A Decade of Teaching Systems Engineering to Bachelor Students

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***Abstract*—The paper treats a setup for introducing systems engineering to undergraduate (Bachelor) students. The teaching module challenges students, and provides them with ample opportunity to employ the systems engineering process, tools and thinking. Through reflection, the students make the learning outcomes explicit. Based on the setup we recommend to teach a technically challenging subject adjacent to the systems engineering course. By having the students work in large groups on a challenging, open and vague problem statement, they learn to appreciate the systems engineering way of working.**

***Keywords*—systems engineering; education; project; Bachelor; undergraduate**

I. Introduction

The present conference focuses on the young field of systems of systems engineering (SoSE). A System of Systems (SoS) is a gathering together of individual systems [1]. This gathering can be in various forms like collaborative or virtual. While there are differences with systems engineering (SE), a considerable part of the body of knowledge in SE also applies to SoSE. Even more so, education of SoS Engineers starts with educating Systems Engineers. This paper will look mostly at the latter.

Ten years ago, we presented a paper on an introductory systems engineering education project, with hands-on experience [2]. Since then, the project has been a cornerstone of the Industrial Design Engineering (IDE) curriculum at the University of Twente. Notwithstanding smaller and larger changes in the IDE program, this project has remained relatively stable. Its effect has been recognized across the engineering disciplines at our institution, and beyond. This has resulted in spin-offs and expansion of the reach of the project. In this paper we will summarize the project set-up, its fundamental elements, and the experiences. We will also look at developments inside and outside the University. The goal is to derive principles for teaching systems engineering to undergraduate students that can be applied at other institutes.

We will recapitulate the original Sensors, Actuators and Systems project in section II. Recent developments in teaching; both at the University of Twente, and general Systems Engineering education, are treated in section III. Section IV treats the Systems in Context module for Industrial Design Engineering Students. Based on this setup, there are several spin-off modules that will be presented in section V. Our experiences and intentions can be generalized into principles for SE education. This is the subject of section VI. The final section VII contains the conclusions.

II. Original SAS project

Industrial Design Engineering at the University of Twente started in 2001. The setup has been from the outset a three years Bachelor and two years Master to conform to the Bologna agreements. The first year gives students an introduction to the field of industrial design engineering, with courses in design, construction and smart products in addition to general subjects like math and mechanics. The second and third year provided a deepening of the individual disciplines, in combination with integration. The latter subject is one of the focal points for the Sensors, Actuators and Systems (SAS) project.

Industrial Design Engineering (IDE) has been based on the paradigms of project-led education, as was Mechanical Engineering (ME), its sister program within the faculty of Engineering Technology. In project-led education [3-5], material that is taught in lectures or other teaching forms, has to be applied in a project setting. Students work together in groups to create a design, analyze a problem, etc. The final marks in such a project depend both on the quality of the project work and the results of tests. This way, learning by doing stimulates processing and internalizing new knowledge and competences. In other words, the project amplifies the teaching and vice versa. The original implementation of project-led education in IDE was that during most of the three years of the program, students work on projects, in parallel to the teaching (also see [2]).

The original Sensors, Actuators and Systems Project (5ECTS[1]) was positioned at the beginning of the second semester of the third (final) year of the Industrial Design Engineering bachelor program. This position means that the project is the final teaching opportunity before students reach out in their individual bachelor (capstone) project. Also, it means that students already have a solid foundation in subjects like design, ergonomics, electronics, software engineering, and mechanical engineering. In parallel to the SAS project, students spent time on a minor to broaden into fields like psychology, philosophy etc.

The setup for the SAS project, as we presented in [2], consisted of the following elements:

- Systems Engineering course;
- Sensors and Actuators course;
- Project.

Both the systems engineering and sensors and actuators course provided knowledge, competences and tools necessary to create a system design in the project. We will elaborate a bit on each of these components. The learning goals for the complete project can be summarized as [2]:

- To learn the physics of sensing and actuating;
- To learn the basics of several types of micro-mechanical sensors;
- To learn the basics and goals of systems engineering;
- To be able to maintain overview in a complex design project.

A. *Systems Engineering Course*

The systems engineering course focused on the systems view, and provided tools to be used during the project. These tools included planning and control (SEMP), documentation, reviews, functional analysis, functional mapping and architecting, risks and FMEA. We included a guest lecture by a prominent systems engineer. The course was supported by the INCOSE SE handbook (second edition).

B. *Sensors and Actuators Course*

We expect industrial designers to create smart products. The IDE program at UT aims at delivering technically well-equipped graduates. As smart products have to interact with users and their environment, sensors and actuators are relevant to the program. The course in particular treated Micro-Electro-Mechanical Systems (MEMS). The focus was less on the technology inside the sensors, and more on application.

C. *Project*

Application of both courses (sensors and actuators for the technology, systems engineering for the approach) took place in the project. Typical assignments include a home climate system (2004) and an “intelligent” car (2005). To mimic an actual design project, groups are large (12-15 students), and they have to organize themselves.

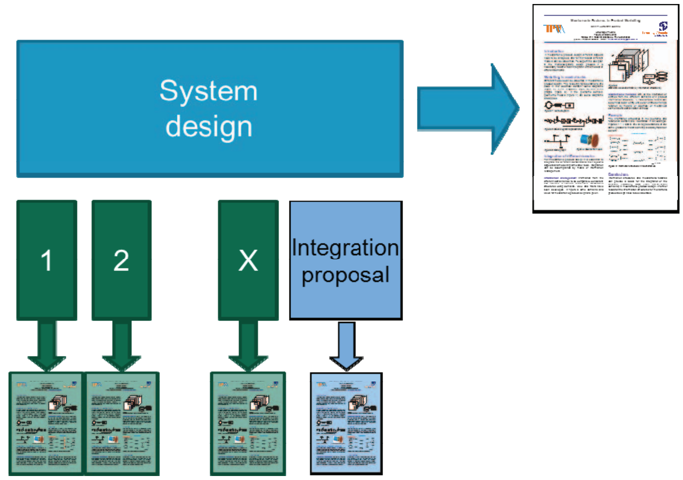

Figure 1: The setup of the original SAS project.

We provided a framework for the students’ work, by defining the following deliverables:

1. System design (after two weeks)
2. Subsystem designs and integration & test proposal (at the end of the project, total seven weeks).

Each of these deliverables are marked as milestones with a design review. Input for the review is one poster for the first milestone, a poster for each subsystem for the second milestone, as shown in Figure 1.

Over the years, the project, including both courses, has been evaluated several times. While space prohibits a detailed exposé on the results, students value the project highly. In particular, they find the subjects highly relevant for IDE students, and the project part is seen as challenging.

For more details on the original setup, we refer to the earlier mentioned paper [2]

III. University of Twente and Systems Engineering Teaching Developments

The previous paper was from 2005. In the years that passed, opinions about and directives for education at the University of Twente have changed. Also, there have been developments in systems engineering education. In the following, we will briefly look at both.

A. *University of Twente teaching model*

As stated earlier, the IDE program has been based from the outset on the project-led education paradigm. We re-used years of experience with this paradigm in mechanical engineering. As it is good practice to continuously evaluate education programs, and adjust where necessary, the IDE program has had a minor revision in 2008, and a major revision in 2013. For brevity we will look only at the 2013 revision that resulted from a decision by the University Board to adopt the Twente Education Model as teaching model for all Bachelor programs

[1] European Credit Transfer and Accumulation System. 60ECTS corresponds to one full academic year. In The Netherlands 1ECTS=28hours.

at the University of Twente. The Twente Education Model (TEM, [6]) bases on the following foundation [6]:

1. a steady workload is better than 'binge learning' for tests,
2. frequent feedback helps students adjust their learning,
3. variety in teaching methods keeps students engaged,
4. community helps students help each other,
5. ambitions must be clear and high, yet realistic, and
6. teachers work best in teams, with minimal regulation.

The University Board's aim is to use this foundation to educate T-shaped professionals, that have a firm foundation in one (or more) disciplines, and are able to communicate across disciplines. This illustrates the need for systems engineering.

The implementation of the foundation results in four thematic teaching modules per year, project-led education, and a uniform curriculum structure for all programs. The thematic modules span 15ECTS, consist of courses and a project, and are completed with one final grade. In addition, first year's students have to pass at least three out of four modules to be allowed further studying in the program.

The result of the implementation of TEM university-wide has been that all programs had to review and reconsider their teaching. This has been an important factor for SE education at the UT, as we will see later.

B. *Systems Engineering Education*

In this section we will discuss some notable developments in Systems Engineering Education since 2005.

Experts have established the Systems Engineering Body of Knowledge (SEBoK), and a Graduate Reference Curriculum for Systems Engineering (GRCSE). The SEBoK project started in fall 2009, and the first release was in September 2012. Current version is 1.5.1 of December 2015 [7]. The SEBoK provides state of the art knowledge and tools for the systems engineer. Please note that the reference curriculum is for graduate (EU: Master) students, while we are here focusing on Bachelor students.

The INCOSE handbook evolved into version four [8]. The handbook remains the prime reference for the practitioning systems engineer. It remains a rich source of information, and it is recommended reading for our students.

There is literature about SE education like [9-12]. Most of these focus on teaching graduate (Master) and post-graduate students. Also the INCOSE vision [13] presents general views on education. The latter stresses the importance of introducing young people to systems engineering & thinking and life-long learning. This is in tension with the fact that there is only a reference curriculum for graduate students.

We like to stress the fact that teaching to Bachelor (undergraduate) students differs from creating a Master (graduate) program that aims at educating systems engineers, ready for the industry. In Bachelor SE teaching, two aspects are crucial:

1. To introduce the interesting field of SE to as many engineering students as possible, so that a good influx to the more maturing Master programs is created.
2. Many engineers will be working in an environment where SE is applied, thus it is crucial that they are aware of basic SE principles. Passive command of SE knowledge and competences suffices for this (larger) part of the population.

So, while a Master (graduate) program aims at delivering systems engineers, Bachelor (undergraduate) SE teaching creates awareness and interest.

Further, Master students are more self-propelling and mature. Note that the difference between undergraduate and graduate students may be larger than between Bachelor and Master students. In the Netherlands students usually enroll into a Master program directly after completing a Bachelor.

IV. Systems in Context module

Based on the above developments, the original SAS project evolved into a complete (15ECTS) module named Systems in Context for Industrial Design Engineering Students. We will present this second to last Bachelor module here.

The core of the systems in context module is formed by three parts:

1. Systems Engineering course;
2. Mechatronic Design course; and
3. Project.

Further, as the minor is removed from the program, the following elements are added to complete it to a 15ECTS module:

4. Design and Meaning course;
5. Reflection on Science and Technology course; and
6. Preparation for the Bachelor Capstone Project.

Items 1-3 are most important for this paper as they form the core of the module.

A. *Systems Engineering*

While most of what we presented in section II.A still holds for the present SE course, there are important differences. The reference material (INCOSE handbook in the original version) was too elaborate for this introductory course. While it was possible to help students find the relevant parts, the book was an overkill. After a few years of using the handbook, we considered other books like [14-16]. We even used the first of those for one year. However, we concluded that all these materials did not fit the audience. The books were either too comprehensive, or too shallow. The SEBoK [7] provides another relevant source of information, but is not very accessible to novices in the SE field. It is better suited as reference for experienced SEs. So, we decided to bundle and update our own material and create a book [17]. This book, of which we have used preliminary versions for some years, shows the basic elements of systems design and engineering:

the SE process, the SE ways of thinking, and a concise description of relevant tools like N2 diagram, FMEA, Risk analysis and Documentation structures. The book uses SE knowledge and competences from three different fields: complex system design, civil engineering and embedded systems.

A second difference is the importance of the SE essay for grading. While we mentioned in [2] that we introduced the essay in the second issue of the project, we did not elaborate it. In a two-page essay, students have to describe their initial expectations of SE, and the way these were realized, or not. A reflection on the SE work done in the project makes sure the students have to process the course contents, and cannot suffice with mere knowledge reproduction. Over the years, the essay has given a lot of insight in the way students perceive the field of SE. Some fail to see the difference between project management and the more technical oriented systems engineering. Others really dive into depth of SE. These students often get so interested that they pursue a further career in SE. A second function of the essay is to get feedback on the course. Minor adjustments may result in better comprehension of the material by students.

With increasing student numbers, the grading of the essays had to be made transferrable to other teachers and teaching assistants. Using a checklist, and a calibration set of essays, all teachers' evaluations were aligned.

B. *Mechatronic Design*

After a few years of teaching the sensors and actuators course, we decided to trade it for a more application oriented, but still technically challenging subject: Mechatronic Design. Mechatronics is the field of engineering where synergetic application of mechanical, electronic and software engineering provides high-performance, yet affordable systems. While the IDE students will not become mechatronic experts, they should be able to communicate with such experts.

In the course we treat basic construction principles, basic control engineering and basic evaluation methods for mechatronic systems. The focus is on understanding that mechatronics are multidisciplinary systems that need to be designed in an integrated fashion. Instead of moving from one domain to another as the design process progresses, students learn how to consider all three core domains concurrently (mechanical, electrical and control). By doing so, the course makes them aware of the importance of trade-offs that span multiple disciplines. By the end of the course, students are proficient in modeling mechatronics systems, as well as creating and evaluating low level conceptual design proposals. The course is evaluated with a written, case study driven, open book test. The test includes design questions, insights questions and modeling questions.

One of the challenges has been finding an adequate book that reflects the goals of this course. Available educational texts aim at training specialists, while this course aims at providing basic understanding. In order to cope with this, a reader has been written by the paper authors. The goal is to transform it into a new book on mechatronics proving the bird's eye view of mechatronics for designers.

C. *Project*

The setup as shown in Figure 1 still represents the project structure. One change that cannot be drawn from the figure is that now all posters have to be in English and that a part of the grade is determined based on the English of a small text.

Most important change is the organization of the final review. As we believe that a systems engineer has to ask constructive-critical questions, we also like the students to show that. However, in a group review, there are always students that are more hesitant than others. In order to give all students a fair chance, in a limited amount of time, the final review is organized as follows.

Two groups of 12-15 each have to be present, designated as group A and group B. The posters of all subgroups have to be handed in timely, and are available to all groups for preparation for the final reviews.

1. Group A presents the work using the posters and if needed a powerpoint presentation (ca. 20 min);
2. Group B presents the work using the posters and if needed a powerpoint presentation (ca. 20 min);
3. Discussion: A subgroup of A sits together with the corresponding subgroup of B. So, the system engineers of A review the work of the system engineers of B and vice versa. Also the subgroups on for instance sensors review each other's work, etc. The exact configuration of subgroups depends on the design choices of the groups.
   The result is a list of questions of each sub-discussion. This list has to be mailed to the project coordinators. (total ca. 20 min);
4. Open plenary discussion based on the lists of questions that have been compiled in 3. Mutual questioning and answering between groups A and B is foreseen. The project coordinators will take part in the discussion, as well. (ca. 30-40 min);
5. Wrap up and finish.

This means that every review takes about two hours for two groups. The grading is then done by the teachers (always more than two present, mostly three teachers present) after all groups have done the final review. The submitted questions are reviewed, and provide a small advantage or disadvantage in the final grade.

In the first issue of the module (2015-2016), the project assignment is to work on city logistics. With the uptake of e-commerce, the number of deliveries in a typical living quarter increases. To meet stringent delivery requirements, suppliers organize their deliveries themselves, or use service providers. The large number of delivery vans causes congestion (in particular in old city centers), pollution, noise and annoyance. The students have to work on an integrated city logistics solution that addresses these issues. Focal point is the (re-) distribution center where incoming deliveries from various sources are reconfigured into a limited number of deliveries per day per quarter. Particular issues are tracking and tracing, insurance requirements, and speed of delivery.

D. Other courses in the module

As said, there are three other parts in the module. While we strive for cohesion in the module, the connection is loose. The course on design and meaning will look at consequences of e-commerce in mega-cities. The reflection on science and technology course specifically addresses mega-cities and the resulting quality of living. The preparation course for the capstone project is not integrated. It provides research methods for handling the capstone project that is not part of this module.

V. SPIN-OFFS

The first two spin-offs of the project were Advanced Technology (AT) in 2012-2013 and Biomedical Technology (BMT) in 2013-2014. Both reused the systems engineering course, but AT did not incorporate the other parts. BMT did reuse most of the Mechatronic Design course. The board of Advanced Technology (AT) decided, in combination with the implementation of TEM (section III.A) that a full-blown SE-based module would be in place from 2014-2015 onward. The last module of the second year was dedicated to this. Based on the setup as described in section IV, a module with SE, Business and Knowledge production was created. Difference with the systems in context module is the close cooperation with companies that deliver the project assignment. In 2015-2016 the SE teaching in this module will also be made available to students of the University of Twente University College ATLAS.

The boards of Mechanical Engineering (ME) and Electrical Engineering (EE) looked for ways to incorporate SE teaching in their programs from 2015-2016 onward. Both have SE in parallel to the IDE Systems in Context module. For ME, the module is called "Production Systems Engineering" to indicate the connection between production systems and systems engineering. The setup is largely the same as we described in section IV. The Mechatronic Design course is replaced by a Production Management Systems course. The other courses are an introduction to Finite Element Modeling, Statistics and Academic research & skills. The latter can be seen as equivalent to the bachelor preparation course in the IDE module, the other two courses replace design and meaning and reflection courses.

For EE, the setup of the Electronic Systems Design module follows the same structure. Embedded Signal Processing (analog and digital) takes the place of Mechatronic Design. Science to Design for Society is equivalent to the reflection course in the IDE module. The EE module reserves time to work on a prototype. A side-by-side comparison of these three modules is shown in Table 1.

All these spin-offs use an essay to evaluate the command of systems engineering. The significant grading work is distributed over diverse experts, and the calibration work mentioned earlier is implemented.

A final spin-off is the second year's bachelor course taught at the University College of Southeast Norway, Kongsberg, Norway. The first author of this paper worked with the teachers there to create an introductory course, as described in [12].

TABLE 1: OVERVIEW OF THE INDUSTRIAL DESIGN ENGINEERING (IDE), MECHANICAL ENGINEERING (ME) AND ELECTRICAL ENGINEERING (EE) SE MODULES.

Module / **Element**	**IDE: Systems in Context**	**ME: Production Systems Engineering**	**EE: Electronic Systems Design**
SE teaching	Systems Engineering; using [17]		
Technical teaching	Mechatronic Design	Production Management	Embedded Signal Processing
Reflection	Reflection on Science and Technology		Science to Design for Society
Other	Design and Meaning	Introduction to Finite Element Modeling; Statistics	Prototyping
Preparation for capstone	Preparation for the Bachelor Capstone Project	Academic Research & Skills	

VI. DISCUSSION AND GENERAL SE EDUCATION PRINCIPLES

So far, we have used a mostly descriptive style. In this section we will expand the decisions and experiences to arrive at more general applicable SE education principles.

Students in our modules are at first overwhelmed by the large groups (12-15 students) and the very open problem description. We have created these large groups on purpose to simulate the way of working in large development teams in companies. After the first two to three weeks, the students manage themselves in smaller teams, as indicated by the project setup, and facilitated by the SE way of working.

The open problem statement challenges the students to work with vague, incomplete and uncertain information. The capability to deal with this is a crucial competence of the systems engineer (and even more so for systems of systems engineers). Relating back to the two aims of SE teaching for Bachelors (undergraduates, section III.B), students are encouraged to reflect on their possible future as systems engineers. The explicit reflection requested in the essay helps in this.

The students are pushed out of their comfort zone by introducing new technologies: Production Management Systems for the mechanical engineers, Embedded Signal Processing for the electrical engineers, and Mechatronic Design for the industrial design engineers. When the students are out of their comfort zone, they experience the lack of information, feel the need to sample the problem space to find the firm foundations, and they no longer can rely on their known ways of working. As a result, the teaching that provides guides for these situations (SE) is more readily absorbed.

Explicit attention to reflection amplifies the learning outcomes. The reflection courses in the different modules stimulate this, so that students get a more reflective practice attitude [18]. The fact that they know from day one that they have to produce an SE-essay strengthens this attitude.

The design reviews require students to communicate in a compact manner. The essence of the systems architecture (first review) or subsystems design and integration plan (second review) have to be presented in a short time slot, and on a poster. This requires the ability to separate important issues from details. The explicit attention to formulating constructive critical questions during the design reviews helps in the development of systems engineers.

While we do not treat systems of systems explicitly, the competences above are equally important for systems of systems engineers, as they are for systems engineers. Given the fact that this module is intended to raise interest and awareness in the students for systems engineering, it is also a basis for further development into systems engineers and even systems of systems engineers.

VII. Conclusions

In a Bachelor (undergraduate) program in engineering, systems engineering should have a place. While it is not possible to educate full-blown systems engineers, a Bachelor course is well suited to raise interest in the discipline, and create awareness. Those that get interested can opt for a Master (graduate) program in systems engineering, and even develop into systems of systems engineers.

To introduce SE to engineering students, it is essential to mimic an actual SE problem. Mere treatment of the SE body of knowledge will not suffice; to really appreciate the strengths it has to be experienced. Therefore, the core of the systems in context, production systems engineering and electronic systems design modules consist of an introductory course in SE, a technically challenging course and a project where both have to be applied.

A challenging and realistic problem setting for the project is essential. Further, students that are out of their normal way of working are more apt to try something new. The use of large groups and a vague and open problem statement are appropriate means for this.

Further, as systems engineers have to be proficient communicators, an SE teaching module has to stimulate communication. The use of overviews and concise means of communication like posters instead of reports is useful.

Finally, students need to reflect on their learnings. An essay on the way systems engineering was employed addresses this need.

At this moment, the integration between the core parts, and the other parts like Philosophy of Science, Design and Meaning and Preparation for the Bachelor assignment is loose. We will look to improve the integration in the near future.

A line of further research is into the contribution of this project to the overall program goals using for instance Bloom's taxonomy. Such a research will further lead to insight on the portability of this project set-up to other domains.

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