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# EDUCATION IN COLLABORATIVE SYSTEMS ENGINEERING FOR PROSPECTIVE STUDENTS

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## ABSTRACT
The increasing complexity of intelligent mechatronic products and their digital interconnectivity lead to new challenges in product development processes. In addition, considering social and ecological aspects in product development is becoming increasingly important to achieve global sustainability goals. This requires increased interdisciplinary cooperation. The theoretical teaching of these technological and methodological processes and interrelationships is often currently still very abstract in engineering education. It requires a high degree of imagination, which can only be assumed to a limited extent, particularly for young first-year students. To better convey this basic understanding, a multi-day teaching format was developed for use at the school/university interface, in which prospective students learn how interdisciplinary, collaborative engineering can be implemented in practice using the example of concrete development of a simple mechatronic and data communicating product. The assignment covers all key phases of product development, from requirements analysis, system design and implementation to verification and validation. This teaching offer aims to sensitise prospective students to the current topics of the product development process of intelligent mechatronic systems and the associated social and ecological sustainability issues and to familiarise them with the future challenges of systems engineering at an early stage. By highlighting practical and socially relevant fields of application, the aim is to sustainably promote interest in studying engineering by demonstrating how engineering themes relate to students' lives or the real world.

*Keywords: Education for prospective students, systems engineering, STEM skills, innovative teaching approaches*

## 1 INTRODUCTION AND CHALLENGES

Advancing digitalisation and the resulting economic and social changes are increasing technical complexity, which is shaping the engineering field [1]. With the associated development of intelligent, networked products, the industry's need for highly qualified engineers with comprehensive specialist knowledge and interdisciplinary skills in systems engineering is growing. At the same time, technological advances are increasingly caught between social and ecological requirements, making sustainability an integral component of engineering development processes.

This requires continuous adaptation and further development of engineering training content and concepts that introduce students to systemic thinking and methodological approaches to systems engineering at an early stage and adequately prepare future specialists for the challenges in research and industry [2] [3].

The aim of engineering education must be to convey this content to students so that they can analyse and evaluate technical issues and develop solutions in a self-directed manner after completing their studies. This requires practical and holistic teaching that promotes skills acquisition through individual, self-determined learning and collaborative and active engagement with the topics and tasks [2].

The development process of mechatronic and cyber-physical products is pursued and taught throughout the entire Bachelor's and Master's degree programme in the Department of Mechanical Engineering. Students acquire the theoretical and practical knowledge required for the digital development of intelligent technical systems.

However, teaching these technological and methodological processes and the complex dependencies between mechanical, electronic and software components is mainly theoretical and abstract. This requires a great deal of imagination, which can only be assumed to a limited extent, especially for young first-year students. One of the most significant difficulties is recognising and understanding the connections between the various technical courses. These courses reflect the interconnectedness of the individual processes within the entire product development process. It is often difficult for students to place the content of individual courses in the context of the holistic product development process, which affects their ability to recognise the logical sequence from conception to the realisation of complex technical systems. This problem arises on the one hand from the large number of specialised courses in the curriculum, each of which deals with different aspects of product development, and on the other hand from the interdisciplinary nature of the topic, which requires systemic and abstract thinking, which is often not yet sufficiently trained in STEM (Science, Technology, Engineering and Mathematics) lessons in schools. This lack of prior knowledge quickly leads to dissatisfaction at the beginning of studies and often to premature dropout [4].

To better convey this understanding even before the start of their studies, a teaching format was developed in which prospective students in mechanical engineering learn how a structured, methodical approach can be implemented in practice within the framework of interdisciplinary, collaborative engineering using the example of the concrete product development of a simple mechatronic and data communicating product that is familiar from real life.

This teaching concept offers prospective students a practical introduction to key aspects of smart engineering and virtual product development even before they begin their studies. The aim is to give them an initial understanding of the interdisciplinary challenges of the subject area at this very early stage of their engineering education. In addition, the programme provides prospective students with authentic insights into the scientific working methods at a technical university and is intended to encourage lasting interest in studying engineering.

This paper presents the conceptual approach and the first implementation of the teaching programme, describes its didactic objectives, and considers potential factors influencing the promotion of young academics in an engineering context.

The teaching format is being developed and implemented as part of the project “Open Digitisation Alliance Palatinate” funded by the Federal Ministry of Education and Research as a part of the federal-state initiative "Innovative University".

## 2 DIDACTIC CONSIDERATIONS

To address the challenges described above at an early stage of engineering education, the product development process of mechatronic systems should ideally be internalised before the start of studies in a practice-oriented approach that is manageable for prospective first-year students.

A mechatronic product of low complexity, which is developed in an interdisciplinary context without specific specialist knowledge, should help to provide prospective students with the necessary overall understanding of the product development process for the later, in-depth examination of the development of more complex intelligent systems. This early understanding is crucial to make the complexity of systems engineering tangible and to provide students with a basis for a structured approach both during their studies and in later professional fields of product development [2] [3].

A fundamental aspect of the concept under discussion is promoting an exploratory and playfully motivated approach. Participants are encouraged to consider technical issues from a perspective relevant to everyday life and research. The focus is on the creative development of individual solutions, intending to strengthen intrinsic motivation and independent work [5]. Concurrently, participants gain practical experience with CAD software and microcontroller programming, develop problem-solving skills, as well as hone analytical thinking and interdisciplinary communication skills.

Note: No subject-specific teaching experts were directly involved in developing the teaching format concept. However, the team responsible has extensive teaching experience in developing and implementing existing teaching formats, some of which was gained in close cooperation with teaching experts.

## 3 DEVELOPMENT OF THE ENGINEERING-ORIENTED TEACHING CONCEPT

Based on established didactic concepts for competence-oriented teaching in STEM subjects [3] [5] [6] [7], an interdisciplinary team from our department, consisting of an electrical engineer, a computer scientist, a mechanical engineer and an IT specialist for system integration, has developed a concept that maps the entire product development process in a way that is tailored to first-year students and greatly simplified. In addition to their specialist knowledge, the team members have extensive experience in developing teaching/learning concepts and in teaching at both schools and universities.

When developing the concept, the following general aspects were considered initially:

1. The prior knowledge of the target group, pupils, prospective students and upcoming first-year students, in the following named as participants, was specifically addressed to ensure a low-threshold introduction to the topic.
2. The concept should be designed in such a way that it can be implemented within the time frame of a school project while still conveying the basic principles of systems engineering in a transparent and comprehensible way. The teaching format should be flexible enough to be integrated into the scheduling of schools. This can be a period of several days up to a week, depending on the time availability of the participants.

In order to design the teaching format, the first step was to select the desired competencies, and the second step was to consider the content and methods with which these competencies could be acquired [5]. The approach must pay particular attention to the skills required for interdisciplinary cooperation in engineering. The concept should promote key STEM skills highly relevant to the future engineering profession. These include particularly complex problem-solving, creativity, communication, teamwork, critical thinking and digital literacy. Furthermore, social skills such as self-confidence, self-awareness, assertiveness and conflict resolution should also be strengthened to promote personal development [8]. To promote these skills, the following teaching methods were considered as most relevant for the teaching format:

1. The participants will go through various work phases in which they will alternately solve interdisciplinary tasks in joint group work and subject-specific tasks in individual and partner work. On the one hand, the ability to work in a team and the willingness to collaborate are trained, while on the other hand, concentration and personal initiative are required. While specific problems are addressed within the individual work phases, different perspectives are brought together in the group phases, and joint solution strategies are developed. A structured alternation between subject-specific and interdisciplinary work phases should enable the participants to acquire in-depth knowledge in their respective fields while also experiencing integrative cooperation in interdisciplinary teams. In addition, alternating between individual and group work phases should promote a balanced development of individual and cooperative skills. During the individual work phases, the slower participants receive increased supervisor support to ensure that all participants complete this work phase concurrently [3] [5] [6] [8].
2. A modular structure of the teaching format at different levels of difficulty was planned, which, depending on the participants' previous knowledge, allows the course to be offered at different levels of difficulty, as a beginner or advanced workshop, or implemented according to the principles of internal differentiation for heterogeneous learning groups. The modular structure makes it possible for high-performing participants to work on more demanding additional tasks, while lower-performing participants can concentrate on the basic task [7] [9]. In addition, the modular structure of the teaching format enables a range of subject-specific depths to be delivered over a period of several days to a week.
3. Peer-to-peer learning also plays a central role in the didactic approach of this teaching programme. The continuous exchange of knowledge, skills and abilities within the group promotes collaborative learning processes that lead to a step-by-step optimisation of the developed products. Discussing other participants' ideas and solutions helps deepen the understanding of different approaches and sharpen the ability for critical reflection. The peer-to-peer learning approach thus supports team development and interdisciplinary communication skills [10]. These skills are of central importance for a later scientific or professional career in mechanical engineering, especially because of the increasing interconnectedness of engineering practice.
4. In order to specifically promote learning processes and interdisciplinary cooperation, modern media technologies are integrated into all project phases in accordance with media-didactic principles.

## 4 COLLABORATIVE ENGINEERING-ORIENTED EXERCISE TASK FOR PROSPECTIVE STUDENTS

The concrete overall exercise task for the participants was to collaboratively develop a smart communicating weather station. The focus here is on integrating sensors and actuators, software-based control of the hardware by a microcontroller, connectivity to a smartphone, and the functional and aesthetic design and production of a housing.

For such development-related tasks, the **Verein Deutscher Ingenieure (VDI)** provides the VDI 2206 guideline to develop cyber-physical mechatronic systems (CPMS), which in turn has been developed by experts from science and industry. Integrating the engineering disciplines of electrical engineering, information technology and mechanical engineering, this guideline provides an objective framework that defines an iterative and interdisciplinary approach for the methodical support of the interdisciplinary development of complex mechatronic systems [11]. It enables the user to understand the logical relationships and to derive individual development approaches for specific applications.
The methodological approach of our teaching format is based on this guideline. To reduce the complexity of the guideline to a level of abstraction that is appropriate for pupils and prospective students, the supervisors have defined key questions and descriptions for each development phase described in the guideline, which serves as a low-threshold, step-by-step guide for pupils and prospective students when developing a mechatronic product for the first time. They are designed to make it easier for participants to grasp the core aspects of each phase and apply them in a targeted manner (Figure 1).
During the course, the supervisors support the participants in each phase and ensures that the product development knowledge is implemented professionally in accordance with the guideline. These specialised supervisors are available to provide targeted technical support and also serve as role models for collaborative interdisciplinary cooperation.

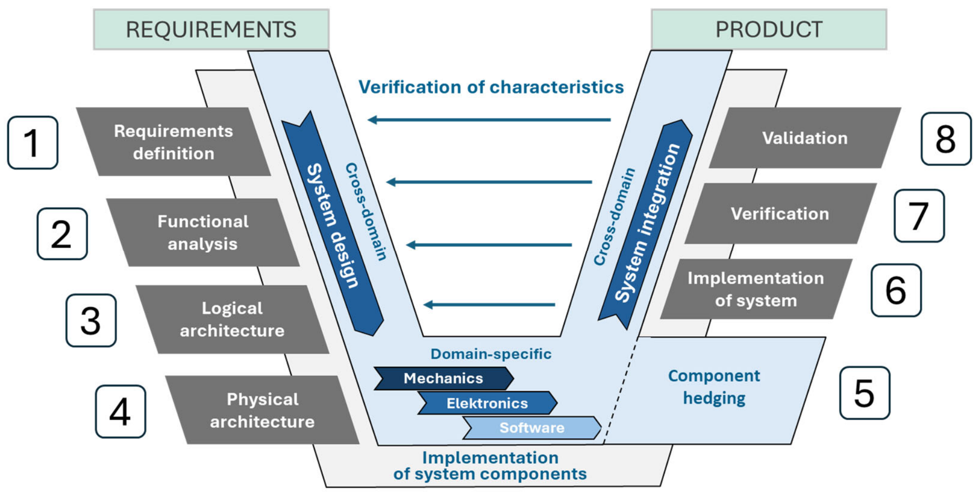


*Figure 1. Task procedure model based on the VDI 2206 guideline [11]*

The following key questions/descriptions were developed for the individual product development phases:

| | | |
|---|---|---|
| 1 | **Requirements definition:** | What should the product be able to do? |
| 2 | **Functional analysis:** | What information does the system need to process? |
| 3 | **Logical architecture:** | How should the system components communicate and process this information with each other? |
| 4 | **Physical architecture:** | How must the system components be connected to each other? |
| 5 | **Component hedging:** | Are the individual system components functioning as required? |
| 6 | **Implementation of system:** | Combining the system components to form the overall system |
| 7 | **Verification:** | Have all requirements been met? |
| 8 | **Validation:** | Test of all required functionalities in a real environment. |

The adapted model supports the participants with the central questions and action descriptions in a structured approach, from system analysis and concept development to validation and integration of the final product.
The teaching course is divided into a theoretical phase and a practical phase. The theoretical introduction gives participants an overview of what systems engineering means [12] and the development of smart, interconnected products. They learn about the technological change of products from previously mainly mechanical products to today's intelligent, mechatronic, and cyber-physical systems, which are given adaptive and communicative properties through digital and sensor-based controls. In the subsequent practical phase, the participants go through the work steps of the process model presented, alternating

between collaborative work in the group to solve interdisciplinary tasks and the processing of discipline-specific tasks in individual and partner work. The aim is to go through the entire product development process of the selected product example, a “smart communicating weather station,” from conception and digital modelling to physical implementation and integration of the system components. This practical example of product development at a rudimentary level is intended to playfully awaken an intrinsic motivation for studying engineering and to reduce any fears that young prospective students may have of the complex topics involved in engineering.

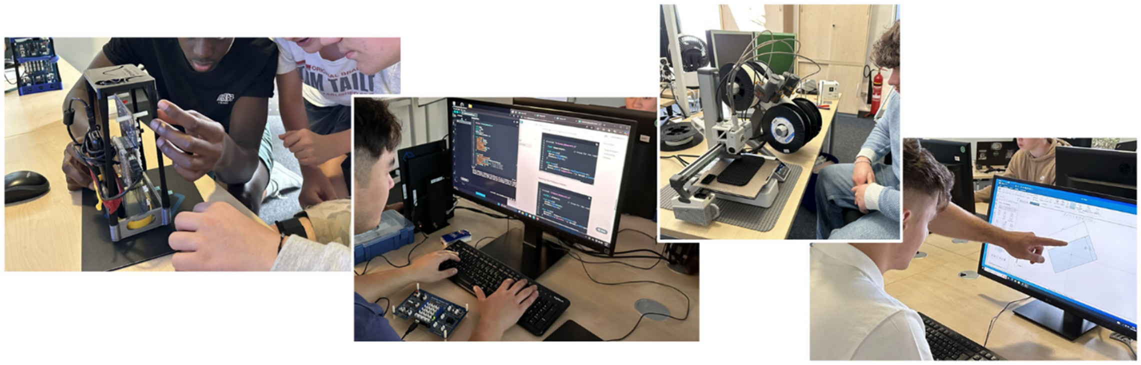

*Figure 2. Pupils working on the "Smart weather station"-project*

## 5 FEEDBACK AND PLANNED EVALUATION

The teaching format was carried out five times in 2024 with 68 pupils. The response was extremely favourable with particular emphasis by school and teachers on the high level of practical relevance and the practical teaching of technical content that cannot be covered in regular school lessons. The programme was characterised by teachers as both a 'unique opportunity for career orientation' and a 'valuable addition to STEM lessons at school'. The participating students also demonstrated a high level of enthusiasm. The opportunity to work independently on a specific technical product, the interplay between digital and practical tasks, and the collaboration between the two teams with different tasks were particularly highlighted. It was emphasised by some that the project had provided a preliminary concrete insight into an engineering degree. Others described the programme as 'varied', 'challenging but exciting', and 'motivating', as it was effective in helping to identify their own strengths and to address technical issues with greater confidence.

To measure the effectiveness of the concept, the development of suitable evaluation indicators is planned for 2025. These should determine the participants' understanding of collaborative development processes and systems thinking and their competence development in interdisciplinary work. A collaboration with didactics experts of the Centre for Innovation and Digitalisation in Teaching and Learning at the university is planned to develop the surveys.

Data is to be collected using a methodologically sound survey using pre-tests and post-tests, which are carried out in the various phases of the project. The objective of the study is to record both the level of knowledge at the beginning and the development of skills during and after the end of the course. We expect to derive both a differentiated analysis of the learning effects and a well-founded assessment of the effectiveness of the didactic concept.

## 6 CONCLUSION AND OUTLOOK

This didactic concept offers an opportunity for a practical and low-threshold introduction to interdisciplinary and collaborative development processes as they are known from the engineering environment, for example, and which are essential for modern engineering education. Combining theoretical foundation and application-orientated implementation as part of a multi-day teaching project teaches basic engineering skills and should promote methodological, creative and problem-solving skills. In addition to the soft skills required for collaborative teamwork, participants acquire practical knowledge in virtual product modelling and systems engineering and the integration of smart technologies.

The concise implementation period of the teaching course, spanning merely a few days, should facilitate recognising the interrelated product development process by upcoming prospective students as a dependent interconnection of individual steps in which different disciplines and skills are required. Later on in the degree programme, when entire lecture units are dedicated to these steps, students will be better able to identify and locate them in the overall process.

Based on the initial experiences with the course participants and their prior knowledge, the observations on the learning pace, and, last but not least, the feedback from the participants, the concept was gradually adapted and optimised. In the theory section, greater emphasis was placed on the V-model in order to give participants a clearer understanding of the underlying development logic. In addition, the complexity of software development was reduced by adding intermediate steps that make it easier to understand how the code works and is structured. In the domain of rapid prototyping, participants were afforded greater opportunities to utilise 3D printing at an earlier stage of modelling to facilitate the identification of modelling-related errors at an early stage, thereby enabling the targeted development of geometric imagination and modelling skills.

These continuous improvements to the concept and adjustments to the teaching format significantly accelerated the participants' learning processes. This indicates that it has the potential to successfully promote young academics in engineering, particularly in the field of mechanical engineering, even before they commence their studies and to generate motivation, interest and enthusiasm for studying engineering what further will be examined and evaluated in 2025.

Schools and teachers emphasised the exceptional added value of the offer. Initial feedback from the participating pupils has been positive, without exception. The increasing demand this programme underscores the motivational added value of the course offering, as well as its relevance and potential in fostering young talent.

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