Resilience-Related Competencies In Engineering Education – Mapping Abet, Eur-Ace And Cdio Criteria

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RESILIENCE-RELATED COMPETENCIES IN ENGINEERING EDUCATION – MAPPING ABET, EUR-ACE AND CDIO CRITERIA

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Conference Key Areas: *Addressing the challenges of climate change and sustainability; Engineering skills and competences, lifelong learning for a more sustainable world*
Keywords: *Resilience, Competencies, Accreditation, CDIO*

ABSTRACT

In view of the increasing intensity and frequency of natural disasters due to climate change, engineers need to be able to design systems and infrastructures that are resilient to disruptions. Resilience, here, describes the ability of systems to not only be prepared for sudden crises and to recover from these, but also to learn in order to build adaptive capacity. However, research has shown that there is a lack of system resilience and related competencies in engineering education at various levels. First, there are only a few studies that address resilience on a system level in engineering education. Second, studies on teaching experiences show that engineering students have little knowledge about resilience and skills to design resilient systems. And third, an analysis of engineering programs in Europe has shown that resilience-related topics and competencies are rarely addressed in curricula. Based on these results this study will explore the extent to which resilience-related competences are included in accreditation guidelines and frameworks such as ABET, EUR-ACE and the CDIO Syllabus. This will then be discussed in the context of previous research on the qualification objectives of engineering degree programs, questioning to what extent these are consistent with accreditation guidelines and frameworks regarding

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systems resilience. This provides a baseline for recommendations for curriculum development in engineering.

1 INTRODUCTION

In view of the increasing intensity and frequency of natural disasters due to climate change, war, political instability and other sources of volatility, engineers need to be able to design systems and infrastructures that can deal with disruptions. Doing so is frequently subsumed under the term resilience, which describes the ability "to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events" (National Research Council 2012). While many definitions of resilience exist, they all have aspects in common, such as the ability of a system, community or individual to recover, to prepare and to adapt to disturbances, to deal and live with change and uncertainty as well as lifelong learning in the context of failure. Moreover, resilience is concerned with analyzing and building mechanisms to cope with those disturbances in order to provide adaptive capacity (Walker 2020, Francis and Bekera 2014, Mayar, Carmichael, and Shen 2022). Note that this is not the same as robustness, which describes "the ability to resist a disturbance by not changing", whereas the idea of learning to live with change is inherent to resilience (Walker 2020). This work primarily addresses resilience as an attribute of systems, not of the engineers who build them.

Both scientific studies and governance reports underline the relevance of resilience and the need to enable engineers to build and design adaptive systems, especially in the context of climate change (Martin et al. 2022, Pearson et al. 2018, UNESCO 2021). At the same time, research has shown that there is a lack of system resilience and related competencies in engineering education at various levels (Winkens and Leicht-Scholten 2023a, b). In line with that, case studies about resilience in engineering education have shown that students have little knowledge about resilience and difficulties in applying the concept to complex real-world problems (Rokooei, Vahedifard, and Belay 2022, Winkens and Leicht-Scholten 2022). Even when it is covered, system resilience is mostly addressed as a teaching content, i.e., teaching engineering students about resilience or the design of resilient infrastructure (Winkens and Leicht-Scholten 2023b).

This gap between research, government demands and educational practice can be addressed at several levels: A previous study focused on resilience-related competencies in engineering study programs. Five large European technical universities were chosen, a qualitative analysis was then based on selected key terms and competencies relating to system resilience with regard to the learning/qualification outcomes of the respective study programs. Findings showed a lack of resilience-related competencies in most study programs, with only a few programs explicitly addressing system resilience (Winkens and Leicht-Scholten 2023a).

In this follow-up work, the previous analysis is expanded to the ABET criteria, EUR-ACE framework standards for accreditation of engineering programs and the CDIO Syllabus, as all three are relevant in that they are meant to serve as a blueprint for learning/qualification outcomes of study programs. Thus, looking at them is important when trying to identify reasons for the lack of resilience in teaching and curricula.

This leads to the following research question: How (far) are resilience-related competencies addressed in engineering education standards and guidelines on European and international level, such as EUR-ACE, ABET and CDIO?

The results are then discussed in the context of previous results on resilience competencies in engineering education research and learning/qualification outcomes of study programs.

2 METHODOLOGY

2.1 Research Framework

In the following, the previous described analysis will be expanded to the ABET criteria, EUR-ACE framework standards for accreditation of engineering programs and the CDIO Syllabus. This allows us to consider different levels of engineering education.

ABET and EUR-ACE were chosen for analysis as they represent requirements and standards for engineering curricula in two different continents. The ABET criteria for accrediting engineering programs in the US include seven general students, i.e., learning/qualification outcomes (ref. Criterion 3) for all study programs and additional discipline-oriented outcomes (ABET 2021). These include complex problem solving, engineering design, communication, recognizing ethical and professional responsibilities, collaboration and teamwork, experimentation and the acquisition of new knowledge.

The EUR-ACE framework formulates standards and guidelines for engineering programs in the European Higher Education Area (EHEA). In this framework, according to the Bologna process program outcomes for Bachelor and Master degrees are formulated, which are "to be considered as the 'minimum threshold' […] and to be fulfilled in order to assure the quality of engineering programmes." (ENAEE 2021). The EUR-ACE program outcomes are categorized in eight learning areas: knowledge and understanding, engineering analysis, engineering design, investigations, engineering practice, making judgements, communication and team-working, and lifelong learning (ENAEE 2021).

The CDIO (Conceive, Design, Implement and Operate) Syllabus is a reference framework for designing engineering curricula and formulating learning outcomes that is both detailed and broad to ensure general applicability. It was based on a systematic process by the education initiative CDIO. The syllabus contains a detailed list of topics which "indicate desirable competences of graduating engineers" (Malmqvist et al. 2022). However, it is not prescriptive, but "intended to be comprehensive" (Malmqvist et al. 2022). Accordingly, the aim is not to address every topic of the syllabus in an engineering program, but to be able to be adapted towards a syllabus for specific program outcomes and requirements. Research showed that engineering programs developed on the syllabus would also meet other accreditation standards, such as ABET or EUR-ACE (Malmqvist 2009, Crawley et al. 2011). This is because the syllabus contains more detail and covers the whole lifecycle of a process, system or product, i.e., it "reflects a more encompassing view of engineering" than other frameworks, such as ABET (Crawley et al. 2011).

2.2 Identification of resilience-related key terms and competencies

The analysis is based on a deductive approach, by applying the already developed conceptual framework for resilience-related competences (Winkens and Leicht-Scholten 2021, 2023a) and specifically searching for the terms and competencies contained in the documents described above. Based on and derived from several definitions of resilience, these key terms and competencies are: anticipating, adapting, absorbing, preparing, recovering, responding, transforming, learning (from failure), recognizing/monitoring threats, dealing with uncertainty and complexity, developing with change and system thinking (for further details see Winkens and Leicht-Scholten 2023a).

Moreover, we searched for the term "resilience" itself as well as resilience-related topics and synonyms such as disaster, threat, hazard, risk, unknown, ambiguity or volatility. In order not to neglect any relevant content that might not contain the search terms described above but could still characterize resilience, we additionally searched the documents inductively for underlying resilience aspects. Both approaches were done by two researchers, independently, and then combined.

3 RESULTS AND DISCUSSION

The analysis of the three frameworks resulted in an assignment of several resilience-related competencies. Most of the above-described 13 competencies were categorized, except for absorbing, recovering and transforming. Moreover, resilience itself was only mentioned once in all analyzed documents, i.e., in the CDIO Syllabus (2.3.2 "Emergence and Interactions in Systems"). Here, resilience was mentioned as a keyword besides, e.g., tipping points and adaptation. For CDIO, we differentiate between the 2.0 and 3.0 versions of the syllabus, as many additional items were added in the latter. Furthermore, some items are only part of the extended version of the 3.0 Syllabus. For ABET, we analyzed the general student outcomes (Criterion 3) and all listed study programs. For EUR-ACE, we differentiate between Bachelor and Master level according to the standards and guidelines.

It must be noted that in some cases we categorized a single item or learning outcome twice. This was done because in these cases one item includes explicit references to two resilience-related competencies, such as the "ability to develop, to design new and *complex products* (devices, artefacts, etc.), *processes and systems*, with *specifications incompletely defined and/or competing*" (EUR-ACE Master). Here, both dealing with uncertainty and complexity are part of the item.

The results are summarized in Table 1 and will be explained in detail in the following sub-chapters.

Table 1. Resilience-related competencies in EUR-ACE, ABET and CDIO

Framework \ Competencies	ABET**	EUR-ACE: Bachelor***	EUR-ACE: Master	CDIO 2.0	CDIO 3.0 Additions
Anticipating				4.3.5	4.1.6, 4.1.7, 4.2.6, 4.4.1, 5.1.2*, 5.1.7*
Adapting				2.3.2, 2.4.3	4.3.2, 4.3.4, 5.1.8*
Absorbing					
Preparing	CYS, FRP				4.2.1
Recovering					
Responding				2.4.3	4.1.2, 4.2.1
Transforming					
Learning (from failure)	General Outcomes	x	x	2.2.4, 2.4.7	2.4.7
Recognizing/ monitoring threats	CYS, CBB	x	x	2.1.5, 4.2.6	4.2.6, 4.3.1, 5.1.6*, 5.1.7*
Dealing with uncertainty	ENV, PET, CIV, SYS, CON		3x	2.1.1, 2.1.4, 2.2.2, 2.2.4, 2.4.1, 4.5.2	2.2.3, 2.3.1, 2.4.1, 4.3.2, 5.1.7*
Dealing with complexity	General Outcomes, CYS, ECT, MIN, NCR, SFT, SRV, SYS	5x	7x	2.1.2	4.1.2, 5.1.7*
Developing with change		x	x	2.3.4, 4.3.5, 4.6.4	2.4.6, 4.3.1, 4.3.2, 4.4.1, 4.6.3
System thinking	CYS, ENV, PET, CIV, SYS, ARC, BIM, CON, EMG, EME, IND, MEX, NAV, OPT		x	2.3: 2.3.1, 2.3.2, 2.3.3, 2.3.4, 4.4.3, 4.5.5	2.3.1, 2.3.2, 4.3.2, 4.3.3, 4.3.4, 4.3.6, 4.4.6, 4.5.5, 5.1.8*

* indicates items from the CDIO Extended Syllabus
** Abbreviations for ABET engineering program categories: CYS – Cybersecurity, ENV – Environmental, PET – Petroleum, CIV - Civil Engineering, ECT – Electrical, Computer, Communications, Telecommunication(s), MIN – Mining, NCR – Nuclear, Radiological, SFT – Software, SRV – Surveying, SYS – Systems, CBB – Chemical, Biochemical, Biomolecular, ARC – Architectural, BIM – Bioengineering, Biomedical, CON – Construction, EMG – Engineering Management, EME – Engineering Mechanics, IND – Industrial Engineering, MEC – Mechanical, NAV – Naval Architecture, Marine Engineering, Ocean Engineering, OPT – Optical, Photonic, FRP – Fire Protection
*** x indicates a mention, 3x/5x/7x indicate multiple mentions

3.1 ABET

The ABET criteria contain several references to resilience-related competencies that were most pronounced for the system thinking category and complex problem solving. However, by themselves these are insufficient to categorize resilience, as the abilities to solve complex problems and system thinking alone do not enable engineers to design resilient systems (Winkens and Leicht-Scholten 2021), since aspects of adaptation, anticipation and learning are also crucial. In total, six out of the 13 resilience-related competencies were categorized (see Table 1).

Considering each study program, Cybersecurity has the most explicit and multiple references to resilience. Here, students are not only to deal with complex systems, but to do so and to maintain operations in the presence of risks and threats. Moreover, they are to test and protect complex devices and systems which – in combination – represents both anticipating and learning from failure. Similar, in Environmental Engineering, one focus is to design systems that includes consideration of risk and uncertainty. Another course, Fire Protection, inherently deals with the design of systems in order to protect the public from the impacts of fire, i.e., a threat/hazard. Degree programs such as Civil, Systems and Construction Engineering cover the statistical management of risk and uncertainty. However, all three of them are devoid of references to adaptation and/or learning from disaster. Finally, in some cases the opposite of uncertainty is addressed, e.g., Data science and analysis calls for conformance of precision and accuracy, which implicitly addresses uncertainty.

3.2 EUR-ACE

The EUR-ACE framework differentiates between Bachelor and Master abilities. In Bachelor programs, a strong focus is set on complex problem solving. At the Master's level, students should demonstrate the ability to solve complex and unfamiliar problems, which can also be incompletely defined or have competing specifications. Both Bachelor's and Master's students have to engage in lifelong learning and to deal with risk and change management. Further, Master's students are to formulate judgements with incomplete or limited information, to handle complexity and to develop and design new and complex products or systems. Combining those abilities, a strong resilience reference can be found in EUR-ACE Master's requirements that systematically builds on the Bachelor level's learning outcomes. Here, six out of the 13 categories with regard to resilience-related competencies were assigned, focusing on learning, recognizing/monitoring threats, dealing with uncertainty and complexity, developing with change and system thinking (see Table 1).

3.3 CDIO

The CDIO Syllabus 3.0 is structured into five sections and subsections with more detailed descriptions. As there were major changes between the 2.0 and recent 3.0. version, with the latter focusing on increasing complexity and several “change drivers” in the context of a VUCA (volatile, uncertain, complex and ambiguous) world, both are discussed here. Notably, the third version was revised with regard to the topics sustainability, digitalization and acceleration (Malmqvist et al. 2022).

Several aspects of resilience are covered in the Syllabus, both on an overall category level and in the category subtopics. For example, system thinking (2.3) is an explicit category, including the subcategories thinking holistically (2.3.1), and emergence and interactions in systems (2.3.2). Moreover, subcategory 2.4.1 represents the initiative and willingness to make decisions in the face of uncertainty and 2.4.3 adaptability, resourcefulness and flexibility. Looking at the next level of detail, i.e., the individual topics contained in the categories, there are several assignments to the pre-defined resilience categories, such as the ability to anticipate, adapt, dealing with uncertainty and complexity as well as recognizing/monitoring threats. The only competency categories which were not assigned are absorbing, recovering and transforming.

In the updated 3.0 version of the CDIO Syllabus, system thinking is covered more holistically by integrating not only a deterministic view on technical systems, but also including socio-technical interactions and the consideration of uncertainty and complexity (Malmqvist et al. 2022). This is also mirrored in the results of the analysis, as most of the categorized items are part of the newer 3.0 version of the Syllabus. As noted above, resilience itself was mentioned here as a topic besides adaptation, as part of the subcategory 2.3.2 emergence and interactions in systems.

The CDIO Syllabus also contains a focus on anticipatory competencies. This is especially the case for the fourth ("CDIO") category of the Syllabus, where, for example 4.1.6 (visions of the future) contains aspects of possible and probable scenario planning as well as long- and short-term concepts and 4.3.4 (system engineering, modeling and interfaces) includes system designs that are non-deterministic, continue to learn and modify themselves during operation. These descriptions inherently describe resilience in a system context. At the same time, the categorized items in the Syllabus are in some cases so explicitly referring to resilience that some items were difficult to assign to only one competency category. See for example the subcategory 4.3.2 (understanding needs and setting goals) which contains the competencies to allocate "margins, responding to change and handling unknown or unanticipated requirements during the lifecycle of a design". This outcome simultaneously refers to adapting, learning and developing with change (see Table 1).

3.4 Discussion

Compared to our previous study on resilience-related competencies in European engineering study programs (Winkens and Leicht-Scholten 2023a), the overall picture is more heterogenous. There, most study programs address dealing with complexity in the context of solving complex problems as well as system thinking. These competencies are central to engineers' toolkit, but in terms of resilience they are not sufficient to design resilient systems. These results are also mirrored in the ABET Criteria: The general requirements contain no competencies that go beyond dealing with systems and solving complex problems, which are a staple of engineering itself. However, some degree programs contain strong references to resilience. The EUR-ACE framework is similar to that at the Bachelor's level, however they still include lifelong learning, and risk and change management. At the Master's level, EUR-ACE requires a stronger set of resilience-related competencies for graduates then it is the case with ABET, especially with regard to the handling of incomplete or competing information.

In comparison, the 2.0 CDIO Syllabus already contains strong resilience reference. The 3.0 Syllabus builds on that and calls for a broad range of competencies suitable to prepare engineers for designing resilient systems. Compared to the ABET and EUR-ACE outcomes, it is notable that not only were more resilience-related competencies categorized in the CDIO Syllabus, but that the latter also contains a focus on anticipatory competencies (which are inherent to and necessary for resilience), as discussed before. However, as already discussed by Malmqvist (2009) and Crawley et al. (2011), a comparison of the proficiency levels of the three analyzed frameworks is difficult. But, as, at the same time, the CDIO Syllabus represents a more holistic view of engineering than ABET and EUR-ACE, is more detailed and also includes the outcomes of other reference frameworks, we still find the comparison to be purposeful.

In the context of our previous results on the lack of resilience-related competencies in European university study programs (Winkens and Leicht-Scholten 2023a), these results are unexpected especially with respect to EUR-ACE: While standard calls for strong abilities in the context of systems resilience, few study programs contain those as learning outcomes. This exposes a clear gap between accreditation requirements and university practice in formulating learning outcomes, an issue which is already well reported (e.g., Passow and Passow 2017, Shuman, Besterfield-Sacre, and McGourty 2005). Whether the gap in our case is due to the selected study programs in the previous study, a delay in implementation, or an example for a systemic issue remains an open question which needs further research. Similarly, for resilience-related competencies, there is no evidence whether and/or to what extent the ABET criteria are consistently implemented in practice, which is also a promising avenue for a follow-up study. Finally, this work indicates that consistently implementing the CDIO Syllabus as a basis for an engineering program could serve to address resilience-related competencies.

4 SUMMARY

All three reference frameworks emphasize solving complex problems as a key element of engineering education, which also contributes to designing resilient systems. Beyond that a small number of ABET courses of study contain a strong reference to resilience competencies and/or more frequently dealing with uncertainty. EUR-ACE is more comprehensive in this regard, but at least for the courses considered in our previous work on resilience-related competencies in European university study programs (Winkens and Leicht-Scholten 2023a), this does not appear to trickle down into course level learning outcomes. The CDIO Syllabus provides an extensive coverage of resilience-related competencies. Notably, this does not only include dealing with complex systems under uncertainty, but also explicitly and repeatedly addresses anticipatory competencies and learning (from failure), which are necessary competencies for designing resilient systems. Finally, the results show that beyond additional research, closing the gap between the Engineering Education Research community, accreditation and actual course content and learning outcomes remains both a major challenge and opportunity for engineering education.

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