EDUCATING ENGINEERING PRACTICE IN SIX DESIGN PROJECTS IN A ROW

Aldert Kamp

Delft University of Technology, Faculty of Aerospace Engineering
Delft, the Netherlands

ABSTRACT

Tomorrow's engineers are required to have a good balance between 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 bachelor curriculum has three mainstreams of about equal study load: Aerospace Design, Aerospace Engineering & Technology, and Basic Engineering Sciences. The Aerospace Design stream 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.

The projects make use of student project spaces in a dedicated building for collaborative learning, and laboratories like wind tunnels, a structures and materials laboratory, a study collection of aircraft and spacecraft parts and subsystems, and a flight simulator.

KEYWORDS

Project education, project-based learning, experiential learning, aerospace engineering, design education, integrated curriculum, intrinsic motivation

INTRODUCTION

University engineering education is increasingly determined by science and technology, whilst tomorrow's engineers are required to have a good balance between a deep working knowledge of technical fundamentals and interpersonal communication and team skills with understanding of project and self-management methods [3][5]. Lecturers and professors are increasingly research based [15], have little exposure to engineering in industries or hardly any practical engineering or design experience. This leads to a decrease in professional visibility of engineers [19]. 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 [16].

In the development process of the innovative bachelor curriculum [11] we have emphasised the acquisition of foundational and disciplinary knowledge and its application to the design of aircraft and spacecraft. Applying theory is a very important skill to be learned: in all years of study students have to learn how to transfer the knowledge and skills they acquire in the classroom, to solve practical problems. The theoretical courses on aerospace engineering sciences and technology are therefore complemented with project-based and experientially orientated curricular elements in which students design, build, test, analyse, model, simulate and experiment and thus get hands-on experience, individually or in teams [10] (CDIO Standards 1 "The Context" and 3 "Integrated Curriculum" [3]). In the integrated bachelor curriculum this has been strengthened and more structured than before, and made explicit in the Final Qualifications and intended learning outcomes (CDIO Standard 2 "Learning Outcomes").

PROFILE OF THE BACHELOR

The reference for our degree programmes aerospace engineering has been the so-called T-shaped professional concept [7]. 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. That is the profile of the graduates we want to educate: aerospace engineers who know what engineering is, not aerospace engineering scientists.

In our bachelor all aerospace engineering disciplines are oriented towards the concept of product development, without losing their academic strength of sophistication and abstraction. The programme provides the broad academic background with a consolidated knowledge of aerospace engineering and design together with intellectual and engineering skills [10]. It 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.

The profile of the bachelor is reflected in the approximate distribution of the study load over the competence areas of our BSc Final Qualifications as shown in Table 1:

Table 1 Distribution of the study load over the competence areas in the bachelor

Competence area	Nominal study load
Engineering sciences	55%
Design	15%
Cooperating and communicating	5%
Research	5%
Scientific approach	5%
Intellectual skills	10%
Societal and temporal context	5%

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 (Figure 1). This cycle forms the logical sequence of themes of the six semesters of the curriculum (CDIO Standard 1 “Context”). 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 (CDIO Standard 4 “Introduction to Engineering”). 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.

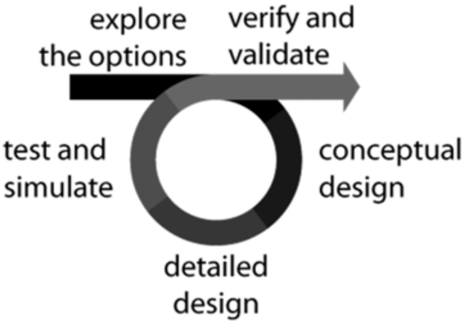

Figure 1 Engineering design life cycle as the template for the themes

The thematic structure (the vertical connection in Figure 2) 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.

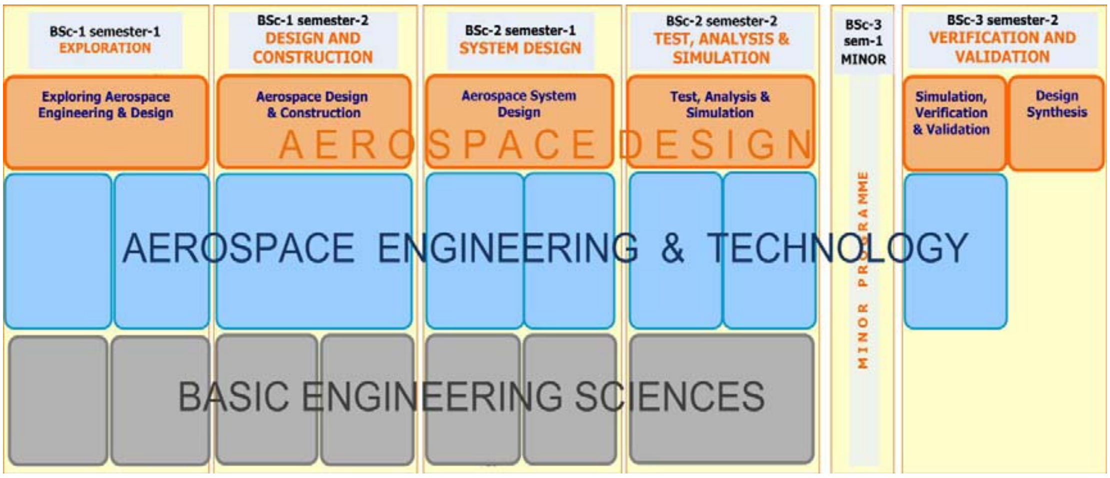

Figure 2 The three mainstreams in the bachelor

Besides the thematic structure, the curriculum has a horizontal structure 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 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 and 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. Table 2 shows the distribution of study load over the mainstreams.

Table 2 Distribution of study load over the three mainstreams

Mainstream	Nominal study load
Aerospace Design	34%
Aerospace Engineering Sciences & Technology	34%
Basic Engineering Sciences	32%

Within each mainstream there are horizontal lines of advancement with a systematic deepening of knowledge and skills over time. Each semester a certain level of knowledge and skills have to be attained. They recur and are practiced in the next year, while a level of complexity is added to what is learned in the previous year. Thus the students mature along the disciplinary lines of advancement and encounter multiple experiences in the open-ended design projects, so that they develop depth and sophistication over time. This arrangement helps students transition from a more concrete perspective on engineering sciences in the first year to one that integrates both the concrete and abstract concepts in later years of study.

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 work in teams and lab work in small groups 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.

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 [8]. 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 [9]. The first objective of the design projects is the implementation of contextual learning: project-based learning right from the beginning throughout the bachelor (CDIO Standard 5 “Design-Implement Experiences”): one capstone project is not enough!

The second objective of the design projects is the “mental organiser” for the students. In the projects they 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 future aerospace engineer and performs in a professional environment. The first year project creates also the appropriate environment to make freshmen students feel at home at university.

The third objective is to learning by doing, individually or together in teams (CDIO Standard 8 “Active Learning”). 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 (CDIO Standard 7 “Integrated Learning Experiences”). Besides the learning of how to design and research, the projects also train engineering students in the very basic skills they often miss [6] 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.

THE TRAIL OF AEROSPACE DESIGN PROJECTS

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 (CDIO Standard 3 “Integrated Curriculum”). Each project is accompanied by a course about design methodologies in aircraft and spacecraft design or a specific engineering skill.

All design projects contain aeronautical as well as spaceflight assignments. They 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. Table 3 shows the breakdown of the Aerospace Design stream (34% of the total study load in the bachelor major):

Table 3 Break-down of the study load in the Aerospace Design mainstream

Constituency	Study load
Design courses	9%
Design projects, excl. Design Synthesis project	13%
Design Synthesis project	10%
Cooperation and communication trainings	2%

1. EXPLORING AEROSPACE ENGINEERING & DESIGN
Design project: Exploring Aerospace Engineering
Design course: Engineering Drawing
Skill training: Personal Leadership

EXPLORATION: The first design project for freshman students has an explorative character in which the design-build-test experience is a concrete learning experience the student can reflect upon. This project cannot yet make use of knowledge and skills from previous projects or knowledge from a previous semester. It is based on the principle of need-to-know learning: learn the principles of an aircraft by understanding this object top-down, thus challenging the students to learn the underlying theories in the context. In the project the students investigate the concept of a flying wing, do their first aerodynamics back-of-an-envelope analysis, design the aerodynamic profile, shape, manufacture and test a small wing made out of foam and test it in an open-jet wind tunnel, analyse the results and iterate the design and finally fly the wing in a competition (Figure 3). The spaceflight perspective is addressed by analysing the wing performance in a Martian atmosphere. The project is accompanied by a course Engineering Drawing in which students learn hand-sketching techniques and 3D-computer drawing in CATIA, a commercial Computer Aided Design software suit frequently used in aerospace industries. The project and course together form the module Exploring Aerospace Engineering & Design.

2. AEROSPACE DESIGN & CONSTRUCTION
Design project: Design & Construction
Design course: Aerospace Design & Systems Engineering
Skills training 1: Technical writing in English
Skills training 2: Information Literacy

The second semester focuses on the second step in the engineering life cycle: **CONCEPTUAL DESIGN**. Since engineering students learn best from the concrete to the abstract, this project is shaped around the design, development, construction and test of a tangible hardware component: a light-weight aerospace box structure of a wing (Figure 4). It makes use of the faculty's model collection of aircraft and spacecraft systems and the materials and structures laboratory. Two trainings, one on information literacy and one on technical writing, are embedded and practiced in the project. Furthermore the project is supported by a course about the first steps in the design and engineering process of aircraft and spacecraft. The course treats Design as an object, i.e. study and understanding of a given design and morphology. Students learn about mission definition, analysis of requirements for aircraft and spacecraft, architectures of aerospace vehicles, airworthiness regulations, and are familiarised with the conceptual design process. The design project and course together form the module Aerospace Design & Construction.

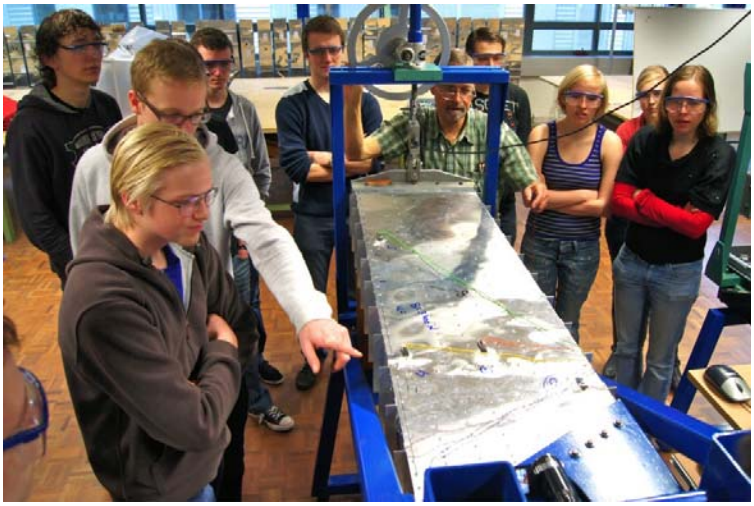

Figure 4 Testing the light-weight structural box of a wing, designed and manufactured in the second design project

3. AEROSPACE SYSTEM DESIGN

Design project:	System Design
Design course:	Aerospace Design & Systems Engineering
Skills training:	Oral presentation in English

The third semester project is about **PRELIMINARY DESIGN** of a subsystem and addresses the more abstract level of engineering and designing of a major aircraft or spacecraft subsystem like a wing or spacecraft structure, taking the relevant disciplines and the applicable design methods in aerospace engineering into consideration. It takes the interfaces with the overall system into account, using simulation models in a Python software environment. Drawings are made in CATIA. This project contains training in oral presentation and therefore has design presentations as a deliverable item. Also this project is supported by a course about the design of aircraft and spacecraft. It introduces the dominant systematic design approach in aerospace. The project and course together form the module Aerospace System Design.

4. TEST, ANALYSIS & SIMULATION

Design project:	Test, Analysis & Simulation
Design course:	Experimental Research & Data Analysis
Skills training 1:	Scientific Reporting
Skills training 2:	Advanced Information Literacy

The fourth semester's theme focuses on **TEST, ANALYSIS & SIMULATION** in which authentic noisy measurement data are acquired and analysed. The project is integrated with a course on experimental data analysis. In this course students familiarise with different measurement techniques (flow, solid mechanics, orbital position measurements) and learn how to formulate a hypothesis, design or select a protocol for engineering measurements, identify and explain sources of errors and evaluate measurement data using statistical techniques. Dedicated trainings on advanced information literacy and scientific writing are included and practiced in the project. Experimentation, instrumentation, measuring and data analysis is an essential skill for engineers and researchers. The module is therefore relevant for the learning of design and research skills.

5. SIMULATION, VERIFICATION & VALIDATION
Design project: Simulation, Verification & Validation
Design course: Systems Engineering & Aerospace Design
Skills training: Self-regulation and autonomy

The one but final phase of the study in the third year of study addresses the last step of the engineering design life cycle: **VERIFICATION AND VALIDATION**. In this course that is about 80% project-based learning, students use advanced simulation models of structural behaviour, flight mechanics and flight dynamics and off-the-shelf measurement data or measurements they acquire during a Flight Test in the faculty's Cessna Citation flying classroom that, in its turn, is an experiential learning element linked to the course on aerospace flight dynamics. The project about verification and validation integrates multiple topics: matching physical with numerical models (verification), propagation of numerical models (simulation), hypothesis testing of the numerical model concerning assumptions and results (evaluation) and the matching of simulation results with reality (validation). The project demands a high level of self-regulation by the students. It is accompanied by the final course on systems engineering. It provides the students with an integrated set of knowledge, tools and skills about the systems engineering method for the engineering of complex aerospace products to meet customer needs.

6. DESIGN SYNTHESIS
Design project: Design Synthesis
Design course: None
Skills training: None

The culmination takes place in the faculty-wide flagship project called **DESIGN SYNTHESIS**. This capstone project is a 10-week fulltime design project in which students engineer and design, but usually do not develop, an authentic aerospace related object or mission, working in self-regulatory teams of 10 members in dedicated project spaces. In this design project the students obtain real-life design experience: they go through the complete design process, from drawing up a programme of demands (set of requirements), conceptual analysis and design, concept selection to the presentation of the final design, in a structured and iterative manner [2].

The students experience the engineering difficulties of making well-motivated design choices, thereby taking conflicting demands into account. They experience that design iterations are necessary to tune suboptimal design decisions to meet the specifications they have drawn up at the start of the project. This project is the bachelor thesis project and provides the opportunity to apply all theory and skills, and build the students' confidence in engineering.

FRAMEWORK OF THE DESIGN PROJECTS

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.

- o 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.
- o Team work. All project assignments are performed in groups of students, but the learning outcomes are always tested individually. So the personal development and performance are tracked, but also free-riders or fringe players are identified.

Promoting intrinsic motivation

Each project has been designed such that it makes optimum use of factors that promote intrinsic motivation with the students [4][12][13]: challenge, curiosity, control, fantasy, competition, cooperation, and recognition (Figure 5). Table 4 describes the factors in detail and how they have been implemented in the projects.

Figure 5 Challenge, Curiosity, Control, Fantasy, Competition, Cooperation, Recognition in the first-year project “Exploring Aerospace Engineering”

Level of self-regulation

Each project has its own level of openness and requires a different level of student self-regulation and autonomy (Table 4). 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.

Table 4 Level of openness of the projects

Level of Openness	**Students**	**Coach**	**Tutor**
Subject defined by Learning objectives defined by Problem defined by Work plan (methods) defined by Regulation of planning and control defined by Criteria for final product/process defined by Assessment by means of criteria done by			

Table 5 Implementation of promoting factors of intrinsic motivation [20]

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 enroute 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 them-selves 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.

Salient features of a design project

The factors that promote intrinsic motivation as well as the themes set “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 these 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

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 aerospace 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 student therefore has been given the role of an Explorer, a **Feasibility Leader**. This is then followed by conceptual design and detailed design: 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 (**Data 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). So 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, agencies or 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 where possible to real-life research or 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 can use in their research. In the culminating Design Synthesis project all customers have real interest in the outcome of the project. Often the customers use the projects to have innovative or advanced system concepts investigated by young engineers on feasibility.

Engineering process

The paragraph 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 of 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 curriculum.

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 from the very start 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 6. 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.

The lines of advancement, indicated by the terminology simple/complex in Table 6 shows the systematic deepening of the knowledge and skills levels. For the definition of the learning objectives of the design projects and the associated skills trainings, it has been important to identify which level of knowledge and skills has to be acquired each year and how these will be deepened and practiced over the years such that the attainment targets and eventually the BSc Final Qualifications are realised. The trail of design projects have been defined such that each year a certain level of knowledge and skills is acquired which recurs and is practiced in the next year, while a level of complexity is added to what is learned in the previous year.

The terminology simple/complex is used to describe the state of novice to expert. They compare with the attainment levels 1 to 3 that have been defined for the Design and Project skills and the Intellectual skills. 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

Design and Project skills are an important development line in the bachelor. They concern the systematic approach in the application of theory and development of models, the development of project skills like teamwork, cooperation, communication, reporting and the systems engineering methodology. Also the societal and temporal context is addressed explicitly in this line.

The **Research skills** are less important in the bachelor because we have made Design as the emphasis. The learning of research skills is an explicit objective of one course plus project (Test, Analysis & Simulation). Table 7 shows indicatively how design or research skills have been integrated in the design projects over the years of study. The table shows when skills are assessed and what level has to be achieved. The skills are developed to a higher level and practiced in subsequent years. Note that design and research skills are mentioned in combination, because most processes in research and design are closely related and similar in nature.

The **Intellectual skills** concern reasoning, reflecting and forming a judgement and an attitude of lifelong learning, and the awareness of the temporal and societal context. The development of these skills is embedded in many curricular elements.

Table 6 Professional roles, products 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 target 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'l skills	novice	simple	advanced	complex	complex	expert
	Communi and Coop'n	simple	simple (oral) advanced (writing)	complex	complex	complex	expert
	Societal context	simple	simple	advanced	advanced	complex	complex

Table 7 Growth in the attainment levels of design and research skills over the bachelor

Bachelor first year
o Making an adequate and appropriate problem definition o Identifying and formulating key questions for research or design studies o Identifying valid scientific reasoning; be able to evaluate arguments, assumptions, abstract concepts and data. o Choosing the appropriate method of analysis to solve a problem
Bachelor second year
o Generating alternative methods of analysis for solving problems o Identifying valid scientific reasoning; be able to evaluate arguments, assumptions, abstract concepts and data, in order to make judgements and to contribute to solution of complex issues o Being able to choose the best alternative, based on logical scientific or design arguments o Carrying through a methodological approach on the basis of selected alternatives o Being able to defend the methodological approach and the results of the study
Bachelor third year
o Planning & time management of bigger projects o Integrating research or design knowledge of previous years o Presenting a research or design proposal (including working documents) either orally or in a written format o Presenting the results either orally or in written format and by means of modelling prototypes o Reflecting on missing elements and recommendations for further study

ORGANISATION AND LOGISTICS

The production of the six design projects through the years of study with their high levels of ambition, in combination with the large number of students, requires a solid organisation. With an annual influx in the bachelor of about 400 freshman students and a team size varying from 6 to 10 students for second- and third-year projects and 11 for the first-year projects (to account for early drop-outs), there is a need to produce annually 30 up to 50 projects for each of the six design projects.

The first three design projects Exploring Aerospace Engineering, Design & Construction, and System Design, and the third year Simulation, Verification & Validation are equal for all students. For these projects the organisation and logistics concern primarily the recruitment of tutors (senior students as teaching assistants); their training in supervision, coaching and assessment; arranging the coaching by faculty staff members to support the student design work; rostering the project spaces, labs and workspaces including their supporting technical personnel; ordering of materials and tooling, and arranging the student instructions on safety (working laboratory environment) and information literacy or communication skills .

The 40 individual second-year projects about Test, Analysis & Simulation and 30 third-year Design Synthesis projects are unique, although some of them may be recycled or adapted versions from previous years or are duplicated to save development time. For these projects the organisation and logistics not only concern the recruitment of sufficient tutors and teaching assistants, the arrangement of student trainings on communication and cooperation, and the rostering, but also the acquisition and control of the in-time availability of the project definitions that have to be generated and submitted by the tutors who are scattered over the research groups. Before these concept projects are released for production, each project assignment is subjected to a screening by faculty staff members (second-year project) or external specialists (third-year project) on level, feasibility and comprehensibility to assure the highest quality of all assignments. To assure uniformity in all project definitions, the Project Coordinators of these projects make a Tutor Handbook available for all tutors. More details about the production of the projects is available in [18].

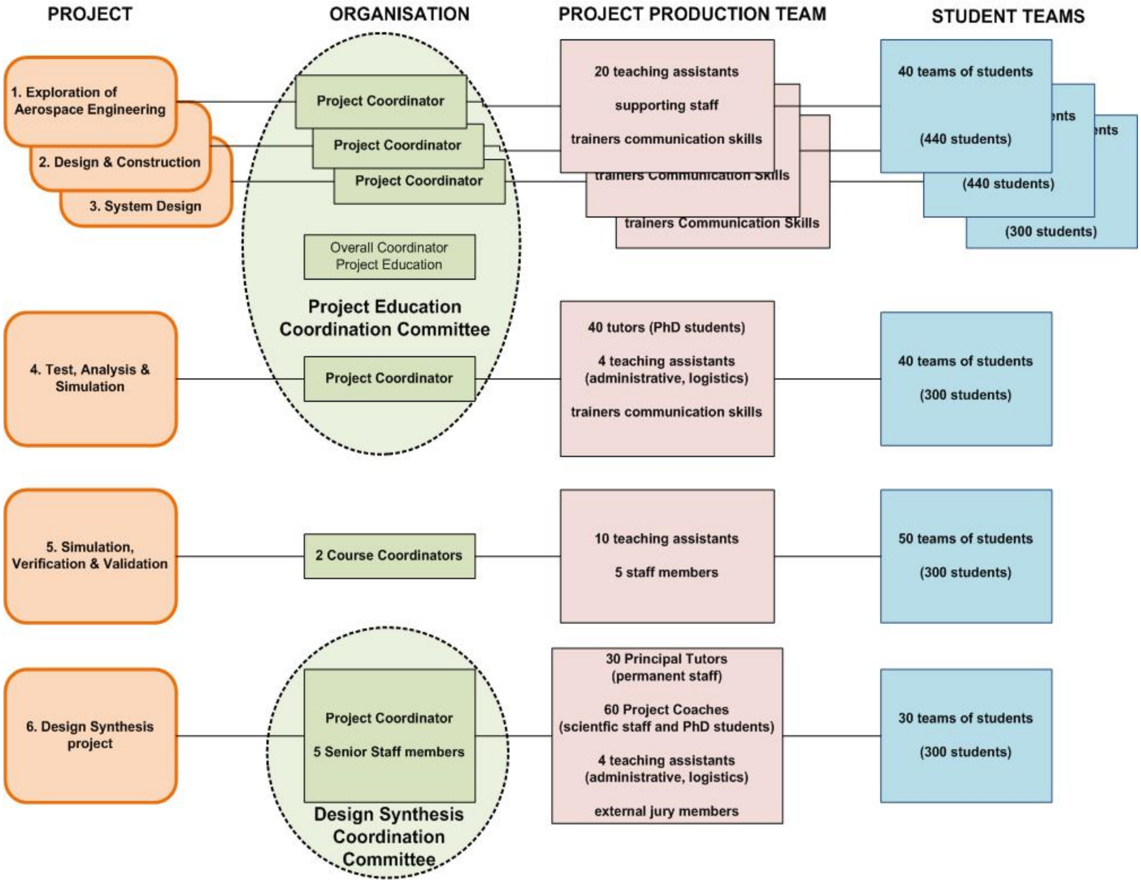

Figure 6 Schematic of design project organisation (indicative numbers)

The ownership of each of the design projects is in the hands of one Project Coordinator. He or she is a senior staff member and has the overall responsibility for the project. He may have one or more delegates in the faculty to ease project acquisition and coordination in the departments. The four Project Coordinators of the first- and second-year projects and an Overall Coordinator Project Education harmonise the projects and share their experiences in the Project Education Coordination Committee on a regular basis (Figure 6). The Project Coordinator of the Design Synthesis project chairs the Design Synthesis Coordination Committee that has six members: the Project Coordinator, one permanent staff member per faculty department (4 off) and a staff member who takes the responsibility of the quality of the individual projects.

The organisation and coaching of the six design projects is intensive. Each Project Coordinator typically spends 600 man-hours on the overall coordination and organisation for his or her design project each year. Each individual Design Synthesis project has a Principal Tutor and two Project Coaches who spend 200 respectively 60 hours each to their project. Also a tutor of the Test, Analysis & Simulation project (one per project) spends about 60 hours to the project definition, supervision, coaching and assessment.

A significant portion of the coaching and coordination on the shop floor of the projects in the first and second years of study is performed by senior students in their position of teaching assistant, under the responsibility of the Project Coordinator. One teaching assistant coaches two groups of students and is employed for 0.25 fte (full-time equivalent) over the full duration of the project. Each year about 90 teaching assistants are involved in the coaching of the design projects. Together they spend about 12,000 man-hours per year. Fresh teaching assistants always get two half days of training [1] to prepare for the job to be done: coaching, monitoring, helping in scheduling, logistics, administration, supporting the assessments.

PROJECT SPACES, WORK SPACES AND LABORATORIES

The Faculty of Aerospace Engineering is known for its facilities that are used for the bachelor design projects, master education and research. We have 45 well-equipped student project spaces in building “The Fellowship”. It was designed simultaneously with the development of the new currriculum to fill the needs for collaborative learning accommodation. Other important facilities that are used in the projects include a flying classroom airplane, subsonic and supersonic wind tunnels, the Delft Aerospace Structures and Materials Laboratory, a study collection of aircraft and spacecraft parts and subsystems and a flight simulator SIMONA with six degrees of freedom (CDIO Standard 6 “Engineering Workspaces”). A clean room for the integration of microsatellites is primarily used by students in the master phase.

EXPLOITATION OF THE PROJECT OUTCOMES

The faculty exploits the results of the projects to the maximum extent. The design and scientific outcomes of the second- (Test, Analysis & Simulation) and third-year (Design Synthesis) projects are used by the faculty’s research groups in on-going research or design work or in advanced feasibility studies. Posters and reports, produced as deliverables by the students, are used in promotion activities on fairs and at the faculty to inform and inspire new generations of students. The results of the Design Synthesis projects are presented in annual symposia by the students to press, fellow students and family. The executive summaries of each of the individual Synthesis Design projects, written by the students, are compiled in a booklet [14]. It has a high added value in the promotion and outreach activities about the state-of-the-art curriculum.

The Design Synthesis Project is the flagstone project that won the Best Practice Award for Project-based Learning at TU Delft. Individual projects of the Design Synthesis regularly receive best-design, best-team, and best-paper awards from industries, foundations or institutes to encourage excellent performances in education. A paper on the Test, Analysis & Simulation project recently won the Best Research Paper Award on the SEFI conference [17].

EFFECTIVENESS OF THE SERIES OF SIX DESIGN PROJECTS

Students take their project roles very seriously and are both enthusiastic and positive about their learning outcomes. Early 2013 the Faculty Student Council reported: *“Students experience the vertical integration of the courses as the series of design projects throughout the bachelor directly refer to courses that are scheduled in that semester. This contributes to the students’ understanding of the theory: they immediately experience how it can be applied. The vertical integration of the aerospace engineering courses is also achieved by the themes. The Design*

Synthesis project is the best project in the bachelor. It is a real test of the skills and knowledge gained in the bachelor and is the first project for which students have to decide by their own which design aspects are important and what theory they have to apply. No doubt it prepares students for becoming a designer".

In the annual student evaluations (CDIO Standard 11 "Learning Assessment"), the students score the Design Synthesis Project 8 out of 10. More importantly 70% of the students say that the projects give them a better understanding of the relationships between the different disciplines in aerospace engineering, 85% feel that the project contributes to a better understanding of design and more than 90% indicate that the project contributes a lot to their competence in working in teams. Since the bachelor innovation the students prove to be better prepared for the capstone project, have better working knowledge of systems engineering and design, and show better leadership and self-regulation.

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. The six design projects in the bachelor provides 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.

This paper describes the objectives, framework and organisational setup for the trail of design projects that forms one of the three mainstreams throughout the bachelor. It describes how the faculty has conceived, designed, developed and produces the six projects for 300-400 students every year since 2009, and the flagship Design Synthesis project already for more than 15 years.

ACKNOWLEDGEMENTS

The author would like to thank all colleagues, teaching assistants and students for their creativity, inspiration, time and patience that have enabled the development of the curriculum, and the trail of design projects in our bachelor Aerospace Engineering in particular. Special thanks to Renate Klaassen, Gillian Saunders-Smits and Mark Somerville (Olin College) who helped to conceive and design the framework of design projects and engineering skills education. In close cooperation with the Project Coordinators Paul Roling, Vincent Brügemann, Mirjam Snellen, Jan Hol, Erwin Mooij, Joris Melkert and Nando Timmer and the instructor of communication skills Pauline Post, we have turned this framework into successful and cutting-edge project-based education in all years of the bachelor. Without their continuous support and perseverance the production and operation of the projects and the overall organisation would never have been the well-oiled machine it is nowadays.

REFERENCES

[1] Andernach, T., Saunders-Smits, G.N. (2006), the use of Teaching Assistants in Project-Based Learning at Aerospace Engineering. Proceedings of the 36th ASEE/IEEE Frontiers in Education Conference, San Diego.
[2] Brügemann, Vincent, et al. (2005), An Example of Active Learning in Aerospace Engineering. In: Erik de Graaff et al., Research and Practice of Active Learning in Engineering Education, Amsterdam.
[3] Crawley, Edward, Malmqvist, Johan, (2007), “Rethinking Engineering Education”, Springer Science and Business Media.
[4] Deci, Edward L., Flaste Richard, (1996), Why we do what we do, Understanding Self-Motivation, Penguin Books.
[5] ECED (2012), Tomorrows engineers – for an attractive Europe. 4th European Convention of Engineering Deans, University of Birmingham (panel discussion).
[6] 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.
[7] Guest, D. The hunt is on for the Renaissance Man of computing, The Independent (London), September 17, 1991
[8] Imel, Susan (2000), Contextual Learning in Adult Education. Centre on Education and Training for Employment, the Ohio State University
[9] Johnson, E. B. (2001) Contextual teaching and learning: What it is and why it’s here to stay. Corwin Press.
[10] Kamp, Aldert, (2011), Delft Integrated Engineering Curriculum. Proceedings of the 7th International CDIO Conference. Technical University of Denmark, Copenhagen, Denmark, June 20-23, 2011.
[11] 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
[12] 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.
[13] 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.
[14] Melkert, J.A. (2011), editor. Delft Aerospace Design Projects 2011. Het Goede Boek, Huizen (and earlier editions).
[15] Royal Netherlands Academy of Arts and Sciences (2010), Quality Assessment in the Design & Engineering Disciplines, A Systematic Framework, Amsterdam.
[16] Ruth, Graham (2012), Achieving excellence in engineering education: the ingredients of successful change. The Royal Academy of Engineering.
[17] Saunders-Smits, G.N., (2011), Research Based Learning in a Project-Based Learning Environ-ment - A Case Study, SEFI 2011 Annual Conference, Lisbon.
[18] Saunders-Smits, Gillian N., et al., (2012), Using the Engineering Design Cycle to Develop Integrated Project Based Learning in Aerospace Engineering, International Conference on Innovation, Practice and Research in Engineering Education, 18-20 September 2012, Coventry.
[19] Schrey-Niemenmaa, Katriina & Jones, Mervyn E. (2011), Attractiveness in Engineering Education Is all as it seems? SEFI 2011 Annual Conference, Lisbon.
[20] Vockell, Edward L., Educational Psychology: A Practical Approach, Purdue University Calumet, on-line book.

Biographical information

Aldert Kamp is the Director of Education for the Faculty of Aerospace Engineering at TU Delft, the Netherlands. He has over 20 years of industrial experience in space systems engineering management and lecturing space engineering & technology. Since 2002 he is involved in university education policy development, quality assurance in higher education, and development of engineering curricula. Since 2006 he has been the instigator and leader of the radical innovation of the bachelor and restructuring of the master and excellence programmes in aerospace engineering. The new bachelor is highly CDIO compatible. Since 2011 he has been an active member of the CDIO Initiative.

Author

Ir. Aldert Kamp
Delft University of Technology
Faculty of Aerospace Engineering
Kluyverweg 1
2629 HS Delft, the Netherlands
Tel: (+31) 15 278 5172
E-mail: a.kamp@tudelft.nl