A roadmap for learning Product Development through Design-Build-Test projects

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Abstract
For the last seven years a successful cooperation between courses in product design and industrial design has been running at the School of Engineering at Jönköping University (JTH), Sweden. The concept of fusing separate courses with different domains of knowledge into one project is of course well known by most teachers, but this course takes this form of education one step further. This paper will describe the experience of coaching over 90 design-build-test projects going through the steps design, build, test but also the steps of fail and learn.

Introduction

Since the profession of mechanical engineering is wide and contains a broad range of different tasks there are many things that students need to learn. Unfortunately, the time available for education is not enough to fulfill all employers wish list and it is challenging to prepare the students for all possible future careers. In addition to the fundamental curricula such as math's and mechanics the students also need some amount of practical experience of design. In some cases this experience is given in project courses at the end of the program hoping that students becomes good engineers by making things in a workshop. However, without proper control of the process, this can act contra productive in learning good development practices.

To excel at product development a designer needs to understand the inputs and outputs to the product design process which means that he/she have to know the processes both upstream and downstream of their profession. To give a realistic experience of this, a course in industrial design and a course in product development were merged to resemble the process from idea to prototype in a controlled environment. Learning design is somehow different from theoretical subjects and there are many practices not written in books. So far we have not come across literature describing "How to design hand held garden products" and maybe this process is not possible to learn from books. In many subjects there is always one correct answer and some different ways to reach it. In design there can be many satisfactory solutions to a given task, but no given way to predict which version the customer prefers. Using analytical methods to optimize one property does not automatically bring increased customer value so it is important to have teachers with experiences of the design process who can see the balance between the parts and the overall product.

The structure of the design education at JTH

Since 2007, JTH is a collaborator of the CDIO Initiative, which provides a framework for curriculum planning and outcome-based assessment, and it has been adopted by over 30 universities throughout the world. One of the twelve CDIO standards states that a curriculum should include two or more design-build-test projects (or design-build experiences), and these kind of projects have been a part of the mechanical engineering program at JTH for the last ten years.

To understand the context of the design education at the Department of Mechanical Engineering a short description of the Bachelor program structure is given. The department has 30 employees and over 200 engineering students. The first 1.5 years of the program is a traditional setting with basic subjects such as manufacturing technology, material technology, math's and physics. Here the centre of attention is not on the generic skills of team work or communications skills. The next year is quite different with design courses in collaborating groups. The last six months is again individual work.
The first large project is a 10 week full time assignment. It is a project between courses in industrial design and engineering design. In this way the design intent is captured from idea to CAD drawings and prototype manufacturing.

The second project is collaboration between the School of Engineering and companies in the surrounding area. In this project the focus is to actually design something useful which also requires the specification and tasks to be very specific. A simpler task has a larger potential to meet the specification. In order to satisfy the companies, two groups of students work in parallel with the same product and so far at least one group in every case have created a satisfactory solution.

The third project is the 15 ECTS thesis work which is usually carried out by two students together at an external company. The thesis is the largest and most important work in the program, showing to what extent students are able to apply and add to knowledge previously gained during studies. During the thesis work, students are judged on their ability to identify and analyze problems. They are expected to describe the method of work and how the solutions fit into the context of the assignment. The thesis comprises a theoretical approach to the subject and a clear presence of analytical and developmental work.

Setup for a DBT project in Mechanical design

After more than 90 design-build-test projects we now have a method that works well in most situations. The project is exclusive for the students of the Bachelor program in Mechanical design and finishes the second year so the students know the fundamentals of mechanical engineering. The class size is between 25-65 students and the project run full time during an extended segment of 10 weeks.

The project is a venture between a course in industrial design and one in mechanical design. The courses provide lectures on different aspects of product design and the project is the arena to implement it. The two responsible teachers have different industry backgrounds and experience in their fields and the setting looks like a consulting firm integrating the industrial design and engineering processes. The students respond to the different tasks in a similar way that a firm would, compete with the other groups.

The learning outcomes from the project are increased technical skills in CAD, in the use of machinery/workshop, and in industrial and engineering design. Equally important are the skills in team collaboration which the students use in their subsequent projects.

The Theme of the year

Having a theme is a factor of success: A given theme reduces the amount of possible solutions and breaking up the theme in pre-defined groups increases the speed in the first conceptual phase which is necessary for the work to converge within reasonable time. Some months before start of the project the teachers involved start discussing the theme of the year. The theme is kept secret and revealed at the day of course start. Scanning the market for upcoming design competitions is usually a good source of inspiration. New products reflecting recent trends or sports equipment also provides fruitful new ideas. Successful themes needs preparation so the teachers explore the possibilities of the theme by doing design works in advance.

Changing themes is not for the change itself but to challenge both students and teachers. Some of the previous themes have been portable vehicles, physical training equipment, and leisure time equipment for disabled children. When the theme requires special knowledge that is not found on the University external lecturers are used. In the case of the products for disabled children three disabled lecturers gave the students insight into their lives. One of them was a Paralympics gold medalist that inspired the groups to design products for rough outdoor use rather than for life in an institution.

The assignment theme and practical arrangement around the project is described in a document of less than 10 pages. All groups are given the same theme, but the nature of the product and possible users and target groups can be varied. For the assignment “training equipment” the different natures “injury preventive” and “muscular strength” were defined. The users were office workers, nursing assistants or factory workers.

The working groups and working environment

Students are usually working in groups of five persons. Each group is put together by the teachers in order to create an inhomogeneous mixture in age, gender and social background. Typically a group consists of:

- 1 older student
- 1 student with different cultural background
- 1 female student
- 2 young male students

Approximately one in five students has more than five years experience of working-life when they begin the Bachelor program. One in five students is born abroad or has a different cultural background with parents born outside Scandinavia. The women can of course be placed in both these groups, and we have experimented with groups of only women or groups with 80% women. One of the remaining young males have at least one year of working experience, but seldom in the design area. The last young man comes directly from upper secondary school.

The effect of this mix is usually a very creative setting, but will most certainly create tensions in the group and special measures are needed to avoid group breakdown and

management consultants are used to help stabilizing the group and to build common values.
The physical environment is more important in teamwork projects than in class room lectures where the students can do most of their learning at other places than the university. Extensive projects need the team to collaborate and usually this means that they have to be at the same place at the same time. If hardware is to be produced there is also a need for shop resources and material.

Hardware is produced in our design laboratory which has most of the tools and material needed. Specific material such as paint or textiles is acquired by the students themselves, often as a gift from different firms. The manager of the design laboratory teaches the students practical issues, but is not building their products.


Figure 1 –Wood workshop

The groups also have project rooms where they do most of their work and where they can plaster the walls with sketches and plans. Project rooms have been varied over the years. One year all of the groups were co-located to the same large room. Other years the groups have been placed into separate rooms. The large room gives better project results since it is impossible to keep any secrets and ideas flow of between teams.

Team building
Most students have had previous experience of projects and/or courses in project planning, but not any first-hand experiences of product development projects. Our mixed groups are usually very creative but have built-in tensions so external management consultants help stabilizing the group and to build common values.

Prior to the structured team building students were often irritated on the behavior of others or their ability to show up on time. In many groups the workload was unevenly distributed and lazy students often avoided “boring” assignments. The rest of the team could get even by assigning them for the compulsory cleaning of the workshop. This kind of behavior takes the joy out of product development so professional help in team building was a major improvement.

Different approaches to teambuilding have been tested in order to find the balance between the time and money spent on team building and the result of the training. In our view a project of this character requires approximately 6 hours of lectures and exercises. After this the groups are able to work independently to make a contract between the members. The training is not enough to create a mature group, but most important is the commitment of each member to agree on the goal of the project and the rules in the contract. Usually the grade for the project is in this contract: “We will try to achieve the highest grade”. Other common things are penalties for late arrivals such as buying coffee for the others. Sometimes one member of the group can not put in time necessary to achieve the highest grade but it is possible to do less work an have lower grade than the other members. The role of leading the team is assigned to a new person every week so every student has had the responsibility to lead the work.

A Project roadmap for the product design process

The roadmap consists of a straightforward project model, some deadlines for documents and an overall timeline. Many companies use a “phase-gate” process in the new product design process and the project setup is inspired by this.

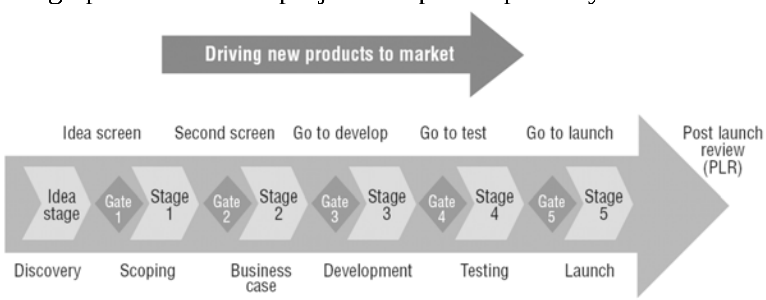

Figure 2 – Cooper’s Stage-Gate model, Cooper (2006)

The project roughly covers the business case, development and testing phases in Cooper’s model of the new product design process. Most of the discovery and scoping of the “market need” is done in advance by the teachers.

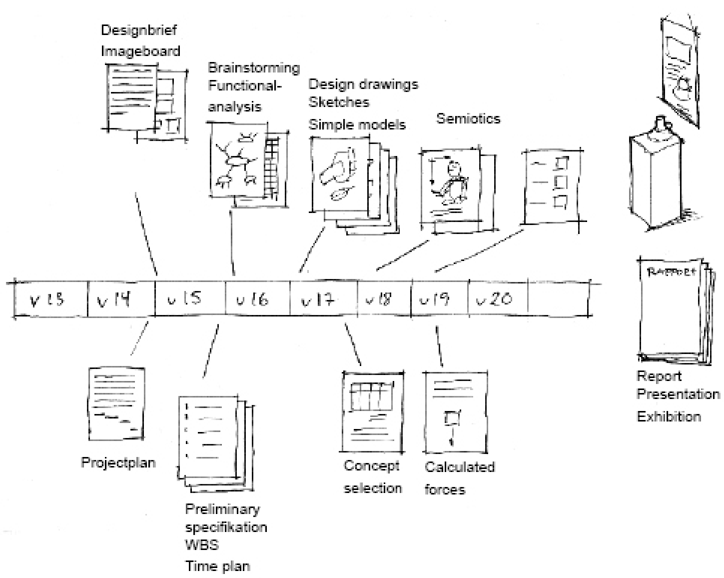

Figure 3 – Example of project timeline

The upper part of the timeline represents important hand-ins for the industrial design course and the lower part represents the hand-ins for the mechanical design course.

The project model is based on Polyas (1973) method of problem solving. It is adapted to fit the scope of the course and consists of the following steps:

Problem Definition:	What is the problem to be solved?
Project Planning:	How do we solve this?
Project execution:	Implement the plan!
Project evaluation:	What can we learn from the project?

Although this seems simple enough, most groups tend to rush into execution as soon as possible. We encourage students to do small experiments to verify ideas early in the project, but we stop any immature time consuming design activities.

Project execution

Standardizing the task of documenting the day-to day work makes it easy to write the report and also to track important events so the first assignment for the groups is to make templates and logotypes for documents. The team leader of the week is responsible for the documentation and the binder where most documents are filed.

To foster an effective meeting routine, the group has prepared the agenda with following content:

- Time spent in the project last week
- Comment on the project plan
- Records from the last group meeting
- Last weeks assignments
- Scheduled work for the next week
- Project questions

Teams have two compulsory meetings every week. One meeting is for coaching and reporting to the teachers, the other is a group meeting for planning the activities of the week.

Assignments and hand-ins

The path from many conceptual ideas to a certain detail in the final design is not straight, and the timing of the assignments is never perfect. Keeping down the sizes of the assignments but giving them frequently will keep the projects at a steady pace. A slow group can always do parts of the assignments, finishing them later when data is available.

If they can not make a specific assignment on their product since they have not decided what product to design, they can pick one of their concepts for the assignment, and update the documents later. The first versions are not mature and will not describe the final result, but the process of writing clarifies product ideas and brings some structure in the firsts confusing phase of the work. A table of the hand-ins is shown below.

Table 1. Table of the hand-ins.

Week nr.	Hand-ins
1	No hand-ins
2	Group contract, project quotation, project plan, preliminary ideas.
3	Design brief, image board, Work Breakdown Structure, detailed time plan
4	Brainstorming, sketches, functional analysis, preliminary specification
5	Product ideas, design drawings, simple models, concept selection.
6	Semiotics and ergonomics
7	Calculations, color settings
8	Preliminary drawings
9	No hand-ins
10	Exhibition, report, presentation

The first hand-ins is the group contract, a project quotation and the project plan. The quotation is an estimate of the cost to develop the product based on the number of hours and cost of material they plan to use. Comparing the different offers in class is amusing since the prices of the offers are very different, prices can vary 400%.

Design brief is a short document describing the product. The brief can be seen as a reply to the project assignment together with the image board, a collection of images that represents the customer. Not surprisingly most groups design products for active people with high income, this is probably an unconscious image of them selves in the future.
Students practice creative methods such as brainstorming, Brainwritning (Method 635) and analogies by searching patents. The hand ins are rough unpolished ideas' in the form of sketches and explaining text. Every group have between 50 and 100 preliminary ideas and the top ten is further refined into well-done sketches. At this stage it is not possible to choose a "best" alternative so the preliminary specification and functional analysis refers to one of the concepts.

The Work Breakdown Structure (WBS) is a method for "dividing and conquering" the project. Project activities are identified by brainstorming and those requiring more than one week of full-time work will be the headings of the plan. In this way it is possible for inexperienced engineers to make plans that handle the important aspects of the project rather than details. A preliminary specification is written and sometimes regulations or safety standards are governing the design of the product. Some regulations are expensive to obtain so the teachers have prepared this in advance. Other specifications are common for many products, for example the all outdoor products must endure rain and ultra violet rays from the sun.

Semiotics is usually hard to explain to engineers, but is easier to grasp with visual aids such as physical models. If the assignment is developing a lawnmower the product should explain which the front end is and where the dangerous high speed rotating blade is. The ergonomics concerns how to start and use the product. The students also use Photoshop or similar programs to see what the product looks like in different color schemes.

Engineering calculations are done on part of the product since there is no time to do a complete study. The teacher suggests which parts are suitable to investigate in detail and these parts are also documented as production drawings. Each group also makes assembly drawings of the whole product even though all parts are not fully finished.
The last week has no assignments and time is spent on report-writing and finishing the models.

Grading

Grading this DBT project is done in the same way as grading a thesis. Examining the structure in the work, progress made and overall quality of the work and the care for details are good indictors. We separate different aspects of the project and grade them separately:

- Quality of presentation
- Quality of report
- Quality of models
- Inventiveness
- Economic potential

The grading is usually done by a committee of persons with knowledge in different areas.

Project presentation and exhibition

The presentation starts in a class-room where the groups present their work. The products are then put on exhibition and the teacher's comments on each of the projects. Soft drinks and snacks are offered and students feel a well deserved relief. The layout and design of the exhibition is planned by all groups and also the size and style of the signs accompanying different products.

Structured Coaching of student projects

One challenge for both students and teachers is to separate the goal from the means. In theory, the goal of a project is not to produce the physical object in it self, they are just means for learning design. The teacher must show how the group can acquire information, knowledge and hardware for the given tasks, and avoid solving the problem for the students. Grading is also hard since part of it is usually to judge the quality of the products produced.

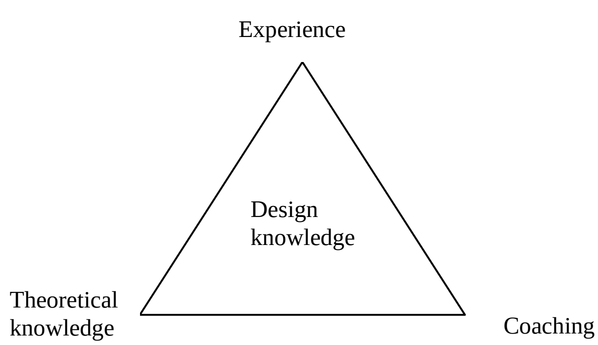

Figure 4 – Our view of design knowledge

The amount of design knowledge in the project can be seen as the area between the factors theoretical knowledge, coaching and experience. In the project we try to increase the amount design knowledge by using theoretical knowledge from previous courses and increase the experience of design by coaching the students.
Most students have little experience of design and in order to learn good working methods coaching is effective. Coaching will increase the output and an example could be the teacher suggesting rules of thumb for dimensioning a part of the product. The less defined the problem the more coaching is needed.

Without theoretical knowledge, the individual can not make use of methods and tools for design so the area of design knowledge is reduced. He/she can not make estimates of the important parameters that govern the design, although experience of similar designs helps to get the product look right.

Coaching
Coaching by teachers is compulsory and occurs once a week. Teachers work in pair and meet each group for 25 minutes at a fixed time. Prior to this the groups have handed in the assignments of the week and the teachers have had time to comment on this.

Coaching is both guiding and corrective. In our view guiding is suggesting different paths to follow rather than prescribe in detail how to manage problems encountered. Corrective actions are equally important but always negative to the students in the sense that it implies rework which sometimes is taken very personal. Problems can be of many types, many groups are lagging behind their time plan. In these cases the groups suggest measures to take in order to finish in time and these changes are approved by the teachers.

The weekly assignments are commented and usually some corrections are needed. When the quality of the work is not satisfactory another hand-in is needed. The rest of the time is spent solving problems, discussing the plan for the coming weeks and issues and needs of the group. In the cases where the students have not put in enough effort the teachers are rather strict demanding immediately action.

A typical discussion could be “which type of transmission can we use in this case; we have read the textbook and could use any of these two belt types, which one is the best?” The teacher would say “It depends on the details. Get some more data on real belts from a supplier such as cost size. Which other components are needed, you must have data on available pulleys”. Students would reply “But which one is the correct alternative?” “You could choose anyone as long as there is a good motivation.” The meeting ends with commenting on the good work that has been done in order to leave the students happy and productive.

Other types of coaching are when the teachers make unscheduled visits to computer rooms or in the machine shop. This happens a few times each week and on these occasions the group members are separated it is possible to comment on their individual work. The workshop manager helps the students to start using the machines but they have to do the work themselves. He also corrects infeasible designs and can do some advanced manufacturing of details. Each student spends at least 40 hours in the shop and get rather familiar with the equipment.

In this first product design course the students are not given lectures or literature in structured product development or concept evaluation methods. The pedagogic twist is that they can do rather well with the structure provided by the teacher, but when methods are introduced in the next course students are eager to use these since they understand the needs.

Finding information
The knowledge of the evolving product is very low in the beginning and most of the important information must be found by the students. Since they have many alternative product ideas we ask them to immediately start searching the internet and patent databases for information on competing products.

To their disappointment they find many identical products but in the coaching situation this is ideal: It shows the importance of not jumping on the first idea that comes to mind, but also that their ideas are good enough to make real products of. They just need to work a little harder to invent something new.

In this phase it is important to get them off the internet and make some real life contacts. We teach simple ways of finding information by making questionnaires, visiting retailers, calling institutes and suppliers or checking market shares of products by reading advertisements for used equipment. In a case of garden equipment the students were given the tip-off to visit a neighborhood with many retired people since they are available on workdays, they often have long experience of gardening and they usually have time to chat.

The level of quality
The level of quality has increased over the years and the interesting part is that high performance is created by the groups themselves. Nobody has made them to spend the extra time to make the product perfect and some groups have spent 800 hours in the workshop. Initially a few good examples from the last years projects are shown by former students who also explain their experience of the project. The quality level is increased by studying other groups and trying to outperform them.

Another factor is that students know that they will be graded on the project so putting in an extra offer will pay off. They also know that many people are going to see the exhibition and we encourage them to bring their relatives to the presentation.

Learning by failing
The frequent hand-ins give short feedback loops and provides an almost instant correction of minor faults. It is off course important to also comment on the positive sides of the project to further reinforce good practices! The summary of last weeks work is a fine tool for discussions on improvements on working methods. In the report an important part is the project evaluation where the students can reflect in what they have learnt and what can be improved in future projects.

Results
The physical output of the project is industrial design mock-ups, functional models and drawings. Students build most parts according to drawings. Usually they have to adjust or scrap many parts that did not behave as expected and redesign them. Many products are innovative and our students have won prices in different national competitions KKS

(2004). We also encourage groups to commercialize their work and there is at least one example of a successful company built around a product conceived in these courses. The project is widely appreciated among the students which can be seen in course evaluations.


Figure 5 – Project exhibition

Discussion

The "Design, Build and Test" concept has one important drawback; the learning outcome is not proportional to the amount of time spent to achieve that level of learning. The learning can also be very unevenly distributed within the teams and between the teams. Prior to the structured coaching of design projects these drawbacks were frequently occurring.

For many students, the idea of planning and thinking ahead is just delaying of the real work in the shop. This is very logical since most students believe that the purpose of the course is to produce prototypes. We must remind them that this is a school and the goal is to learn design methodology. If the assignment had been to learn the tools in a workshop, the project lay up had been different.

Design to test or design to learn?

When students are to learn practical engineering by designing and building a physical object it is tempting to let them free in the work shop, letting them build and design in parallel. In this way the design work becomes a happening, using the available materials and resources but not connecting to their knowledge from previous courses. This can be displayed when designs rigid enough to carry elephants are used to support bicycle wheels and the teachers must help them to see why this design is incorrect.

Figure 6 – Is chaos always equal to learning?

The learning outcome from unstructured projects is often that “things takes a lot more time than planned” and that the teamwork at some point broke down. To address these drawbacks of DBT-projects some focus was changed from learning design to learning teamwork and project planning in a design course.

Conclusions

Having a theme has been a factor of success in our DBT projects but be prepared to invest time in it such as new educational material, background research and special lecturers if needed. Other important factors are:

- A clear structure for the project that guides inexperienced students not to get lost in the design process.
- Frequent hand-ins every week that will keep the pace and give short feedback loops. Writing things down helps structuring unfinished thoughts.
- Professional help in team building
- Small experiments to verify ideas early in the project
- Build most parts according to drawings
- Project evaluation for collecting knowledge for the next project

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