Six Aerospace Design Projects to Learn How to Engineer

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Abstract

Tomorrow's engineers are required to have a good balance of deep working knowledge of engineering sciences and engineering skills. In the Bachelor in Aerospace Engineering at TU Delft, students are educated to master these competences so that they are ready to engineer when they graduate. The mainstream Aerospace Design is built up semester after semester of a design project and an accompanying design course. The main objectives of the design projects are related to contextual learning, learning by doing together, and learning and practicing academic and engineering skills, and being a mental organiser for the students. Over the years of study the design projects increase in complexity and openness, from knowing to application and synthesis, from tangible to abstract, from mono- to multidisciplinary, and from mostly individual to team work. All projects exploit the factors that promote intrinsic motivation (challenge, curiosity, control, fantasy, competition, cooperation, and recognition). To assure that the intrinsic motivation factors and the semester themes are well addressed, each design project is characterised by a storyline, professional role, client, real-life problem, engineering process, and certain attainment levels of engineering skills.

Keywords: Project-based learning, experiential learning, intrinsic motivation

1 Introduction

Especially undergraduate engineering education is tensioned between the ever increasing body of technical knowledge and the growing recognition that young engineers must also possess a wide array of personal, engineering and design skills (Ruth, 2012). In the development process of the innovative Bachelor in Aerospace Engineering (Kamp, 2013) the acquisition of foundational and disciplinary knowledge and its application to the design of aircraft and spacecraft have been the prime points of departure. Applying theory is a very important skill to be learned: students have to learn how to transfer the knowledge and skills they acquire in the classroom, to solve practical problems, throughout their study. The theoretical courses on aerospace engineering sciences and technology have therefore been complemented with project-based elements of experiential learning in which students design, build, test, analyse, model, simulate and experiment and thus get hands-on experience in engineering, individually or in teams (Kamp, 2011). The curriculum is highly compliant with the Standards of the CDIO Initiative, an innovative educational framework for producing tomorrow's engineers (Crawley, Malmqvist, 2007; www.cdio.org).

2 The profile of the bachelor

The reference for our Bachelor and Master degree programmes in Aerospace Engineering has been the so-called T-shaped professional (Guest, 1991). Today's job market is calling for engineers with a broad knowledge who are capable to look beyond the boundaries of their own discipline: deep problem solvers in engineering, science and management who can also interact with and understand specialists from other disciplines and functional areas. The bachelor provides the broad academic background with a consolidated knowledge of aerospace engineering and design together with intellectual and engineering skills (Kamp, 2011). All aerospace engineering disciplines are oriented towards the concept of product development, without losing their academic strength of sophistication and abstraction. The programme educates what aerospace engineering is all about and is fundamentally about how one engineers aircraft and spacecraft. It tells this story from the beginning till the end and has a well-structured knowledge base in a motivational context of engineering themes. The students' experience in the bachelor is about the engagement and enjoyment of the thrill of the profession of an aerospace engineer.

3 The framework of the integrated bachelor

The bachelor curriculum has a thematic structure that is represented by the life cycle of an engineering design process. This cycle forms the logical sequence of themes for the six semesters of the curriculum. The first semester emphasises the first and explorative phase of an engineering design process: it is about exploring the aerospace domain. The freshman students are introduced to the variety of aspects of aerospace engineering in an exploratory fashion through an introductory course and a design project that provide the student with the "big picture", the framework for the practice of engineering and the context for his study in the coming years of study (Figure 2). The second semester focuses on the conceptual design, the third on the preliminary design, the fourth on analysis, test and simulation, and the fifth on verification and validation. The series is concluded by a design synthesis.

The thematic structure (columns in Figure 1) allows for the multi-disciplinary integration of knowledge and an embedding in the societal context. The themes tie the content together in each semester. The content is organised in courses of mostly mono-disciplinary knowledge or skills. It is important in engineering education that the basic engineering sciences and the sub disciplines of aerospace engineering and technology are identifiable and visible elements of the curriculum.

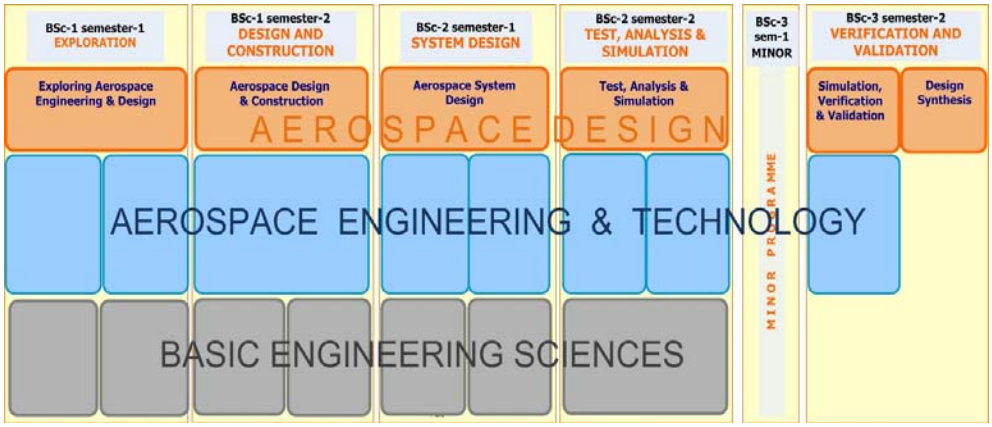

Figure 1 The three mainstreams in the bachelor

Besides the thematic structure, the curriculum has a horizontal structure (rows in Figure 1) of three contemporary mainstreams: The upper stream is about **Aerospace Design** with one module per semester. Each module contains a design project and complementary engineering design course. The middle stream is about **Aerospace Engineering & Technology**. It contains the courses in the aerospace domain about aerodynamics, aerospace materials and structures, production engineering, flight and orbital mechanics, systems and control, flight and orbital dynamics, aircraft and rocket propulsion. The courses in this stream address the semester theme, relate with each other and the design project. The lower stream of **Basic Engineering Sciences** consists of courses about mechanics, physics and mathematics. Examples and applications in these courses relate to aerospace engineering but are not directly to the semester theme.

The courses in the Aerospace Engineering & Technology mainstream provide the theoretical basis and academic strength for the projects; the projects provide the motivation and application for the theory. So besides the disciplinary lines of advancement, also project and lab work in teams is an important line of advancement that extends over the three years of study. In combination with the themes, the projects form an important organiser of the curriculum. They are the spaces in the curriculum where the young students develop into critical and tenable professional engineers.

4 The objectives of the design projects

The meaning of what students learn is coupled to their life experiences and context. The learning is constructed by themselves, not by their teachers; it is anchored in their context of real-life situations and problems (Imel, 2000). This type of learning is referred to as contextual learning. Learning primarily occurs when students process new knowledge in a way that it makes sense to them in their own frames of reference. This approach assumes that the mind naturally seeks meaning in context, in relation to the person's current environment, and that it does so by searching for relationships that make sense and appear useful (Johnson, 2001). The first objective of the design projects is the

implementation of contextual learning throughout the programme: project-based learning right from the beginning till the end: one capstone project is not enough!

The second objective of the design projects is the function of "mental organiser" for the students. In the projects students integrate the theory from the past year, such that knowledge, skills and attitude can build and grow over the three years of study (longitudinal learning). The structure in which each semester is organised, around a theme and with a design project as the engaging and binding element, fulfils this function. Practically this means that for each semester a real-life project is defined in which the student plays a specific role of the profession of an aerospace engineer and also performs in a (simulated) professional environment. The first year project creates also the appropriate environment to make freshmen students feel at home at university (social integration).

The third objective is learning-by-doing, individually or in teams. Due to an increased engagement in their learning, the students become independent learners and pivotal to managing their own learning process. The projects are a compelling counterbalance for the theoretical courses. They create the opportunity for students to work on a central design problem, that has a narrative with leading research or design questions that have to be solved.

The fourth objective of design projects is to learn and practice academic and engineering skills. Besides the learning of how to design or research, the projects train engineering students in the very basic skills they often miss (Goldberg, 2008) but will need in their engineering profession:

1. **asking** questions: to learn what a design or research project is about, what has been tried in the past, what critical sources of data and theory exist, and what other resources could be helpful in solving this problem.
2. **labeling** technology: to learn how components, assemblies, systems, and processes have to be labeled in a design project.
3. **modeling** problems qualitatively: to learn how to make lists of system elements or problem categories or describe how things work in words
4. **decomposing** design problems: to learn how a big design problem can be broken down into smaller manageable sub-problems
5. **gathering** data: to learn that start modeling mathematically is not the right approach; they have to find out that efficient and effective solutions often depend on simple experimentation or searching for information in a library or on the web.
6. **visualising** solutions and generating ideas: to learn how to hand-sketch or diagram solutions to problems, and how to brainstorm a sufficiently large number of solutions.
7. **communicating** solutions in written and oral form.

Since each semester has its own project-based learning activity, the projects form a highly visible trail of Aerospace Design throughout the curriculum, even though their volume is only 15% of the study load in the bachelor. Each project is aligned with the theme of the semester and explicitly trains the students in one or more personal and interpersonal skills or product, process and system building skills. Each project is accompanied by a course about design methodologies in aircraft and spacecraft design or a specific engineering skill. A more detailed description of the framework is available in (Kamp, 2012).

Figure 2 Explorative hands-on learning by conceptualising, designing, manufacturing and testing a flying wing in the first-year design project

The design projects increase in complexity from the first to the third year of study, from knowing to application, synthesis and evaluation, from tangible to abstract, from mono- to multidisciplinary, from mostly individual to team

work. The Design Synthesis project is the bachelor thesis project that assesses the final competence levels the students have achieved in designing.

5 Framework of the design projects

5.1 Common boundaries and outline

Each design project is characterised by the following elements:

- Multi-disciplinary setting in aerospace engineering.
- Professional environment (design, research, experimentation, test) in which the students work in professional roles on an authentic case. The result is a professional output product like a piece of hardware, test results, technical report, essay, paper, poster, abstract, presentation.
- Deepening the knowledge and developing engineering or interpersonal skills.
- Applying recent theory and re-applying theories and skills from the periods before. The general skills that are practiced are project and team skills, communication skills, intellectual skills and design skills.
- Team work. All project assignments are performed in groups of students. The learning outcomes are always tested individually. So the personal development and performance are tracked, and free-riders or fringe players are identified.

5.2 Promoting intrinsic motivation

Each project has been designed such that it makes optimum use of factors that promote intrinsic motivation with the students (Deci & Flaste, 1996; Lepper & Hodell, 1989; Malone & Lepper, 1987): challenge, curiosity, control, fantasy, competition, cooperation, and recognition. Table 1 describes these factors in detail and how they have been implemented in the projects.

5.3 Level of self-regulation

Each project has its level of openness and requires a different level of student self-regulation and autonomy. A project is defined as a:

- Level 1 project or Assignment Project: in which planning and control is done by the tutor (supervisor) and the problem and subject are chosen beforehand by the tutor. These projects are used in the first year of study.
- Level 2 project or Subject Projects: a definition of the subject is provided by tutors beforehand, but students choose the problem analysis and solution method in collaboration with the project coach. These projects are used in the second year of study.
- Level 3 project or Problem Projects: the problem determines the choice of disciplines and methods. Planning and control is the responsibility of the students. These projects are used in third year of study.

5.4 Salient features of the design projects

The factors in Table 1 that promote intrinsic motivation together with the themes, set the “boundary conditions” for the projects. The themes define the types of activities and roles students undertake in the project, but not the specific context nor the content. Within the boundaries, the expertise and passion of faculty academic staff define compelling projects. They provide the concrete, authentic context for student’s work – students not just learn the theory, they use the theory in cooperation with young designers or researchers, so that they develop an appreciation for what the theory means in practice.

To assure that both the intrinsic motivation factors and the themes are sufficiently addressed, each design project is developed using the following binding elements:

- Storyline
- Professional role
- Client
- Real-life problem
- Engineering process
- Engineering skills

Table 1 Implementation of promoting factors of intrinsic motivation Error! Reference source not found.

Factor	Description	Implementation in the projects
Challenge	Students are best motivated when they are working toward personally meaningful goals whose attainment requires activity at a continuously optimal (intermediate) level of difficulty.	Each design project sets meaningful goals. The attainment of the goals is probable but not always sure. In the course of the project, tutors give en route performance feedback. Each project has a client who challenges the students in the team.
Curiosity	Something in the physical environment attracts the student's attention or there is an optimal level of discrepancy between present knowledge or skills and what these could be if the student engaged in some activity.	The narrative of the project contains aspects and assignments that stimulate curiosity. They make students wonder about something, i.e. stimulate the student's interests.
Control	Students have a basic tendency to want to control what happens to them.	Tutors of the projects make the cause-and-effect relationships clear between what students are doing and the consequences of their actions, of the things that matter in real life. The projects give a certain level of autonomy to the students, increasingly over the years of study. They are allowed to freely choose what they want to learn and how they will learn it.
Fantasy	Students use mental images of things and situations that are not actually present to stimulate their behaviour.	The project assignments are increasingly open-ended. Tutors stimulate the students to be creative and thus make a game out of learning. The tutors help the students imagine themselves how they can use the knowledge they have learned in the courses and information they can retrieve the authentic in real- life settings. The project definitions and tutors inspire the students and make the fantasies intrinsic rather than extrinsic.
Competition	Students feel satisfaction by comparing their performance favourably to that of others.	Within the teams competition occurs naturally. Some of the projects have a competitive element, for instance achieving the longest flight duration of their flying wing, withstanding the highest load factor at minimum weight, and presenting the system design to a professional jury (Design Synthesis project).
Cooperation	Students feel satisfaction by helping others achieve their goals.	All projects are performed in team work. In the design projects student have little to no free choice for their team mates. Cooperation occurs naturally and sometimes has to be enforced. It is more important for some students than for others. Cooperation is a useful real-life skill. It requires and develops interpersonal skills.
Recognition	Students feel satisfaction when others recognize and appreciate their accomplishments.	All projects have predefined deliverables like reports, posters, presentations, structures, flying wings, etc. Also the roles of the students in the projects create a level of visibility of the individual students. This visibility in the learning process is required for recognition. Recognition differs from competition in that it does not involve a comparison with the performance of the fellow students in the team.

Storyline

Each project has a storyline. It introduces a real-life problem that matches to the theme in a way that is beyond a simple restatement of the task and concludes with a summation of the theme or problem. The storyline is defined at a higher level from which the project idea is derived (e.g. a story about human-powered flight, which leads to the

project idea "build a flying bike"). The story also depends on the professional role the students take. So projects are not described as "students will build X" or "students will calculate Y". Such kind of project descriptions leave out the idea that students have to take a professional role. To show the interrelations, the storyline of each project has multiple connections to the content learning objectives for a semester, and demonstrate what these connections are.

Professional role

Each project focuses on the kind of roles and activities that aerospace engineers fulfil during the different phases of an engineering project. Initially, any engineering project requires exploration of the problem space: What is the context of this project? What do the requirements really mean? What solutions already exist? In the first project the students therefore are given the role of an Explorer, a **Feasibility Leader**. This is then followed by conceptual design and detailed design in the following semesters: What kind of structure should we build (**Structural Engineer**)? What are the subsystems involved, and how do they interface with each other (**Lead Engineer**)? How should we document it? Real engineering problems require extensive analysis, modelling, and testing, verification and validation in the end: What experiment should we run (**Test Engineer, Experimentalist**)? How can we model the system (**Analyst, Test Engineer**)? How do we evaluate and prove the proposed solution (**Validation Engineer**)? How do you design a complete system or mission (**Systems Engineer**)? The deliverable products depend on the professional role of the students. Having students come up with a scientific report (Data Analyst) is quite different from delivering a 3D CAD design with explanation (Lead Engineer). The assessment method and criteria depend on the role the students take.

Client and Real-life problem

All projects have a client who challenges the students with a real-life problem in a realistic professional environment. The clients vary from tutors and teaching assistants in the first year of study, to scientific staff and PhD students in the second year, and real customers from faculty, external institutes and industries in the third-year Design Synthesis project. The tutors of the projects in the first year represent virtual customers.

For instance in the first-year project Design & Construction the students become a member of a team of structural design engineers who received a contract from a virtual company in aerospace industry AMYE (Aircraft Manufacturing by Young Engineers) to design and develop a wing box for their new aircraft. In the second-year project about System Design the student is made a Lead Engineer who is invited to join a task force who works on new wing designs for a Next Generation aircraft (real situation) under the responsibility of Randy Green, former employee of Scaled Composites, who headed the aerodynamics department of this Mojave, California based aircraft design and prototyping company. The second-year project about Test, Analysis & Simulation relates to real-life research and design work in the faculty research groups. Each team gets an individual project assignment that is supervised and owned by a researcher or PhD student. The tutors of these projects challenge the students and are eager to get valuable results they may use in their research. In the culminating Design Synthesis projects all customers have real interest in the outcome of the project. Often the customers use these projects to have innovative or advanced system concepts investigated by young engineers on feasibility.

Engineering process

Chapter 5.3 about the Level of Self-regulation already stated that it is important that each project is sufficiently open-ended. Ultimately the students have to learn how to make decisions and not just follow a set of prescribed steps. The project activities provide opportunity for and encourage students to make mistakes and reflect on their learning, their actions and the consequences, without jeopardising their academic success through inappropriate or excessive assessment.

In all projects the students focus on the final product. For the developers of the assignments for Level 2 and certainly Level 3 projects this requires an open attitude. It could easily lead that projects are defined too limited in scope, because of the "students don't know very much yet, so they can't do very much" argument. If a developer sticks to this kind of approach, we would end up with boring projects, as the tutors choose projects that they think students can do at a professional level. However, in educational projects it is desirable for students to do projects that require some additional knowledge, and it should be appreciated that students will not produce perfect final products – so long as they learn in the process. Although the outputs of for example the final Design Synthesis project may not be perfect and at an industrial standard, students do learn an enormous amount in the process of doing this project – and that lesson can be applied and further exploited elsewhere in the study programme.

6 Educating engineering skills

Engineering design is a process of devising a system, component, or process to meet desired needs. It is a decision making process, often iterative, in which basic and aerospace engineering sciences are applied to convert resources optimally. In their study the students have to experience what engineering is. That is why all projects are designed around real-life cases, in which students apply theory and skills and have to learn how to simulate the profession of an aerospace engineer in a representative role in a real-life environment. The professional roles familiarise the students with their future professional environment and stimulate the development of their skills. The professional roles and environment, the learning objectives and final product are defined in Table 2. The design projects are harmonised with the learning outcomes of the aerospace engineering courses (row "science"). The themes deepen each year from simple to complex with regard to various aspects, and also use the information dealt with in the previous project. The projects have an increasing level of abstraction and complexity to challenge the students in the development of their skills.

Table 2 Professional roles, product and attainment levels of engineering skills

		BSc-1 semester 1	BSc-1 semester 2	BSc-2 semester 1	BSc-2 semester 2	BSc-3 semester 2a	BSc-3 semester 2b
	Design Projects	**Exploring Aerospace Engineering**	**Design & Construction**	**System Design**	**Test, Analysis & Simulation**	**Simulation, Verification & Validation**	**Design Synthesis**
	Professional role	Feasibility Leader	Structural Engineer	Lead Engineer	Data Analyst Test Engineer	Validation Engineer	Systems Engineer
	Main learning outcomes	project skills; design skills; problem definition; application and retrieval of new knowledge; experimental skills	requirements definition; conceptual definition, analysis and design of an aerospace structure; experimentation; instrumentation; reporting; oral presentation; self-reflection and reflection on group performance	design and design analysis of an aircraft or spacecraft subsystem; self-reflection and reflection on group performance	model of a test set-up, prediction of its performance data analysis; correlation of model with test results and observations peer review and report annotation	application of simulation techniques; simulation plan; simulation model	design and development of an aerospace project, taking into consideration the societal and temporal context
	Output products	small design, analysis, test reports; poster; flying wing (hardware)	literature review; design report; production plan; instrumentation plan; test report; design drawings; cover letter; wing box (hardware)	design and analysis reports; design drawings; essay on design process; oral presentation	literature review; scientific report; self-reflection;	simulation plans; analysis reports; synthesis report	design report; project plan; presentation to review board; presentation to external jury
Attainment levels	**Science**	novice	simple	advanced	complex	complex	expert
	Research			simple	advanced	advanced	advanced
	Design	novice	simple	advanced	advanced	complex	expert innovative
	Scientific approach		simple	simple	advanced	advanced	expert
	Intellect. skills	novice	simple	advanced	complex	complex	expert
	Comm. & Coop.	simple	simple (oral) advanced (writing)	complex	complex	complex	expert
	Societal context	simple	simple	advanced	advanced	complex	complex

The terminology simple/complex in Table 2 shows the systematic deepening of the knowledge and skills levels. It is used to describe the state of novice to expert. They are a combination of the level of the competence and the complexity of the environment in which they are achieved:

- level 1 is a level of introduction or familiarisation with practice in simple problems
- level 2 is an extension level in which the skill is developed to a more mature level by training, practicing and feedback in advanced, intermediate complex problems
- level 3 is a mature status in which the skill is ready for use in complex problems

7 Conclusion

Throughout the bachelor the students learn how to transfer what they have learnt, in solving complex practical problems of tomorrow's engineers: applying theory and analysing and solving practical problems, but also in listening, presenting, criticizing and accepting critics, and working in teams. Students take their project roles very seriously and are both enthusiastic and positive about their learning outcomes. The six design projects provide hands-on experiences where learning-by-doing-(together) creates good interaction with others and an atmosphere of collaboration. Each project is designed around an authentic and relevant problem in the life of an aerospace engineer. The projects are supported by dedicated courses on design methods or skills trainings that are directly applied in the project.

The series of six increasingly open-ended design projects in combination with the courses on Aerospace Design and Systems Engineering make a difference indeed and have lifted the levels attained in engineering and design to higher levels.

References

Crawley, Edward, Malmqvist, Johan, (2007), "Rethinking Engineering Education", Springer Science and Business Media.

Deci, Edward L., Flaste, Richard; (1996), Why we do what we do, Understanding Self-Motivation, Penguin Books.

Goldberg, D. E. (2008), The Missing Basics and other Philosophical Reflections for the Transformation of Engineering Education. Excerpt from "What engineers don't learn and why they don't learn it: and how philosophy might be able to help". Abstracts of the 2008 Workshop on Philosophy and Engineering, 85-86.

Guest, D. (1991),The hunt is on for the Renaissance Man of computing, The Independent (London), September 17, 1991

Imel, Susan (2000), Contextual Learning in Adult Education. Centre on Education and Training for Employment, the Ohio State University

Johnson, E. B. (2001) Contextual teaching and learning: What it is and why it's here to stay. Corwin Press.

Kamp, Aldert, (2011), Delft Integrated Engineering Curriculum. Proceedings of the 7th International CDIO Conference. Technical University of Denmark, Copenhagen, Denmark, June 20-23, 2011.

Kamp, Aldert, (2013), Making curricular change: Case report of a radical reconstruction process. Proceedings of the 9th International CDIO Conference, Massachusetts Institute of Technology and Harvard University School of Engineering and Applied Sciences, Cambridge, Massachusetts, June 9 – 13, 2013

Kamp, A. (2012), The Trail of Six Design Projects in the Delft Bachelor Aerospace Engineering. Proceedings of the 8th International CDIO Conference 2012, Queensland University of Technology, Brisbane, Australia, July 1-4, 2012.

Lepper, M.R. & Hodell, M. (1989). Intrinsic motivation in the classroom. In C. Ames & R. Ames, Research on Motivation in Education: Goals and Cognitions (Vol 3). New York: Academic Press.

Malone, T. W., & Lepper, M. R. (1987). Making Learning Fun: A Taxonomy of Intrinsic Motivations for Learning. In R. E. Snow & M. J. Farr (Eds.), Aptitude, Learning and Instruction: III. Conative and affective process analyses (pp. 223-253). Hilsdale, NJ: Erlbaum.

Ruth, Graham (2012), Achieving excellence in engineering education: the ingredients of successful change. The Royal Academy of Engineering.

Worldwide CDIO Initiative, www.cdio.org accessed 14 March, 2013