DESIGN-IMPLEMENT EXPERIENCE FROM THE 2ND YEAR CAPSTONE COURSE "INTEGRATED DESIGN AND MANUFACTURING"

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Abstract
This paper reports/discusses experiences from a new design-build project course "Integrated design and manufacturing" which is held during the fall semester of the second year of the Master of Science program in mechanical engineering at Chalmers University of Technology, Sweden. The course was given for the first time in 2006 within CDIO engineering education context. In the course, the students are trained to solve open engineering problems that have a wide solution space. The project assignments are generated and defined by companies within the industry and are therefore relevant problems associated with existing products. Through a value-management focus the students have to enhance the customer value of a product. The result can be a redesigned product or a completely new one. Throughout this process, group dynamics are trained in a natural way since the students are assigned different roles, which are changed after a rotating scheme. Each student will, for example, experience the project-manager role which includes chairing meetings, managing decisions, and contacts with supervisors, etc. Within the scope of the course communication is also trained. After the conceptual design phase the chosen concept is presented to a fictive project steering group. The final product is again presented at the end of the project and a technical report is written.

Keywords: *design-build-test, project management, product development, customer value, communication, team work, engineering practice, prototyping.*

Introduction
The Master of Science program in mechanical engineering at Chalmers University of Technology, Göteborg, Sweden has taken part in the development of the CDIO-initiative for engineering education since the start in 2000, see [1]. Since 2000, the program has changed with the aim to strengthen engineering fundamentals and engineering practice including communication, team work and project management according to the CDIO-initiative. For example, engineering fundamentals are strengthened through common projects between mathematics and mechanics. Engineering practice is, e.g., strengthened by Design-Build-Test

(DBT)-courses where the students solve real industrial problems from identifying a need and generating solutions to a self-built prototype. The DBT-projects are the most efficient and relevant way to fulfill the program aims and goals when it comes to engineering practice, developing tools to handle today's complex products and systems as wells as project management, team work and communication. The DBT-projects include the following actions:

- problem solving and generating ideas,
- project management,
- communication and team work,
- professional skills,
- design and analysis,
- building a prototype.

From the academic year of 2004/2005 Chalmers changed the educational system in accordance with the Bologna structure for higher education. Although the MSc-programs are five years program they are divided into two cycles. The first cycle consists of three years of full time studies and corresponds to 180ECTS and results in the degree of Bachelor. The second cycle is a two years (120 ECTS) international masters program. After finishing both cycles the students have earned the Swedish degree "Civilingenjör" as well as the degrees of Bachelor and Master of Science. As a consequence of the change of educational system the mechanical engineering program changed the curriculum. The following changes were introduced:

- The full view of product and system development is emphasised through DBT-projects. Focus is on entirety and context.
- Common tasks and projects between parallel taught courses in mathematics and mechanics are given to strengthen engineering fundamentals and motivate the studies.
- Computational (numerical) aspects of mathematics (including programming in Matlab) and analytical (symbolic) aspects are completely integrated in the basic courses of mathematics, see [2]. This kind of mathematics makes it possible to consider the complete problem: from modelling and solution to simulations of the system and comparison with physical reality. Further, by introducing computational tools the quality of the analyses in the DBT-projects can be significantly raised.
- Engineering fundamentals appear early in the curriculum. The reason for this is to be able to develop realistic and advanced products in DBT-projects.
- Communication, team work and project management are integrated (taught and used) in the courses.
- A half semester (15 ECTS) collaborative Bachelor diploma project is introduced in the end of the third year. The project is carried out in teams of three to six students. Communication, team work and theory and methodology of science are taught, practiced and utilized.

The program plan is shown in table 1 (the year is divided into fours study periods, quarters of eight weeks). The DBT-project courses are marked grey.

Table 1. The program plan for the first three years of the MSc program in mechanical engineering

<table>
<tr><th>Year 1, Quarter 1</th><th>Quarter 2</th><th>Quarter 3</th><th>Quarter 4</th></tr>
<tr><td>Programming in Matlab
4.5ECTS</td><td>Calculus in a single variable 7.5ECTS</td><td>Linear algebra
7.5ECTS</td><td>Calculus in several variables
7.5ECTS</td></tr>
<tr><td>Introductory course in mathematics
7.5ECTS</td><td>Thermodynamics
4.5ECTS</td><td rowspan="2">Mechanics and strength of materials 1
7.5ECTS</td><td rowspan="2">Mechanics and strength of materials 2
7.5ECTS</td></tr>
<tr><td colspan="2">Introduction to mechanical engineering
7.5ECTS</td></tr>
<tr><th>Year 2, Quarter 1</th><th>Quarter 2</th><th>Quarter 3</th><th>Quarter 4</th></tr>
<tr><td rowspan="2">Mechanics and strength of materials 3
7.5ECTS</td><td rowspan="2">Machine elements
7.5ECTS</td><td>Mechatronics
7.5ECTS</td><td>Industrial production and organization
6ECTS</td></tr>
<tr><td colspan="2">Integrated design and manufacturing
7.5ECTS</td></tr>
<tr><td>Material science and engineering A
7.5ECTS</td><td>Material science and engineering B
7.5ECTS</td><td>Manufacturing technology
4.5ECTS</td><td>Industrial Economics
4.5ECTS</td></tr>
<tr><th>Year 3, Quarter 1</th><th>Quarter 2</th><th>Quarter 3</th><th>Quarter 4</th></tr>
<tr><td>Environmental and energy systems 7.5ECTS</td><td>Automatic control
7.5ECTS</td><td colspan="2">Bachelor diploma project
15ECTS</td></tr>
<tr><td>Fluid mechanics
7.5ECTS</td><td>Elective 1
7.5ECTS</td><td>Elective 2
7.5ECTS</td><td>Mathematical statistics
7.5ECTS</td></tr>
</table>

The first DBT-project course *Introduction to mechanical engineering* includes a collaborative project. The project task is open and unstructured and a physical prototype should be designed and built by the team. Team work and communication (oral and written) are taught and utilized in the project. The students are then introduced to general aspects of communication, report writing and oral presentations. Moreover, an introduction to the program and the prototype workshop is given. Further, the role of the professional mechanical engineer is discussed.

In the second DBT-project course *Integrated design and manufacturing* more team work and communication are taught and practiced together with deepened practice of project management. The communicative activities are focussed on presentation skills but also report writing is practiced in the course. The project tasks are taken from the industry. Relevant analyses using knowledge, principles and methods from the preceding fundamental engineering courses should be carried out. The task includes generating ideas, design and building a physical prototype.
The final step in the design for communicative activities is given in the third year when the students complete the bachelor diploma project involving both presentations and report writing

Integrated Design and Manufacturing

Aim and learning outcomes

The aim of the project course is to provide possibilities for the students to participate in industry related product development projects, to train problem-oriented learning and to act in a project environment. The projects have focus on early product development, i.e., concept study phases and test and evaluation of physical prototypes or simulation models, and value-based management.

The projects in the course are industrial product development tasks formulated in cooperation between Chalmers and the local industry. Each problem-oriented study has a clear target and is mainly a theoretical activity focusing on evaluation of alternative solutions and planning of activities and resources needed to demonstrate a concept, e.g., in a vehicle.

The project course also involves management of the team, project definition including deliverables, time planning including milestones, risk analysis and group dynamics. The project management process used in the projects focuses on how to master the development phase in a project and at the same time creates unrivalled customer value.

After the project course the student should be able to:

- Create a project definition by
    - clarifying stakeholders, roles and responsibilities for the team members,
    - creating a project goal statement,
    - analyzing objectives, deliverables and boundaries, milestones and Gantt plans and
    - identifying and assessing risks and changes.
- Recognize the connection between products and customers by
    - describing lifecycles of products,
    - listing customer requirements and demands,
    - recognizing Voice of the Customer,
    - analyze the process of customer value creation by,
    - identifying main, additional, supportive and undesired functions of a product,
    - creating functional models,
    - evaluating commercial position of products and therefore be able to identify create and choose strategies for further development and
    - generate new technical concepts, combine and compare them.
- Create, test and evaluate the concept by
    - designing technical solutions in CAD,
    - constructing and assemble a prototype,
    - evaluating the results from a functional test of the prototype and the targets in the product specification and
    - assessing whether the project has succeeded, if not analyse necessary steps; a need for another loop in concept generation.
- Argue and defend the developed system at an oral presentation and in a written report and evaluate and criticize other presented solutions.

Methodology

From earlier courses, during the first year and the first semester of the second year, the students have obtained substantial analytical knowledge and skills in basic mechanical engineering topics such as mathematics, mechanics, strength of materials, metallic and polymer materials, thermodynamics, machine elements and mechatronics. In particular, a common methodology for mathematical modelling and abstract thinking is emphasized aimed at strengthening their abilities to apply a modern way of working based on modelling, simulation and analysis. The goal is to provide the students with appropriate tools to handle realistic and complex applications. These skills are now put into practice as the students work with creating and designing new solutions to the given problems.

The Value Model has a holistic view on the product development process [3]. The Value Model may be looked upon as a practical tool that uses several of the modern methods for product development in a structured order. The term *Customer Value* is a central focus and guides and supports the team in the process.

Customer Value is defined as the relationship between the perceived benefits the customer gains from a product and the total expenditure in time, money and other effort demanded by obtaining and using this product [3]. By "product" we mean any combination of hardware, software, services and support offered to customers. The applied definition of customer value is:

$$\text{Customer Value} = \frac{\text{Percieved Benefits}}{\begin{array}{c}\text{Total Expenditure}\\ (\text{time, money, efforts})\end{array}} = \frac{\text{Percieved Benefits}}{\text{Total Costs}} \tag{1}$$

The fundamental idea of a free market economy is open competition between rival organizations to win customers. Satisfied customers become loyal customers, and loyal customers greatly strengthen profitability. Those companies that deliver most customer value have the most satisfied customers as a result of which they are the most profitable companies within their branch or industry [3]. This is why customer value is of such a great importance in product development and the reason why the concept has been adopted in this course. The best way of achieving success is to ensure superior customer value

The course follows a pre-defined product-development process, including customer value creation, project management and team management. Customer value is created through understanding the customer's needs and translating these into viable functions. This is the most critical part in a product-development process and therefore the importance of this phase is highlighted. The functions are discussed with the companies early on, before the creational phase of devising solutions starts.

Besides the development of the product and the technical aspects, the Value Model also includes the two other important dimensions of a project; the creation and inspiration of the team and the satisfaction of the owner, sponsor and contributor to the project by delivering a product that responds to required expectations. The role of the project manager in the process is therefore very clearly defined.

The course includes about eight lectures and a one day workshop on Value Management in product development. There is one supervised occasion every week. In the course the students work in teams of five to six students supervised by two Chalmers instructors and one company representative. Each group constitutes themselves in an organized and structured way. Every project team needs a project manager all the students in the team should have acted as project manager for three to four weeks. The project manager's responsibilities are the development of the project.

The pre-defined process that the students should follow is summarized in nine different *Steps* which are briefly described below. Step 1 to 6 is *the conceptual design phase* which is followed by Step 7 to 9 which include detailed design procedure that includes cost estimation and selection of manufacturing processes. A prototype of the complete product or a critical sub-system of the product is then built by the students. The prototype is tested and evaluated based on the specified functions.

The project results and achievements from the different steps are continuously uploaded by each project group on a designated website [4]. The supervisor will evaluate and grade the results and then give feed-back to each group. The grade is thereby built as an accumulated moving average which the students are able to follow. In addition, all project managers should report to the supervisor weekly. This weekly report is an opportunity for the student to discuss personal experiences and to reflect over the role of being project manager.

Step 1. *Establish the project.*
Start by defining all the stake holders and players. The Value Model specifies the four most important players within a project: the customer, the team, the sponsor, the project manager. Create a project definition by:

- establish the team,
- clarifying the stakeholders and players as well as roles and responsibilities within the team,
- formulate a verbal goal statement,
- define the deliverables and boundaries,
- identify and manage risks and changes and
- establish the project control system.

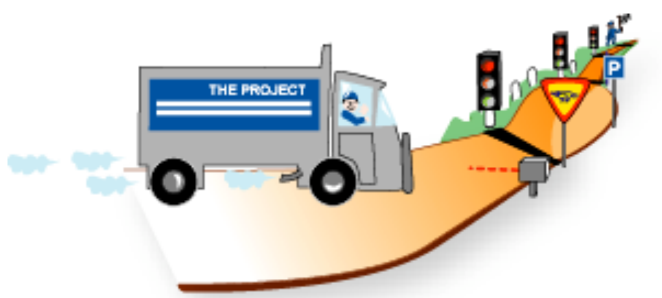


Figure 1: A planning process with milestones are used

Step 2. *Describe the product.*

The first step towards mastering customer value is learning how to systematically analyze and identify important areas in which superior customer value can be created. By observing how the customer interacts with an organization or company and its products knowledge and understanding of important areas can be achieved. The customer interaction becomes evident when it is broken down into a number of phases: prospect, buyer, recipient, user and decommissioner.

By applying value based methodology the customer value can be described by main functions, additional function, supporting functions and unwanted functions. The perceived benefits for the customer are the total sum of all this functions.

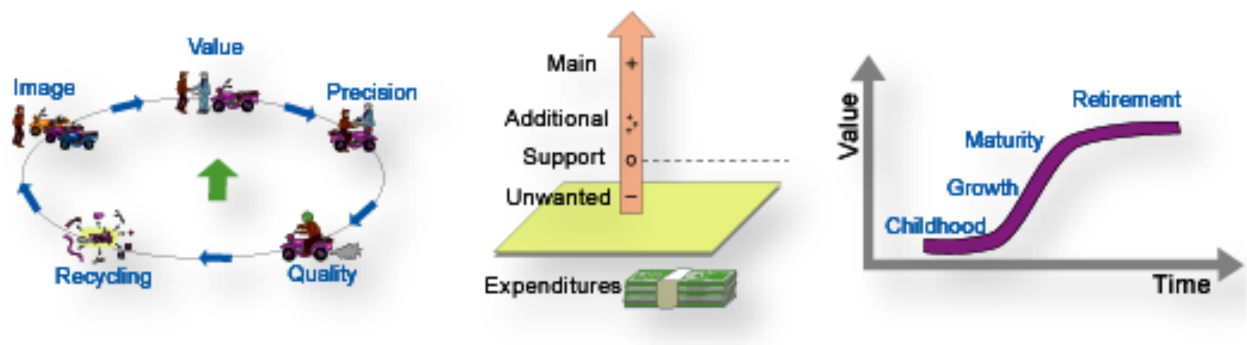


Figure 2: Interaction between customer and product, functionality and the progression of development are of importance then the product is described.

The “S-curve” is used to pinpoint the development of the products value with time. Depending on the position different product development strategies are then applied.

Step 3. *Analyze the customer needs.*
The customer value creation process comprises capturing, interpreting, concentrating, translating, building, refining and managing information. The information proceeds through four different levels of concretization. These levels are usually called *Needs*, *Functions*, *Solutions* and *Processes*. The Kano model is used as a tool to understand the spoken and unspoken needs.

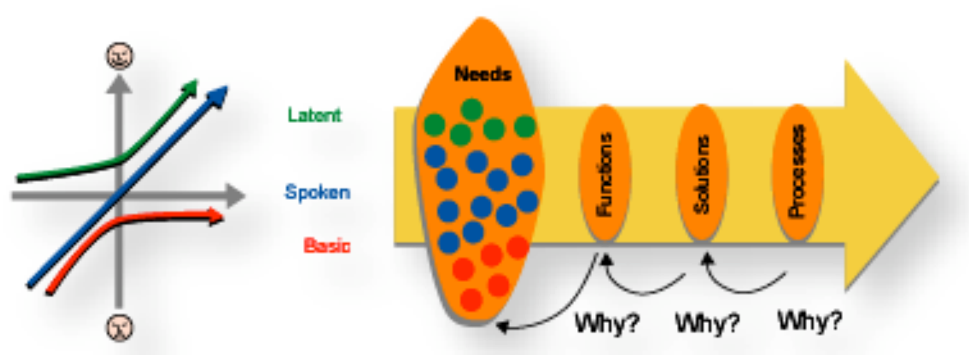


Figure 3: The Kano model describes the difference between unspoken and spoken needs.

Step 4. *Analyze existing solutions by functional modeling.*

Existing solutions and product are searched and analyzed. Functional modeling is applied to understand how the customer needs are fulfilled by the functions executed by existing products. An existing solution is chosen as a reference for further evaluation.

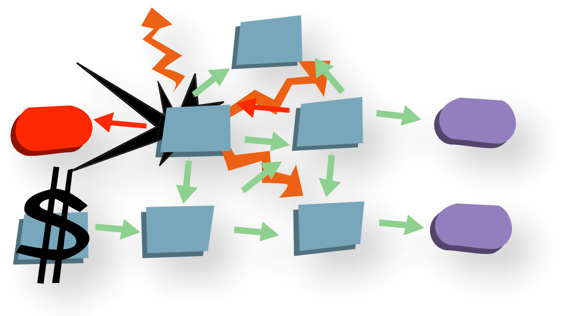


Figure 4: Functional modelling is an essential part of the product development process in the course.

Step 5. *Create a new concept.*
This step is the most creative part of the process. Different methods (brain-storming etc.) are used to find solutions and principles that can offer functions that fulfill the identified customer needs. The principles are combined and further to concepts of equal detail level. The concepts are combined to new concepts if possible. Pugh's concept selection matrix is the applied to select the best concept. The advantage of this method is that it quite clearly shows why a specific concept has been chosen and why others have been rejected. It also often leads to new and better alternatives coming to light by the skilful combination of different concepts. The reference solution used in the Pugh matrix is the one from Step 4.

Step 6. *Set target values for the functions and costs of the new concept.*
When a product concept is chosen a final product specification can be established. A customer value based product specification specifies functions and cost performance metrics in the following way:

- the formulation of the product's main, additional and undesired functions,
- functional performance metrics and units,
- functional performance target values and
- the buying price, operating cost and decommissioning cost and the metrics selected to measure customer expenditures.

When Step 6 is completed after five weeks a first oral presentation is given where the selected concept is presented.

Step 7. *Design the product.*
The different functional elements of the new product are structured by system architecture. The product is thereby divided into one or more modules. The system architecture also defines the interfaces between the modules and the test standard for the methods by which each module can be independently verified and tested. Each module can now be designed in detail by the students. They can now practice their skills retrieved in the preceding courses of the program. Components and assemblies are modeled by using ProEngineer. DFM, DFA and cost analyses methods are applied.

Figure 5: During the design stage of the process the students are able to practise the skills they have retrieved in earlier courses.

Step 8. *Verify the customer value of the product.*
A prototype of the complete product or of a critical part of the new concept is manufactured in order to verify, test and evaluate that the product specification in terms of customer value have been fulfilled. If the target values in the product specification can not be met, the process should start over again from Step 5. However, this is normally not required by the student because of the limited time available.

Step 9. *Write a report and present the new product.*
All the Steps above have been continuously reported to the supervisors during the project. The last step in the course is then to write a final report and to give a final presentation of the results. The written report and the presentations form the central part of the communication scope of the course. During the oral presentation the students give feed back to each other and every group has to oppose on another presentation.

Figure 6: The results of the projects are presented in a written report and at an oral presentation.

Communication
During the course each project group gives two presentations, and the groups are given feedback after each presentation. The first presentation is held after the conceptual design phase. The students' task is to present the chosen concept to a fictive project steering group. The second presentation is a presentation of the final project and is given at the end of the project. This presentation is more of a sales pitch and requires the students to show the qualities of their own products, to explain how it solves problems other designs might have and to consider things such as functionality and customer satisfaction.

These two presentations thus have slightly different purposes, which attunes the students to the importance of adapting form and content to a given audience and purpose. The aim is to strengthen their ability to analyze communicative situations and choose material that is appropriate for those situations, considering aspects such as time, audience and professionalism.

In 2006 when the course was given for the first time, a great deal of attention was given to the oral presentations and the outline for that part worked very well. The reports written were however not equally satisfactory. Evaluations and experience showed that more and different attention had to be paid to report writing. First of all, several of the reports did not fulfil the standards that a report should have. Secondly, both supervisors and students noticed that there was some discrepancy between the advice given by supervisors and that given by teachers of communication.

In order to address the problems identified and to improve the course, a couple of measures were taken. First of all, supervisors and teachers of communication discussed and evaluated what the requirements of the course report should be. This process was completed through a two-hour meeting where the whole team of teachers and supervisors discussed what instructions should be given to the students. This resulted in document containing short writing instructions that gave a general overview of report writing and that commented on problems specific to the report type written in the course. Secondly, a slight adjustment was made to a writing workshop, so that focus was more on the specific problems that individual groups saw. For this workshop, the students were asked to prepare questions that had appeared during their writing process, as writing pedagogy has shown that student initiated response is often effective type of supervision [5]. This is also a step in teaching the students to take responsibility for their own text.

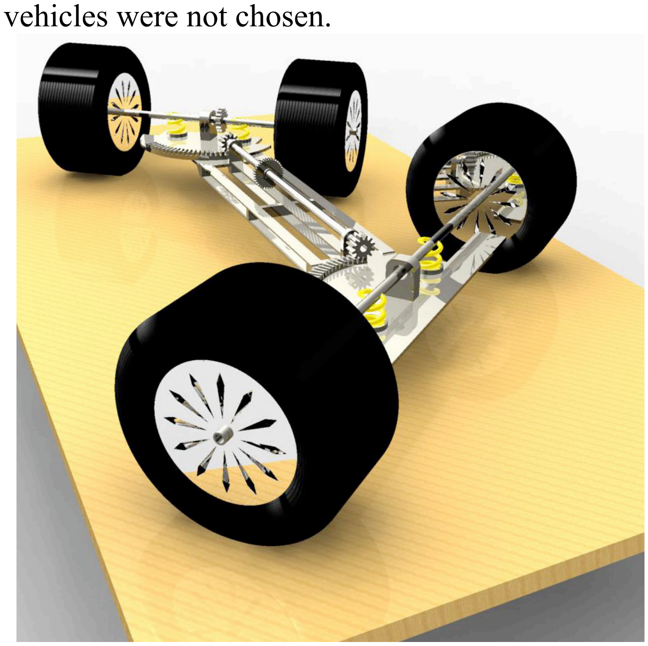
All in all, the aim has been to integrate the communicative activities in a natural way into the project course. The activities have been designed to target central aspects of the CDIO syllabus, such as analyses of different communicative situations, argumentation and technical writing.

Example: Chassi design for an autonomous lawn mover

A company specialized in management and maintenance of golf courses wanted an autonomous lawn mover for cutting the grass on the fairways. The main business idea was to cut the grass during the nights and thereby increase the availability for the users. The lawn mover should be autonomously controlled by a positioning system which reduced the need for labor. As a fairway can have a complex geometric shape it is important that the lawn mover has a small steering radius while maintaining its stability. Maneuvering close to buildings and walls is also needed. Furthermore, the lawn mover should be gentle to the grass, i.e., the contact pressure should be low and no shearing should occur.

Figure 7: Golf course fairways put special requirements on the design of an effective system for cutting the lawn.

The solution suggested by one of the groups is shown in the figures below. The suggested concept has steering on both the front and the rear axle. In order not to damage the grass by scuffing a solution with a permanent or semi-permanent pivoting joint as used in articulated vehicles were not chosen.



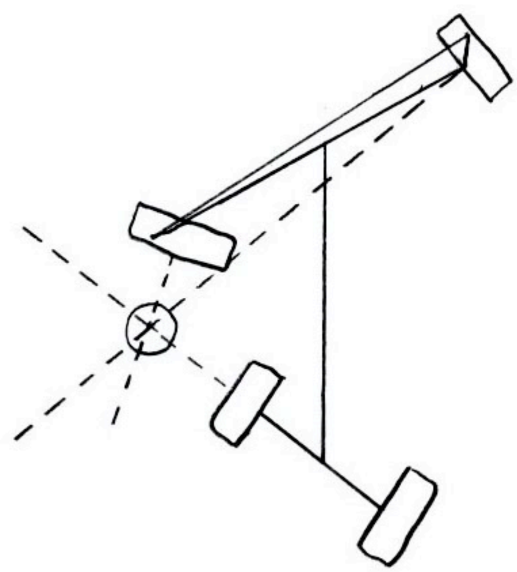


Figure 8: Suggested design of a lawn mover chassi and steering system. By applying Ackermann´s principle the steering radius was analysed.

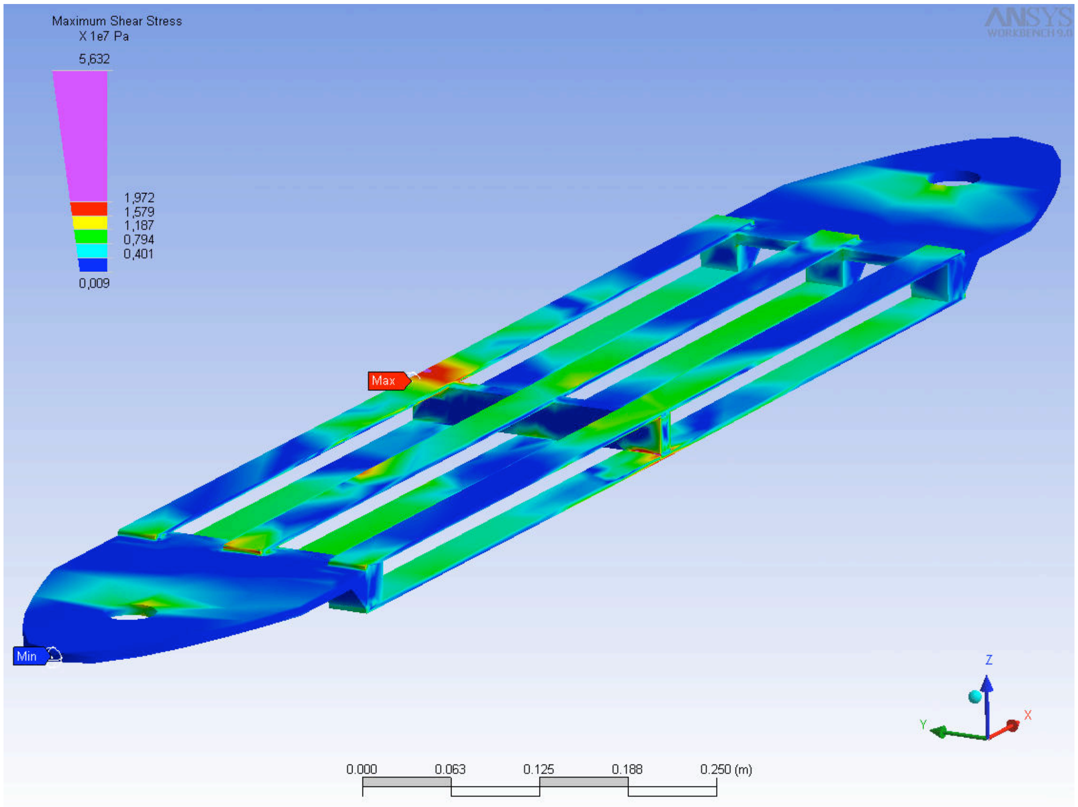


Figure 9: FEA stress analysis of the lawn mover body.

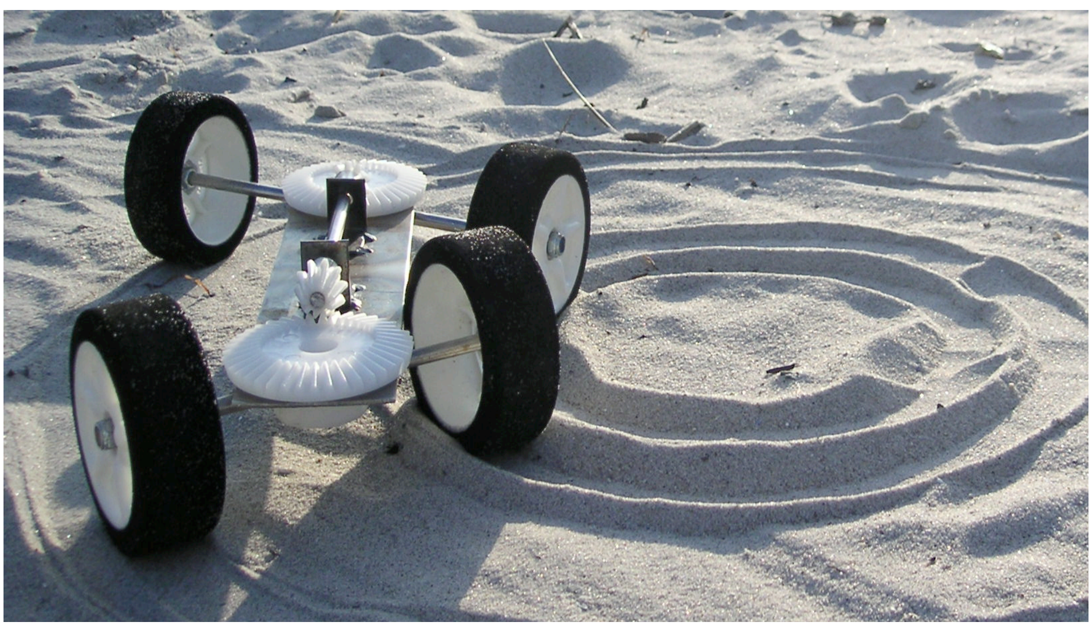


Figure 10: Test of the steering radius of the lawn mover chassi prototype.

Evaluation

The course is evaluated in cooperation between the program, the examiner and a group of five students. The evaluation is based on three meetings and an evaluation form to be completed by all students of the course. It is clear that the students are happy with the course. They find it relevant, fun and motivating. They find that the course add realism to the education. In particular, they appreciate to work with the Value Model which they consider to be very useful, realistic and relevant. The students like the principle of alternating project manager although the work load can be very high during the period of project manager. This can be troublesome if the course taught in parallel has a high work load at the same period of time. The students have found that their skills and knowledge in three-dimensional computer aided design (CAD) are insufficient. They mean that they need mote training before taking on the course.

From the program perspective it is clear that the course gives an overview of the development of a product and solid training in communication, team work and project management. Further the course trains the students' creative abilities, connects theory to practice and enforces the students to utilize and practice knowledge and skills from earlier fundamental engineering courses. In the third year when the students chose masters program (specializations), we have noted a considerable larger interest for programs in the core of mechanical engineering (e.g., Applied mechanics, Automotive engineering and Product development).

Conclusions

The course trains the students in handling complex open problems. The Value model increases the understanding of the product development process and project management. Further, the students gain insight in the difficulties in team work and get methods and tools overcome such problems. Moreover, the students have trained substantially in oral presentations and report writing.

The projects are carried out in close cooperation with the industry. The industry is very pleased with the course, the solutions as wells as (and more important) the knowledge, the skills and the attitudes that the students have gained. The latter are highly wanted by the employers.

The stated learning outcomes are satisfactorily fulfilled. The average grade is around four with a maximum of five and the drop outs a very few. We have also noted an increase in the students self confidence and that the students are more motivated to study engineering fundamentals as mechanics.

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