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Conceptualizing an Academic Teaching and Learning Laboratory for Systems Engineering

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ABSTRACT

In an increasingly complex world of goods and services and in the context of digitalization and industry 4.0, previous product development for intelligent technical systems is reaching its limits and new approaches to development are required. However, the use of new development approaches, such as advanced systems engineering (ASE), is accompanied by far-reaching changes for the organization and all people involved. Such new development approaches require a redesign of work organization and versatile competencies and skillsets going beyond classical engineering. Thus, new competencies and qualifications for future engineers are necessary for product development. Against this backdrop, the expansion of targeted competency management and higher education in the engineering sciences must adequately take these developments into account. In this paper we outline the required competencies for engineers in the context of advanced systems engineering and derive a novel empirical competency model. Based on this empirical model, possibilities for the conceptualization of competency measures through the framework of constructive alignment at the academic level are presented.

Keywords: Systems engineering, Competencies, Advanced systems engineering, Engineering education, Constructive alignment

INTRODUCTION

In an increasingly complex world of goods and services and in the context of digitalisation and industry 4.0, traditional product development for intelligent technical systems is reaching its limits. Due to shorter life cycles, increasing complexity and a growing number of product variants, as well as increasing demands from stakeholders, etc., new development approaches are needed (Dumitrescu et al., 2021; Haberfellner et al., 2019). One promising approach is Advanced Systems Engineering (ASE). ASE builds on the concepts of Systems Engineering (SE) and Model-Based Engineering (MBSE), and opens up new ways of designing intelligent, networked and socio-technical systems. ASE combines methods for systems analysis and requirements management with AI-influenced engineering processes in which all relevant information - from the business idea to market success - is integrated into the development process across disciplines to efficiently shape the development of complex cyber-physical systems (Dumitrescu et al., 2021). The emergence of this new approach to development goes hand in hand with new demands on higher education in engineering. With the introduction of flat hierarchies or cross-functional working structures in ASE, the development and training of advanced competencies and skills for future engineers is crucial, for example to adapt to an agile approach or to be able to cope with dynamically changing tasks and teams. In this context, higher education needs to adapt and respond to these newly required specific skills and competencies of future engineers. Specific learning activities and settings need to be conceptualized and designed to ensure these learning outcomes while incorporating state-of-the-art, learner-centred, active and scalable learning. Therefore, this paper presents current progress in conceptualizing an academic teaching and learning laboratory for ASE through the constructive alignment (CA) framework (Biggs, 2014, 1994; Biggs & Tang, 2011) to address these new demands on the skills and competencies of future engineers.

Teaching and Learning Labs in Engineering

Laboratories are an indispensable part of science and engineering education in European universities (Schmidgen, 2011). They have become an integral part of applied and research-oriented teaching and learning environments at all levels (Tekkaya et al., 2016; Terkowsky et al., 2020). The teaching and learning laboratory can be defined as a course, learning venue or learning environment where students learn to carry out empirical research such as observing, measuring, experimenting, testing and analysing under controlled conditions as part of their science or engineering studies (Trumper, 2003). However, university practice does not always exploit this potential in the sense that many teaching and learning activities are still based on more traditional inductive-instructive and more subject-oriented approaches to laboratory didactics. As a result, they are designed to impart subject knowledge (e.g., technical skills) rather than to promote competencies holistically by integrating advanced soft skills that are necessary to adapt to future job requirements (Terkowsky et al., 2020).

The ongoing digital transformation, which calls for competency-promoting agile, self-directed, creative and collaborative research-based learning, holds great potential for the competency-oriented use of teaching and learning laboratories (Tekkaya et al., 2016; Terkowsky et al., 2020). However, competency-based laboratory didactics have only been marginally implemented to date. Therefore, there is a need for a holistic, competency-based approach to laboratory didactics (Terkowsky et al., 2020).

To meet this need, we propose the concept of CA as a conceptual framework for an academic ASE teaching and learning laboratory for systems engineers.

Constructive Alignment

Constructivist learning theory and task alignment with intended learning outcomes are the twin pillars on which CA is based (Biggs & Tang, 2011). CA is a method of outcomes-based teaching (Biggs, 2014, 1993). It focuses on the design and transparent support and assessment of student learning (Mappes & Klink, 2011). CA involves aligning learning or competency objectives, called intended learning outcomes (ILOs), the design of content and related activities, called teaching/learning activities (TLAs), and the acquisition or demonstration of performance, called assessment tasks (ATs): with the ILOs as a central primary component of the approach. The careful and considered construction of ILOs determines how they are taught (TLAs) and how they are to be assessed (ATs) (Biggs, 2011; Biggs & Tang, 2011). Figure 1 shows these three main aspects of constructive alignment adapted for the teaching and learning laboratory and how the aspects relate to each other.

CA makes it possible to subsequently assess the extent to which the competency objectives and levels targeted in the ASE teaching and learning laboratory have been achieved. But how can this be done? CA proposes four stages to enable alignment for any given course (Biggs, 2014; Biggs & Tang, 2011):

1. Describe the ILOs using activity verbs
2. Create a learning environment with TLAs using the activity verbs
3. Use ATs to assess student performance using the activity verbs
4. Translate the performance into standardised grading criteria

In order to put the stages of CA into the context of the ASE teaching and learning laboratory, the necessary ASE specific competency requirements must first be defined and formalised as a basis for describing the ILOs.

Identifying and Defining ASE-Specific Competencies

The starting point for identifying ASE-specific competency requirements were the 12 SE roles according to Sheard (Sheard, 1996). These were compared and merged with the established INCOSE Competency Framework (Gelosh et al., 2018). Based on this information, a systematic literature review was conducted between September 2020 and February 2021. For this purpose,

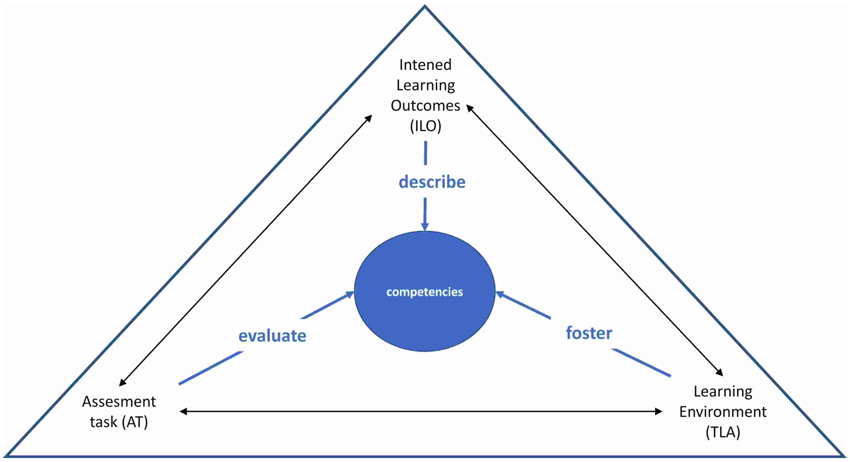

Figure 1: Schematics of the constructive alignment concept (Biggs, 1993) for the teaching and learning laboratory.

the identified publications on the topics of Systems Engineering (SE), Model-Based Systems Engineering (MBSE), Integrated Product Development and Concurrent Engineering were analysed and central aspects of ASE were identified, which were then derived into necessary competency requirements for companies and employees. As a first step to develop a unified role description and a competency model, the collected data material from the literature review was classified and categorised using standardised competency frameworks (Heyse, 2017; Heyse & Erpenbeck, 2009). In the next step, the theoretical findings were enriched by an online survey (*N* = 99) and expert interviews (*N = 8)* in various industrial projects in the context of systems engineering. The survey material was then coded using qualitative content analysis according to Mayring (Mayring, 2015) and competency categories were deductively formed using the INCOSE competency framework (Gelosh et al., 2018). The competency categories were grouped and bundled into three requirement levels: *basic competencies*, *agile working competencies*, and *ASE-specific competencies*. Based on these findings, a competency model was further developed, which ultimately consisted of seven competency dimensions and 22 associated competency facets (Arslanparcasi & Karasek, 2023).

CONCEPTUALIZING THE ACADEMIC ASE TEACHING AND LEARNING LABORATORY

The derived ASE-competency model for systems engineers (Arslanparcasi & Karasek, 2023) was used as a basis for the conceptualization of the learning laboratory. From this, the stages of CA for the academic ASE teaching and learning laboratory are elaborated, focusing only on *agile working* competencies. As a work in progress, the methodology outlines two of the four proposed stages of alignment.

Describing the Intended Learning Outcomes (ILOs)

Before defining the ILOs, all competencies and their facets were reviewed for their applicability in a learning and teaching laboratory environment and for faculty-specific requirements. The selection was then reviewed by higher-education experts and didacticians. Based on the reviewed competencies and facets, 10 ILOs were formulated that address different dimensions of cognitive processes (Anderson et al., 2014). For the purpose of this paper, the focus lies on the five identified competencies for agile working. Table 1 shows the derived ILOs and their cognitive process dimension and knowledge type (Anderson et al., 2014) for the selected competencies for agile working to be addressed by the laboratory. The five derived ILOs consist of one or at most two signalling verbs (Biggs, 2014; Biggs & Tang, 2011), which allows students to understand the scope and expected complexity level of the ILO (knowing what to do and at what level). The verbs used therefore also imply specific teaching/learning activities (TLAs) that facilitate the achievement of the ILOs (knowing how to do). In addition, the specificity of the verb used in the ILOs, for example its cognitive process dimension, defines the boundaries

Table 1. Overview of ILOs, cognitive process and knowledge dimension for the ASE laboratory.

ILO	Cognitive Process Dimension	Knowledge Dimension
select and implement different methods of agile and team-based working methods in the work process	Understand/Apply	Factual/Conceptual
implement and design work planning and communication in the team in a constructive and goal-oriented way	Apply	Procedural
structure and process project tasks independently through the appropriate use of division of labour and cooperative collaboration	Apply	Procedural
evaluate and reflect on the methods of agile and team-based working methods used in the work process	Analyse/Evaluate	Procedural/Meta-Cognitive
present the results of project work in a target group-specific and prepared manner during a final presentation	Create	Meta-Cognitive

of appropriate assessment tasks (ATs) of student performance (knowledge of assessment criteria), thus demonstrating the centrality of the ILOs.

Furthermore, the ILOs were designed taking into account the type of knowledge expected (Anderson et al., 2014; Biggs & Tang, 2011). The cognitive process dimension targeted by the ILOs were selected from among lower-level dimensions (e.g., ‘understand’, ‘apply’) and higher-level dimensions (e.g., ‘evaluate’, ‘analyse’ or ‘create’) and were assigned to different knowledge dimensions. The selected and applied cognitive process dimensions reflected the recommendations for academic teaching and learning laboratories, focusing mainly on the dimensions ‘apply’.

Teaching and Learning Activities (TLAs)

As mentioned earlier, learning and teaching laboratories offer an opportunity to provide holistic skills training that meets the demands of the (future) workplace. However, specific faculty and curriculum regulations had to be taken into account when translating ILOs and creating TLAs within the chosen learning environment. These predetermined regulations were:

- duration of two weeks
- group setting (min. 3 to max. 12)
- must meet the specific curricular criteria of a ‘tutorial’
- prerequisites: master’s students in engineering or related disciplines
- fixed workload/credit-point ratio

Based on recommendations from academic didactics and in order to meet the requirements of the faculty, global TLAs were first formulated that are most likely to enable students to interact with the verbs listed in the respective ILOs that operate on the specific process dimension assigned to them (Biggs & Tang, 2011). Table 2 shows the global TLAs assigned to each ILO for agile working competencies. The formulated global TLAs reflect the nature of the laboratory setting, which gradually shifts from teacher-managed TLAs to student- or individually-managed activities. Many of the teacher-managed activities more closely resemble teaching and learning environments than actual teaching and learning activities, depending on whether or not the required student learning-related activities take place. The environment, that is, the teaching and learning laboratory, merely defines the general framework within which learning takes place, whether it is a lecture, a group task or reflective learning.

Table 2. ILOs and global TLAs for the academic ASE laboratory.

ILOs	Global TLAs
select and implement different methods of agile and team-based working methods in the work process (understand/apply)	Teacher managed with little to active student participation (e.g., lecture, teaching study skills in context) Student managed (e.g., working groups/group assignment)
implement and design work planning and communication in the team in a constructive and goal-oriented way (apply)	Teacher managed with little to active student participation (e.g., keynotes, teaching study skills in context) Student managed (e.g., working groups/group assignment)
structure and process project tasks independently through the appropriate use of division of labour and cooperative collaboration (apply/analyse)	Student managed (e.g., working groups/group assignment)
evaluate and reflect on the methods of agile and team-based working methods used in the work process (analyse/evaluate)	Individually managed (e.g., reflective learning)
present the results of project work in a target group-specific and prepared manner during a final presentation (create)	Student managed/Individually managed (e.g., reflective learning, working groups, group assignment)

Next Steps

In order to further develop the ASE teaching and learning laboratory, specific and diverse learning initiatives targeting the ILOs will be selected and implemented in specific contexts to allow for appropriate alignment between activities and TLAs. Thus, the proposed global TLAs will be further specified and carefully considered for applicability within the regulatory and didactic framework. In addition, aligned ATs will be derived to allow transparent and criteria-based assessment of student performance, reflecting the ILOs and the holistic competency focus of the laboratory setting. Due to the novel nature of the ASE learning and teaching laboratory concept, evaluation and proof-of-concept measures will be implemented, such as formative and summative evaluation formats. This will allow for ad hoc adjustments, e.g., adaptation of learning activities to student needs, as well as overall evaluation of the laboratory approach.

CONCLUSION

University practice often relies on rather traditional inductive-instructive and purely subject-oriented approaches to laboratory didactics, designed to impart subject knowledge, and thus does not always make use of this potential of a competency-oriented teaching and learning laboratory. As a result, many teaching and learning activities potentially fail to adapt to new demands on the skills and competencies of future engineers. A promising concept to address future needs and competencies is the proposed constructively oriented ASE teaching and learning laboratory. By utilising empirical evidence and combining it with the didactic concept of constructive alignment, the proposed learning and teaching laboratory concept aims to demonstrate the potential of combining constructive alignment with competency-promoting laboratory didactics in academia.

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