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The Concept of Failure in Engineering Education – A Transdisciplinary Perspective

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Abstract. Research into engineering education covers models, methods and approaches to characterise, measure and improve teaching and/or learning performance. The majority of the academic state of the art focuses on how to improve performance based on an understanding of critical success factors for engineering education, which is itself based on underlying models of learning as a process of knowledge acquisition, retention, application and sublimation into 'higher-level' learning outcomes. The state of the art covers both qualitative and quantitative methodological approaches, with a strong focus on characterising and measuring learning outcomes. However, while success factors have been identified, much less attention has been paid to what can go wrong in engineering education. This paper aims to provide an initial definition and typology of failure in engineering education, based on a transdisciplinary approach involving concepts and methods from reliability engineering and (engineering) education. Subsequently, avenues for future modelling, testing and application of the concept of failure are explored.

Keywords. engineering teaching and learning, engineering education, failure, transdisciplinary engineering education

Introduction

Research into engineering education covers models, methods and approaches to characterise, measure and improve teaching and/or learning performance. Within this broad area, a predominant focus is on the improvement of outcomes. Outcomes can be defined along various dimensions and perspectives, but two major streams of research focus respectively on 1) student retention, addressing the urgent question of how to ensure that societal requirements for sufficient volumes of qualified engineers are met; 2) curriculum and course design, addressing the question of how learning and teaching approaches can be improved within course and curriculum settings to improve student outcomes. In this space, outcomes can be variously defined as progression, retention, realisation of learning objectives, and more – a point which will be revisited in Section 1. Within these streams of research, the majority of the academic state of the art focuses on how to characterise, monitor and predict student success. Both qualitative and quantitative studies leverage transverse and longitudinal data to arrive at an understanding of influencing factors for success in engineering education. Some studies

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engage with variables describing student, environment and organisational attributes to model and predict student progress and/or retention [1-3]. Other studies leverage underlying models of learning as a process of knowledge acquisition, retention, application and sublimation into 'higher-level' learning outcomes to characterise good teaching and learning practices [4].

However, while success factors have been identified and categorised, much less attention has been paid to what can go wrong in engineering education. This gap in the current state of the art is addressed (partially) by only a few studies. These for instance describe characteristics of 'bad teaching' [5], though it is noted that eliminating bad practices does not necessarily mean that good practices are left. Nevertheless, for both beginning and experienced teaching and learning practitioners and designers, the ability to identify and avoid bad or unproductive practices would be worthwhile. In effect, this can be hypothesised to help to lift overall education outcomes by removing practices that lead to substandard outcomes. The aforementioned gap in the state of the art is compounded by a lack of consistency and completeness in definition of success (and failure) in education outcomes. Furthermore, practitioners lack effective modelling tools to characterise complex interacting factors which result in student outcomes; current studies involving regression and/or path analysis make numerous assumptions regarding directionality, (in)dependence, distribution and behaviour of contributing factors which may not be valid in all contexts, nor operationalised effectively to assist in course and/or program design[2].

Similar issues have been encountered and addressed in various other fields. In particular, the whole field of reliability engineering is focused on the detection, diagnosis and prediction of failures in engineered systems and the constituent elements [6]. Definitions of failure and success are available to inform subsequent modelling and analysis, which are typically probabilistic in nature. These methods allow to represent the uncertainty involved in the manifestation of failure in practice, on the basis of underlying, frequently unobserved physical deterioration processes. Reliability models and tools have been successfully employed for decades to improve system performance and design, notably through a relentless focus on identifying and resolving non-conformance to design, manufacturing and operational specifications (i.e., failures). Such an approach may have valuable lessons for other areas, including education.

To this end, this paper aims to provide an initial definition and classification of failure in engineering education, based on a transdisciplinary approach involving concepts and methodologies from reliability engineering and education. In particular, concepts, methodologies and tools from reliability engineering are synthesized with education models to arrive at a definition and typology of failure in engineering education. Besides this synthesis, the proposed approach has the transdisciplinary characteristic of addressing a so-called 'wicked problem', namely the ongoing issues with improving education quality and performance relative to educational outcomes.

The structure of this paper is as follows. In Section 1, the theoretical context of the problem will be explored in more depth, including a review and synthesis of definitions of success in educational outcomes at various levels of interaction. In Section 2, a brief overview of the applied research methodology is provided, followed by definition of the concept of failure which is coupled into the preceding review and synthesis efforts to accurately delineate the focus of this research. This includes a discussion of related

[2] In this work, the term 'program' is used to identify a program of study. The term 'curriculum' is often used in an interchangeable fashion.

(categories of) variables that can be used to model failure in education. Subsequently, drivers of failure in education are classified using concepts from reliability engineering in combination with existing representations of educational outcome success factors. Finally, conclusions are given and a brief discussion highlights future research pathways.

1. Theoretical context

The theoretical context regarding success and failure in egineering education is predominantly focused on the aspect of success. In this section, the definition of success in engineering education will be discussed in detail, followed by a brief consideration of existing models to characterise drivers of success, leading to the identification of research gaps.

As noted by Van Den Boogaard [2], the concept of (student) success is broad and it "can be operationalised in many different ways", using a variety of measures. Many researchers connect success to measures of retention, i.e., the continued and active presence of students in a program, potentially spanning the whole path from initiation to to completion of their degree. Examples include the work by Tinto [7], where drop-out is the main variable to represent retention over time. Boles & Whelan [1] have performed research on identifying barriers to student success in engineering education, where success is not formally defined but is related to retention in the introduction. Another example is the work by Calvert [8], where student success is defined "in relation to the student's study/qualification aim and this is the basis for the model described here. Retention and completion are modelled as the student progresses". The notion of progress is also taken up by Boles & Whelan [1], though not explicitly operationalized. Progression, i.e., the ability of students to progress through and complete the program or individual elements of the program such as courses in a timely fashion, is a measure of success which is used often in literature. As summarized by Van Den Boogaard [2], operationalised measures of progress may include "the number of credits students that obtain in a set period of time, the average grade that can be used to serve as an indication of the quality of the learning outcome (e.g. Bruinsma and Jansen 2007) and student re-enrolment in the next academic year (e.g. Ohland et al. 2008)". Finally, Tynjälä et al. [4] note that "Learning outcomes are often operationalised with quantitative measures such as course grades" but criticize this approach as course grades may be a reflection on learning strategies (e.g. rote learning) as much as actual attainment of learning outcomes. Instead, the authors propose the use of three separate indicators of study success, namely the grade point average (GPA) across all courses for individual students, the credits gained per year and self-evaluations of learning.

There is a notable shortcoming in the preceding discussion of success: none of the proposed measures is explicitly linked to different levels of aggregation in outcomes. In other words, there seems to be an implicit assumption that measures such as drop-out (representing retention) and credits gained per year (representing progress) are meaningful for multiple stakeholders at multiple levels of the educational system. An assumption seems to hold that, say, a national accreditation body views a outcomes as measured via drop-out rates in the same terms as an educational institution, a program manager / coordinator, an individual teacher, or an individual student. This assumption may hold up for specific measures but 1) is not explicitly identified in most if not all related literature; 2) is not investigated and tested in literature; 3) may give rise to incorrect interpretations of findings. To address this issue in a preliminary fashion,

Figure 1 gives a multi-level representation of success and failure concept interpretations in educational settings (with failure interpretations further discussed in the next Section).

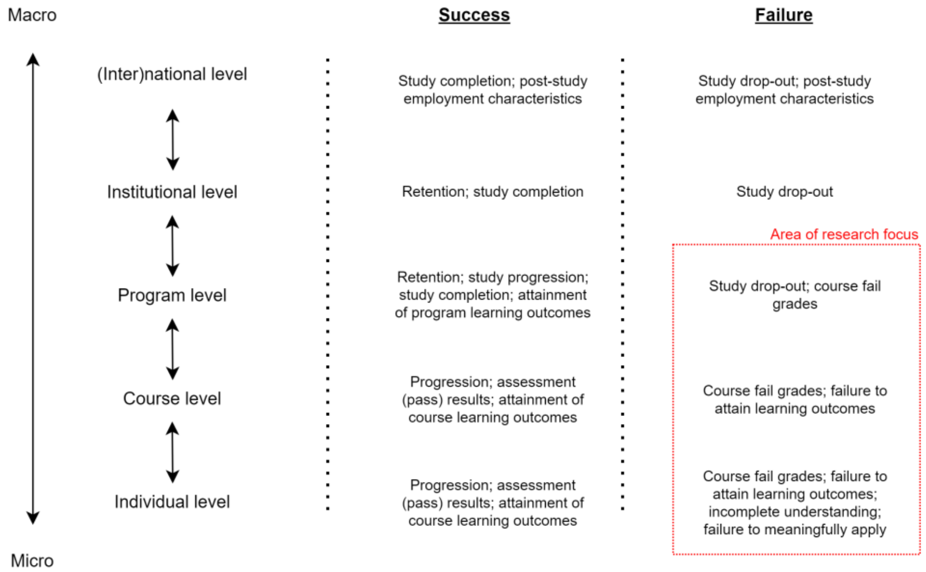

Figure 1. Multilevel representation of success and failure concept interpretations in educational settings.

While the definition of success in education has been addressed above, one can consider which factors exert an influence on success. Various models have been proposed in literature. Boles and Whelan [1] identify three major categories of influences, namely the learning environment, student behaviour and personal interests. Within the learning environment, influences on success involve student-academic interactions, curriculum design and organisation, assessment and feedback, learning support and campus environment. In terms of student behaviour, student preferences regarding individual or collaborative work as well as effort and time-on-task are highlighted. Personal interests capture self-regulation and perception of self, as well as academic capabilities and workload. The model can be challenged on several accounts. For instance, why is workload considered to belong to the personal interest category, and not to the learning environment (as workload may strongly relate to student-academic interactions, curriculum design and program alignment)?

Van den Boogaard [2] presents a more high-level representation where external factors may influence intake characteristics, economic factors, social and psychological factors as well as educational factors. These aspects jointly exert an effect on overall study progress.

Compared to the two previous models, the model of student learning proposed by Tynjälä et al. [4] is more focused on a detailed representation of the learning process. The model involves background factors, educational orientations and conceptions of learning as inputs to the learning process. This process involves a variety of aspects, including student conceptions of their learning methods and processes, study orientations, and situational study strategies. Together, these aspects combine to generate outcomes of learning, as operationalised by the three measures mentioned previously.

The work by Jackson [5] focuses in much more detail on one of the aspects which the previous models touch upon, namely the effect of educational influences. In particular, Jackson [5] discusses the effect of good and bad teaching on educational experiences, where what is 'good' and 'bad' is discussed on the basis of a large-scale survey of students having graduated a significant time (>25 years) ago since publication of the research in question.

The previous considerations of the theoretical context highlight a number of challenges:

- There is a lack of consistency and completeness in definition of success (and failure) in education outcomes. Models to identify factors of influence on success are available, and can be used to predict outcomes. Nevertheless, both the definition of success and the associated models are highly dependent on context. The overview given in Figure 1 aims to address this issue to a partial extent.
- Building on the previous, practitioners lack effective modelling tools to characterise complex interacting factors which result in student outcomes. Much of the state of the art (of which only a small subset has been discussed) involves attempts to model and predict student outcomes through statistical techniques like multilinear regression, path analysis and Structural Equation Modelling (SEM). These approaches typically involve numerous assumptions regarding directionality, (in)dependence, distribution and behaviour of contributing factors which may not be valid in all contexts, nor operationalised effectively to assist in course and/or program design. Furthermore, findings of these statistical studies sometimes seem to suffer from the high quantity of independent (predictor) variables being assessed, with weak correlations and lack of statistical significance occuring.

2. Failure in engineering education

The current research is exploratory in nature and seeks to define and typify the concept of failure in the context of engineering education. These aims are reflected in the structure of the next (sub)sections. From a methodological point of view, a transdisciplinary approach is used by combining findings from educational theory with concepts from reliability (engineering) theory. The research methodology comprises desk research, where findings from a core set of papers (N = 7, comprising references [1-5 and 7-8]) are used in conjunction with qualitative clustering to group drivers of failure into a few distinct underlying drivers. The analysis can be considered to give preliminary findings, with a subsequent iteration planned to focus on 1) extending the core set of papers; 2) applying natural language processing techniques to identify core terms and drivers of interest in a quantifiable approach, akin to Scott et al. [10].

2.1. Defining failure in engineering education

Similar to the previous discussion, a definition of failure in engineering education can act at different levels. Several possible interpretations of failure are highlighted in Figure 1. Several of these interpretations, for instance drop-out, share a characteristic with the notion of failure of physical systems as described in reliability theory. This characteristic is that the associated variable is binary: either something succeeds or fails – there is no intermediate representation. Similarly, a student either passes or fails a course, or drops out of a program or stays in.

As with physical system failures, the representation of failure in education can account for intermediate expressions. For physical systems, degradation in performance, reduced functionality, or non-performance under conditions outside of design specifications all relate to various degrees of success or failure of a system. Equivalently, the attainment of learning outcomes (either at program, course or individual level) can be measured and expressed on an interval or ratio scale, rather than a binary pass / fail representation.

In this paper, failure in engineering education is further considered from the program, course and individual levels, as highlighted in red in Figure 1 and further discussed below.

2.2. A typology of failure in engineering education

The choice to focus on the program, course and individual levels is motivated by the realisation that not all influencing factors on study success and failure can be influenced! In other words, this research focuses on the characterisation of factors that can be controlled or influenced directly by individuals such as teachers and learners, program designers or managers / coordinators.

To facilitate a better understanding of failure in engineering education, a typology of failure is proposed in Figure 2. This typology is based on concepts from reliability theory, namely:

- **Failure (metrics):** the concept of failure in engineering education has been defined in the previous subsection. Figure 2 adds typical metrics which can be used to observe and measure failure in education.
- **Failure modes:** the concept of failure mode refers to how technical products fail; in more complete terms, a failure mode describes the manner in which an item or operation potentially fails to meet or deliver the intended function and associated requirements of a technical product. Theoretically, the number of failure modes for any given technical product is infinite, though in practice the number of observed failure modes is typically limited. The concept of failure mode is translated to manifestations of failure drivers in engineering education practice, i.e., the ways in which failures occur in program, course and individual settings. The examples given below are non-exhaustive, and largely based on literature [1-8].
- **Failure mechanisms:** in reliability theory, failure mechanisms represent the underlying physical processes which generate failure in technical products. The number of failure mechanisms is limited; common examples include wear, corrosion, fatigue, radiation, chemical deterioration, and others. Translating this to failure in education, it becomes possible to distinguish several main categories of failure drivers. In this research, existing models and quantitative studies into study success are used to identify and group failure drivers in education; four categories are proposed here (see Figure 2). This limited number of failure driver categories gives rise to a large number of manifestations of failure-driving aspects in education.

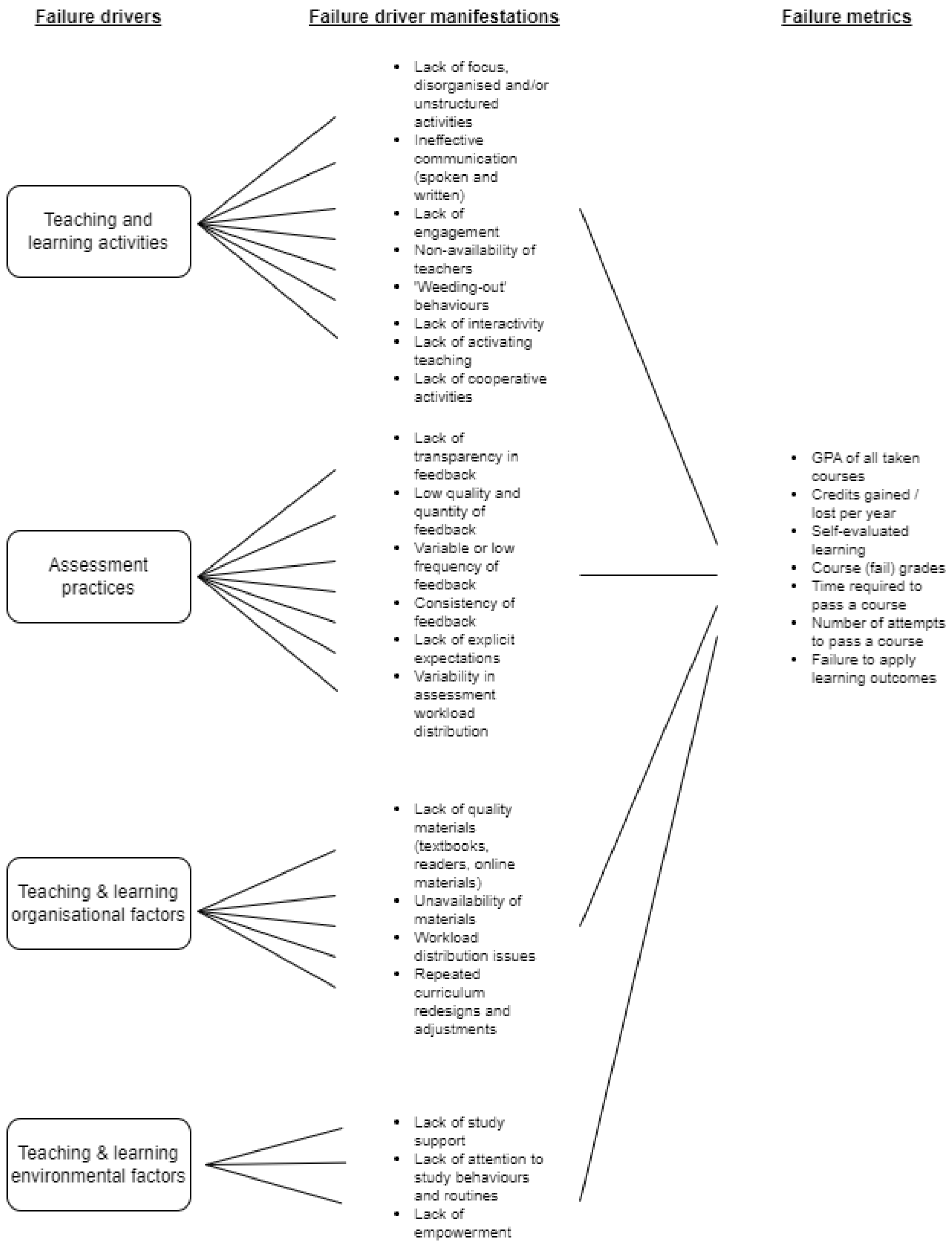

Figure 2. An initial typology of failure in engineering education.

2.3. Modelling failure in engineering education

The preceding typology of failure in engineering education opens up an avenue towards modelling of this phenomenon. It is possible to discern the following major types of approaches:

- **Statistical and probabilistic models:** analogous to existing models of study success, the application of multivariate regression techniques, path analysis, SEM and other similar techniques may leverage failure metrics data as well as predictor data associated with failure drivers and their manifestation to construct statistical models. Several of the proposed failure metrics lend themselves to represent one or more random variables of interest. One or more random variables can be used to construct probabilistic models (ranging from distributions to extended regression models to Markov models). Extended (Cox) regression models are particularly interesting as they allow for the inclusion of explanatory variables to more accurately predict failure behaviour. One major limitation is the amount of explanatory variables that can feasibly be used in such models, as this amount is typically not large – which may conflict with the amount of data available in typical quantative studies into education.
- **System models:** the preceding statistical and probabilistic models can be used to inform models representing (elements of) the education system. To give an example, once again from reliability theory: approaches such as Fault Tree Analysis utilizing Fault Tree Diagrams (FTD) can be used to cover the complex interactions between education failure variables. Fault tree diagrams show "the logical interrelation of the basic events that taken apart or together may lead to a system or device failure, the top fault, using a combination of "and" and "or" symbols." [9]. Interestingly, FTDs and other system modelling approaches allow for the identification of 'weak points' – single points of failures in FTA parlance – in product designs. A similar role could be filled in design and refinement of engineering programs and courses.

Having mentioned these approaches, there are a number of considerations to take into account. First of all, this overview is not necessarily complete. For instance, AI-based approaches may have a role to play in this area. More importantly however, several assumptions and limitations have to be acknowledged. In terms of assumptions, one major assumption is that the quantity and quality of data regarding failures as expressed in failure metrics is sufficiently developed. This is not a given, as many aspects highlighted in the failure typology have not been studied, captured or tracked systematically. Furthermore, this work assumes that the identification and characterisation of failure in engineering education will actually support improvement of education, in effect by eliminating non-performing elements and raising the bar of education performance.

An obvious limitation of the preceding discussion is that there has, as of yet, never been an attempt to apply these modelling approaches to the concept of failure in engineering education. The feasibility, validity and value of these proposals are yet to be proven.

3. Conclusions and recommendations

This research has demonstrated initial work relative to the concept of failure in engineering education, revisiting the concept of succcess in more detail, subsequently proposing a definition of failure and using this to propose a failure typology on the basis of a synthesis of concepts from reliability and education theory. To demonstrate and usefully apply these elements in further study has to be supported by proper modelling approaches, several of which have been put forward as suggestions.

This leads into recommendations for future work. Much remains to be done to apply, verify, test, validate and translate these concepts into something useful and of impact. In particular, the suggested failure metrics and associated drivers may help to define, plan and execute both qualitative and quantitative studies. This can address the current gap in the state of the art, where the vital question 'what doesn't work?' seems to be overlooked too often.

Future stages of this research are planned to focus on 1) extending the core set of papers; 2) applying natural language processing techniques to identify core terms and drivers of interest in a quantifiable and reproducible approach.

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