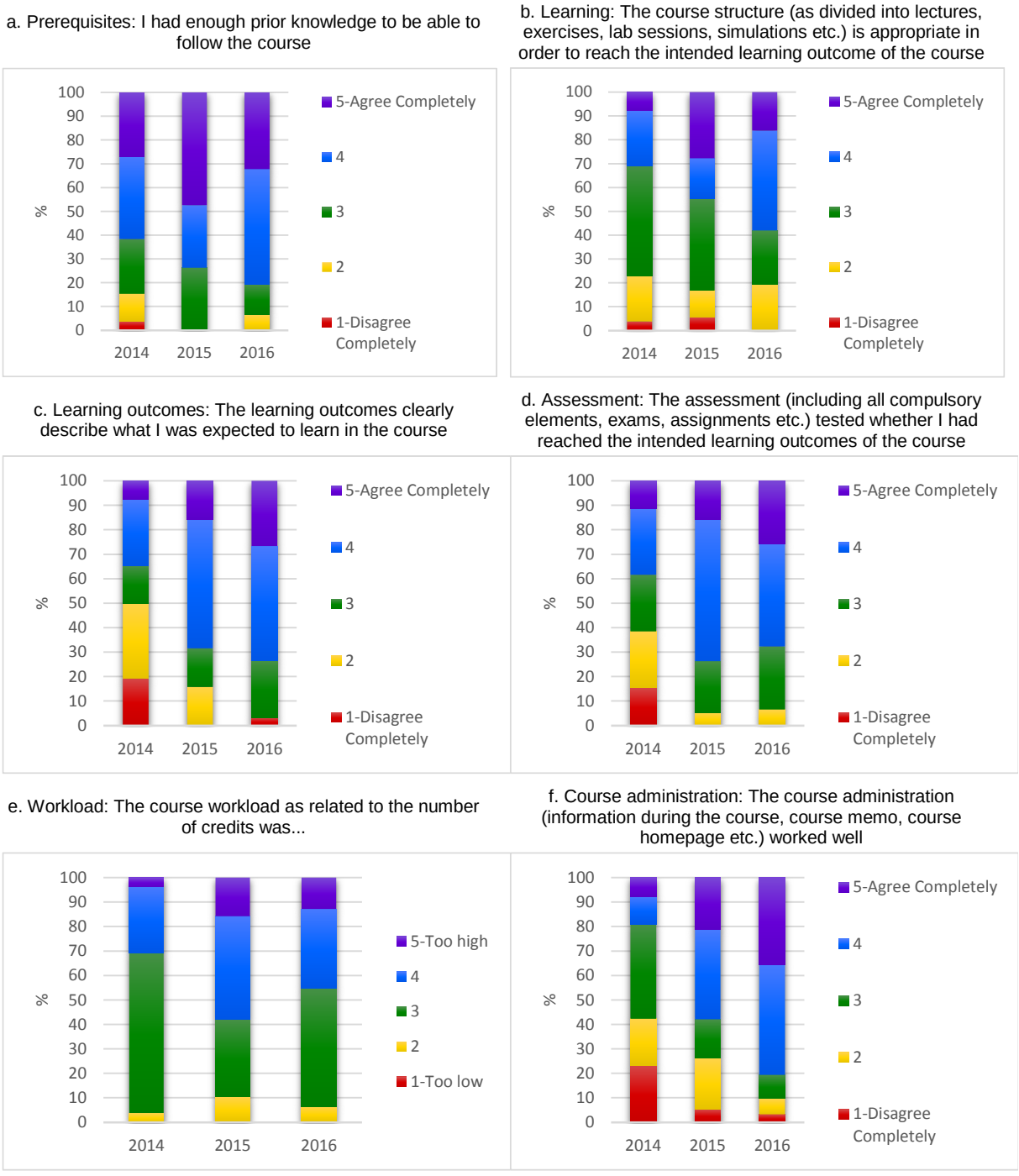

Figure 5. Course Evaluation Survey Results

When the students were asked about what to preserve in the course, one of the most frequent comments was about keeping the project assignments, lectures, online videos and use of different CAE tools. Students found the project assignments challenging and rewarding and appreciated the group work, the cross-disciplines problems and knowledge sharing with peers from different background.

"The first assignment, it was very challenging and rewarding"

"Excellent! It feels good to work with students from different backgrounds, give me new vision of the engineering design."

"The mix of theory and practice."

When students were asked about what to change in the course, comments were about better scheduling coordination with workshops and lectures according to assignments, and students also asked for more mathematical exercise sessions. Although students appreciated the frequent communication with the teachers, they demanded more dedicated time for project supervision. There have also been comments regarding better formulation of the project assignments, which has been taken into consideration resulting in improved formulations.

"Very good intention, but contents should be more focused."

"Overall the course was very interesting and is a course I recommend other to take. But because all the different subjects it gets a bit messy."

"A good course that covers things that the bachelor program (M) missed out but would need more time to become really good. The course is way too compact in terms of the time span."

Overall, students appreciated the course and found it intriguing and useful for future career. The course provided the aimed cross-disciplinary thinking and interesting design-built-test projects. Some of the comments from students are highlighted below:

"Really nice with all of the workshops and CAE tools."

"Excellent course with a lot of material that was totally new to me."

"This is by far the most useful course I have taken at Chalmers. When I signed up for the course I was not quite sure what to expect, but I am so glad that I did. This course has given me valuable knowledge about evaluating designs in so many different ways than I would have thought optimization applied to. Before taking this course I did not know exactly where optimization applied, but now I see how it can be used in ALL of my other coursework, for one thing or another.....The information that I learned from the EDO class will be used throughout my career as an engineer, this I am sure of."

"Best course during my five years at Chalmers, got to use previous knowledge from several courses to solve "real" problems."

"It was a really nice preparation for the "working life" after Chalmers due to the way of reporting and presenting."

DISCUSSION

In general, the course has been perceived by the students as a valuable and important course even though there have been some apparent challenges as well. Some of the key aspects and factors we believe have been contributed to the successful attributes of the course are listed without order below.

- CDIO framework for course development including integrated-design-build-test experiences.

- Cross-disciplinary collaboration among three different departments with engaged and cooperative teaching staff.
- A dedicated funding program for new courses allocating resources for course development.
- Strong focus on fast design iterations and several loops within the design-build-test cycles.
- Emphasis on studying small subsystems or components in order to facilitate distinct system boundaries, requirements, constraints and real detail design.
- A combination of dedicated software workshops linked to theory lectures facilitates quick learning integration between theoretical concepts and software implementation in the project assignments.
- The workspaces and facilities developed within the ME program including for instance more than 40 student project rooms and a well-equipped and staffed prototype laboratory including a full mechanical workshop, CNC and 3D printing machines.
- Integration of a variety of communication and reporting techniques into the project assignments including A3-reports, oral presentations, technical briefing reports and simulated technical briefing meetings.

Some students consider the course as a capstone course based on the survey results. The students described how knowledge from most other mechanical engineering courses was needed in order to successfully excel in the course. This was not intended specifically from the beginning of the course development hence it is an interesting finding from the survey. With a similar motive and need as for this engineering design and optimization course, a new meeting platform called the National Optimization Arena in Sweden took form during 2015 to strengthen Swedish industries and academia. Chalmers University of Technology together with Volvo Car Group were the initiators for this platform which aims to develop competence methods, tools and processes for optimization-driven development. A strong message voiced by the industrial partners is the importance for modern engineers to at least know the language of optimization even though not all of the students will continue their careers specifically in the field. The language of optimization is a generic and cross discipline bridge builder since the formulation of problems with objectives and variables follow a similar structure across engineering disciplines.

CONCLUSION

A new course integrating optimization with engineering design has been developed based on the CDIO framework including several design-build-test experiences. The intended learning outcomes (ILO) of the course have been outlined in close cooperation among faculty from three different departments and have become entrenched in the industry through discussions in program advisory boards, as well as several theses in cooperation with industry and in emerging research collaborations. The course was designed systematically using design matrices to maintain links between ILOs, teaching activities and assessments to ensure that every ILO is covered and assessed.

The course successfully combines theory in optimization problem formulation and analysis, optimization algorithms, and implementation in MATLAB into the mechanical design process including material selection and finite element analysis. The three integrated project assignments follow the iterative design-build-test cycles with focuses on topology optimization, reverse engineering and multi-objective optimization. Course design matrices verify that the project assignments are the backbone as they train and assess all ILOs, which is also obvious

from students' evaluations of the course in which they attribute much of the value of the course to the project assignments.

The interim and final outcome of the different design-implement experiences provide an opportunity for student self-assessment in terms of both the learning progress as well as results and modelling validity. The students strongly believed that the course prepared them well for work as professional engineers as well as for theses and research studies. Moreover, the course has had a strong impact on the students' choice of master's thesis projects with the number of projects on optimization has increased from two or three to around 15 annually. The course has also tied faculty from the different departments together through the Optimization Arena and several joint multidisciplinary theses that involve optimization.

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