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(article starts on next page)

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Bringing the Entrepreneurial Mindset into Mining Engineering Education

Aarti Sörensen[1] · Rudrajit Mitra[1] · Erik Hulthén[2] · Tobias Hartmann[1] · Elisabeth Clausen[1]

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Abstract
There has been an ongoing debate on how to transform engineering education to better prepare students for today`s professional world that is characterized by increasingly complex problems and challenges that engineers are tasked with upon entering the industry. Within the conceive–design–implement–operate (CDIO) framework, entrepreneurship education presents a valuable pedagogical approach to foster the necessary skills of the students through integrated, hands-on, active learning experiences. While numerous publications have addressed possibilities of how experiential, problem-based, project-based and active learning can be integrated into engineering curriculum, there has been hardly any attention on mining engineering with respect to adopting this approach. This paper will address the possibilities of integrating entrepreneurship education into mining engineering programs in particular. This paper will enhance and foster discussion among academics from mining engineering on how to integrate elements of entrepreneurship education on a course, program and departmental level to infuse value creation experiences across the curriculum.

Keywords Engineering education · Entrepreneurial education · AMT · Learning Factory Mining 4.0 · Mining engineering

1 Introduction

"*To change the world, you have to be taught differently*" says TU Delft's Aldert Kamp [1], loosely adapting the famous quote by Albert Einstein, which states that you cannot solve a problem with the same means or tools that created it. Both elude to the fact that to solve the complex societal challenges of today, different approaches to learning and teaching are needed.

Consequently, there has been an ongoing debate on how to transform engineering education to better prepare students for today's professional world that is characterized by increasingly complex problems and challenges that engineers are tasked with upon entering the industry. There certainly is no shortage of propositions that have been put forth to enhance contemporary engineering education, from fostering critical thinking, creativity and unstructured problem-solving to interdisciplinary and systems thinking, communication and collaboration, to sustainability and responsible engineering. This broad range of skills and competencies that future professionals ought to develop as part of their higher education have been summarized, for example, in the concept of the T-shaped professional [2]. However, this does not yet elude to "how" these skills can be effectively fostered and cultivated in students.

One of the most influential global organizations for transforming engineering education in university programs, and therefore for offering a comprehensive approach on "how" to adapt the educational model, has been the conceive–design–implement–operate (CDIO) initiative providing an educational framework for curricular planning and outcome-based assessment. Developed with input from academia, industry, engineers and students, the CDIO initiative provides a framework of 12 standards with indicators for different levels of implementation that can be adapted and adopted by any engineering school. The CDIO approach has been implemented worldwide at more than 120 partner universities and in various engineering disciplines (aerospace, applied physics, electrical engineering and mechanical engineering) [3].

✉ Rudrajit Mitra
rmitra@amt.rwth-aachen.de

1 Institute for Advanced Mining Technologies, RWTH Aachen University, Wüllnerstr. 2, 52062 Aachen, Germany

2 Department of Industrial and Materials Science, Chalmers University of Technology, 41296 Gothenburg, Sweden

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Further, due to the fact that business creation plays an integral role for economic development and growth, the concept of entrepreneurship education has drawn much attention over the past decade. This has resulted in an EU Entrepreneurship 2020 strategy and various projects, reports and guidelines by the EU Commission [4] and has also affected university education.

Within this framework of CDIO, the authors would like to argue, entrepreneurship education presents a particularly valuable pedagogical avenue that makes it possible to foster many of the above-mentioned skills through integrated, hands-on, active learning experiences (directly addressing CDIO standards 6,7,8) [3] while adding an additional layer of value and potential student motivation by focusing on creating actual value for stakeholders outside the university campus.

While numerous publications have addressed possibilities of how experiential learning, problem-based learning, project-based learning and active learning can be integrated into engineering curricula, with only a few exceptions [5–8], there has been hardly any attention on the discipline of mining engineering with respect to adopting a CDIO-based approach. This paper will enhance and foster discussion among academics from mining engineering on how to integrate elements of entrepreneurship education on a course, program and departmental level to infuse value creation experiences across the curriculum.

In the context of this paper, entrepreneurship education is purposefully defined in its wider scope to include aspects such as personal development, creativity, self-reliance, initiative taking, action orientation and particularly important, this is defined by creating value and doing something for someone else, i.e., becoming entrepreneurial, as being the main objective. The process of becoming entrepreneurial in this definition is valued equally to the outcome of entrepreneurial action [9].

This paper builds on a recent project funded by EIT RawMaterials between 2016 and 2020, over the course of which the CDIO principles were applied for the very first time to raw materials related education, with a special focus on mining engineering [6]. Inclusion of entrepreneurship education, from a CDIO perspective, as part of this project aligns well with the objectives of the EIT RawMaterials [10], which are to foster entrepreneurial activity and creative solutions along the entire raw materials value chain in Europe.

In the following sections, this paper will therefore take a closer look at current developments in mining engineering education, then review core terminology around entrepreneurship education to define the appropriate approach for the context of this paper. In a third step, current methodologies used to foster the entrepreneurial mindset will be reviewed, followed by exemplary good practices. The world's first Learning Factory Mining 4.0, which is currently being established at the Institute for Advanced Mining Technologies (AMT) at RWTH Aachen University, will be discussed along with the Chalmers Tracks project, as two current benchmark projects for integrating entrepreneurial education in modern engineering programs, and, in the case of the Learning Factory, in particular to mining engineering curricula.

2 Current Issues in Mining Engineering Education

Interestingly, mining engineering has always been, in its essence, an integrative discipline and interdisciplinary field of study as it integrates different engineering disciplines, e.g., mechanical, computational, electrical and mining engineering. Since mining encompasses everything from mineral exploration to extraction to processing, engineers have to be able to bridge different disciplinary boundaries during their course of study as well as on the job. Yet, with changing societal values and increasing demands of stakeholders for responsible mineral production and safe and environmentally sound practices as well as with the increasing digitalization and automation of mining operations, the job profile of the mining engineer is constantly changing.

Webber-Youngman [11] and others have stated similar views on what the mine of the future will look like. According to these studies, the following will be the main aspects characterizing future operations:

1. Remote control of most mining activities, if not all,
2. Reduced man–machine interface risk through the use of advanced robotics and autonomous or near autonomous driverless vehicles,
3. Virtual reality and augmented reality applications for supporting decision-making processes,
4. Real-time mine production monitoring and analysis through scanning and other monitoring initiatives and related real time response to the information obtained,
5. Real-time mine planning, design optimization and control—the digital twin concept and
6. Mine design holography as part of an enhanced visualization strategy for mines.

New technologies are being tested and implemented and new ways of working are emerging as remote-controlled machinery and robotic or autonomous equipment requires different skillsets. Therefore, as other fields of engineering change, the work environment and skills required for mining engineers are also changing and thus imply the need for educational curricula to adapt. In particular, mining engineers of tomorrow need to be flexible to adapt to demands and work environments that will continue to change with the ongoing digital transformation in the industry and be able to tackle complex problems of raising complexity and the need for deeper understanding of a wider range of evolving technologies.

In addition, mining companies have to deal with an increasing number of stakeholders, such as local communities, environmental groups, non-governmental organizations and shareholders as well as regulators. The “social license to operate,” which implies an imperative for mining companies to increase the value creation for those affected by large-scale mining operations, is challenging mining companies to redefine their priorities, business models and role in society.

According to an internal report by Smith [12] as stated in Mitra et al. [13], it is thus no longer appropriate to educate mining engineers in only how to design and operate mines safely and productively. There is a need to redefine the attributes and competencies of mining engineers in order to accommodate the increasingly diverse and complex responsibilities across multiple disciplines and technologies. He also indicates the critical need to effectively incorporate the social license to operate, environmental and social impact assessment, regulatory and permitting constraints, risk assessment and management across the mine life cycle. Smith [12] defined three dimensions which is required to be included in a future undergraduate mining engineering curriculum in order to produce graduates with the ability to understand and operate within the holistic nature of mining engineering:

1. Core technological competencies that encompass the impact of Industry 4.0 on mining processes and people;
2. A fundamental understanding of the skill sets, techniques and best practices across the environmental and social dimensions of the social license to operate; and
3. The capability to operate effectively in an increasingly interdisciplinary environment, especially relating to social intelligence, emotional intelligence and leadership skills.

A workshop was conducted at the School of Mining Engineering at the University of the Witwatersrand considering the redesign of the curriculum of the Mining Engineering program. This workshop included participants from both academia and industry. The main message from the workshop was that entrepreneurship, innovation, automation, personal skills, among others, are necessary inclusions into the program. Currently, there are very few Mining Engineering programs in the world that have included these as part of their program [13].

Further, the Education Committee of the Society of Mining Professors (SOMP) undertook an initiative looking into the Future of Mining Education. The objective of this study was to develop a framework for training mining engineering graduates of the future. One of the preliminary outcomes from this study also pointed out that there is a need to include entrepreneurship among others in future program [14].

3 Definitions of Entrepreneurship Education

In a more traditional definition of entrepreneurship education, it is part of business and management education and is considered essential to foster entrepreneurial activity with the primary objective of fostering the creation of new businesses [15]. In this definition, entrepreneurship education prepares (business) students for starting their own business and is aimed at fostering direct business activity. Because business creation is necessary for economic development and growth, this concept of entrepreneurship education has drawn much attention over the past decade also for other disciplines.

However, there is also a more comprehensive definition of entrepreneurship education which considers aspects of personal development, creativity, self-reliance, initiative taking, action orientation, as well as in particular the aspect of becoming entrepreneurial, as the main objective. This definition of entrepreneurship education implies more of a mindset instead of a skillset and is about enabling students to become more creative, opportunity oriented, proactive and innovative; it is about becoming entrepreneurial [9]. This more comprehensive concept of entrepreneurship education changes not only the meaning but also the purpose of entrepreneurship education and makes it accessible for and applicable to other disciplines outside of business education programs, including engineering programs.

Gibb [16] proposes a new approach to the study of entrepreneurship and a new paradigm as a basis for entrepreneurship education. Such an approach is unlikely to come from university business schools and would need an organizational revolution which, can be managed within a university as a whole. Further, according to him, key trigger for the growing interest in entrepreneurship is globalization.

With respect to learning, this concept of entrepreneurship education, according to Bruyat and Julien [17], is not about the outcome (a new venture), but primarily about the learning that occurs in the process of value creation through interaction with the environment.Learning and value creation are thus seen as two main aspects of entrepreneurship education. Consequently, “*if a pedagogical intervention lets students learn to create value for other people (own group and lecturers excluded), it is indeed entrepreneurial education*” [9]. Becoming entrepreneurial then means to be able to act upon opportunities and ideas and transform them into value for others, whereby that value can be financial, cultural or social [18].

Thus, entrepreneurship education in its more comprehensive meaning, which also forms the basis for the arguments put forth in this paper, encompasses the "*content, methods and activities that support the development of motivation, skill and experience, which make it possible to be entrepreneurial, (which is) to manage and participate in value-creating processes"* [18].

Creed et al. [19] introduced the term entrepreneurial engineer, who needs a broad range of skills and knowledge, above and beyond a strong science and engineering background. According to them, these engineering entrepreneurs would work with small, highly focused multi-disciplinary teams, comprising not only engineers, but also individuals with varying backgrounds such as business, marketing, the humanities and law. Engineering education is increasingly introducing the concept of entrepreneurship education. Numerous educational designs used to introduce entrepreneurship education have been extensively discussed; however, a clear scheme for the classification of such methods is not yet available [20]. It has been observed that engineering students are being exposed to "*entrepreneurship coursework and experiential learning opportunities*" more than the past, both within and outside their disciplines [21].

Since entrepreneurship education is at its heart about acting on ideas and participating in value creation processes, it should be noted here that these actions and processes are not happening in a vacuum and if they are to have actual meaning and impact, the dimensions of ethics and sustainability should be included, if not with the definition itself, certainly in any considerations for integrating value creation approaches into the curriculum or course. Thus, entrepreneurship education with a focus on value creation processes should be founded on ethical values and an understanding of societal and global challenges, such as the United Nations Sustainable Development Goals (UN SDGs). In fact, Kamp from TU Delft points out in a recent blog post that "*one of the current challenges in engineering education is the integration of ethics education in engineering programs, as part of training for engineers and designers*" [1]. In his blog, he also provides a report of a meeting in April 2019 where 76 thought leaders and educators as well as entrepreneurial educators met at MIT and Olin College to discuss the future of engineering education. He notes that "*pathways to socially responsible engineering, including the integration of the UN SDGs in curricula, turned out to be the hottest topic that had high interest of many universities*" as they are "*facing a moral imperative to pursue the UN SDGs as institutions.*" At the meeting, these thought leaders stated that "*there is not sufficient social awareness and a lack of ownership of the consequences of their work among engineering students and hence engineers*" and that "*society needs people who can break down disciplinary silos and engineers who do care about social responsibility*" [1]. Additionally, it is important to note and highlight that entrepreneurial actions and processes specifically in engineering education can only take place and happen on a solid basis of natural sciences and engineering fundamentals.

4 Classification of Teaching Approaches for Entrepreneurship Education

"*How to make students more entrepreneurial is probably the most difficult and important question in this domain*" states Lackéus [9], and rightfully so. Therefore, it is important to differentiate not only between the narrow and wider definition of entrepreneurship education but also between different teaching approaches and subsequent methodologies in order to consciously choose the methodologies that are mostly in line with the desired learning outcomes.

This section provides an overview of a two-level classification for teaching approaches that make it possible to delineate suitable methodologies based on the desired learning activities and outcomes.

The first classification, which is widely applied and well established, is the classification into teaching "about" (content-laden theoretical approach), teaching "for" (occupationally oriented approach for entrepreneurs) and teaching "through" (process-based experiential approach where students go through an actual entrepreneurial learning process) entrepreneurship. There is ample evidence that shows the effectiveness of the "through" approach compared to the "about" and "for" approach, even though the "about" approach is still widely practiced [22]. There seems to be indeed a growing consensus that using experience-based or learning-by-doing methods are crucial to developing an entrepreneurial mindset and "*that traditional educational methods, like lectures, do not correlate well with the development of entrepreneurial thinking*" [22]. In addition, "*there is increasing consensus among researchers that letting students work in interdisciplinary teams and interact with people outside school or university is a particularly powerful way to develop entrepreneurial competencies among students*" and if this kind of experiential learning based activity creates some kind of value for the stakeholders outside university, it can be classified as entrepreneurial [9]. In this kind of interactive and action-based learning activities, the coordinator becomes more of a moderator and coach rather than a lecturer.

The second-level classification, proposed by Lackéus [9], provides further distinction between approaches for teaching "through" entrepreneurship, which is, as indicated above, the most suitable approach for developing an entrepreneurial mindset. Lackéus suggests four categories for action-based ("through" approaches) to entrepreneurship education:

creation, value creation, venture creation and sustainable venture creation (Fig. 1—Level 2 classification).

Since the venture creation and sustainable venture creation approaches imply an increasing complexity for the lecturer and are clearly focused on creating ventures and start-ups, for the purpose of this paper, the focus is placed on the creation approach versus the value creation approach. The creation approach, albeit action-based, is focused on traditional methodologies such as business plan writing and project-based approaches with artifacts mostly being created as deliverables for the lecturer. In contrast, the defining feature of the value creation approach is that actual value is created to stakeholders outside of the university. This implies a higher degree of creativity and gives more responsibility and meaning to the student work while still having an acceptable level of complexity on the part of the lecturer. According to Lackéus [9], there is evidence that this approach provides higher degrees of motivation and satisfaction to students, resulting in deep learning experiences (and potentially entrepreneurial activity). Consequently, the author states that "*teachers should give their students assignments to create value (preferably innovative) to external stakeholders based on problems and/or opportunities to the students identify through an iterative process they own themselves and take full responsibility for. To alleviate the levels of difficulty and uncertainty such an assignment can result in, a team-work approach should be applied giving the students access to increased creative ability and peer learning opportunities*" [9].

This second level of classification, although not as widely applied yet, is insightful because it allows for an additional valuation of methodologies with respect to their efficacy in fostering entrepreneurial mindsets in students. The value creation approach, contextualized within a framework of ethical values and sustainability, then presents a suitable approach for achieving the outcome of fostering entrepreneurial thinking in students and for empowering them to act on their ideas. The next section will present two methodologies that are in line with action-based or "through" approaches of learning through iterative, creative processes and with the value creation approach.

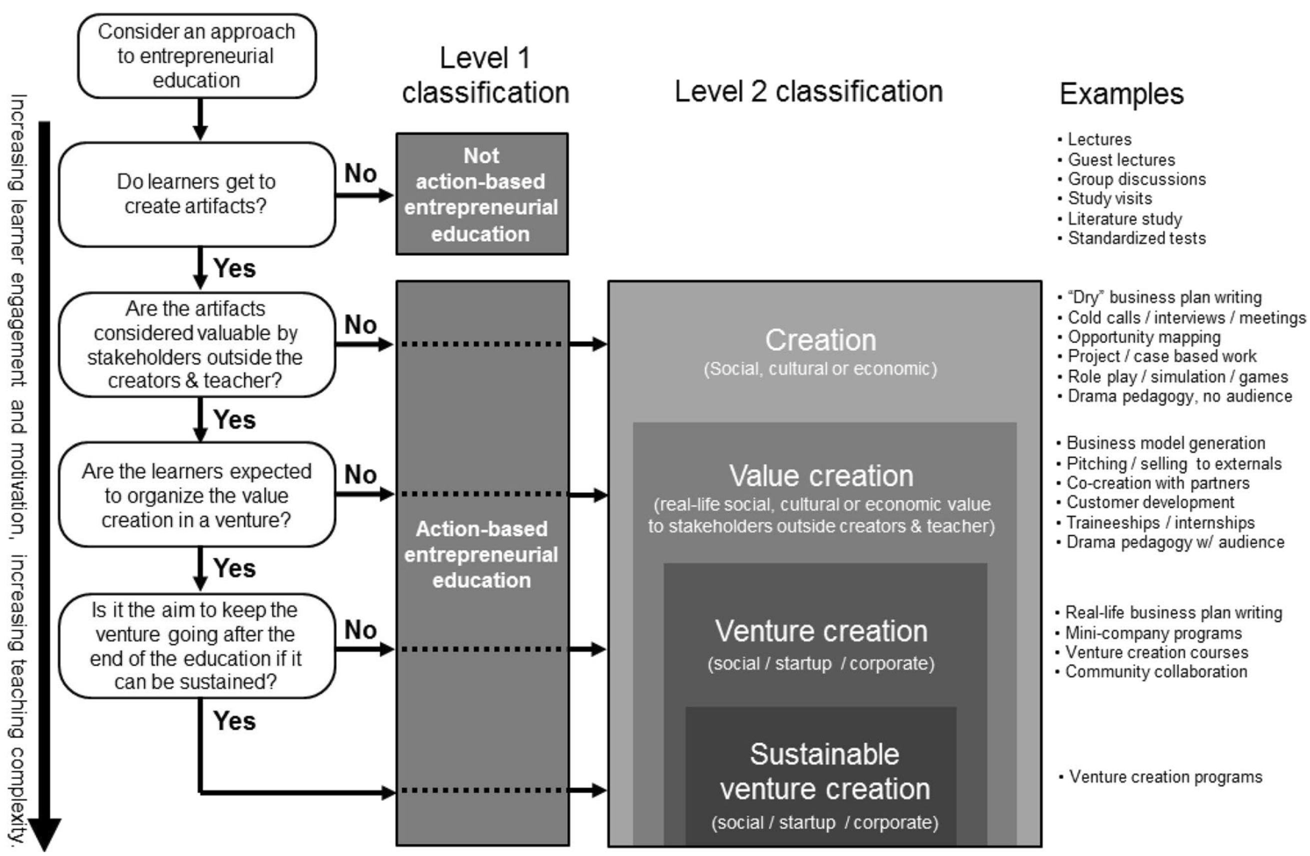

Fig. 1 Classification of action-based entrepreneurial education [9]

5 Selected Methodologies for Value Creation Approaches

The two methodologies that have been selected for further description here are Effectuation and Design Thinking, both methodologies that Lackéus also considers suitable to implement the value creation approach. The first approach, *Effectuation*, comes from inside the field of entrepreneurship education, whereas the second one, *Design Thinking*, originated outside the discipline [9]. Both are well-established methodologies and proven frameworks for active and deep learning as well as for fostering creativity and original thought. In addition, by constituting a learning-by-creating-value approach, they bear the potential to increase student motivation and engagement when applied appropriately. With respect to student motivation and engagement, there is actual evidence from psychology research that "*student motivation and enjoyment is enhanced through actions that are perceived both as controllable and valuable, and that participation in valued and challenging goal-oriented activities can result in strong feelings of confidence, happiness and motivation*" [9]. This is why a learning-by-creating-value approach seems best suited to achieve the desired outcomes of fostering entrepreneurial thinking and potentially entrepreneurial actions in students.

5.1 Effectuation

Effectuation was originally developed by entrepreneurship professor and leading scholar on the cognitive basis for high-performance entrepreneurship, Saras Sarasvathy. Effectuation is a heuristic concept for entrepreneurial logic and decision making in situations and circumstances characterized by high degrees of uncertainty [23]. Since originally proposing her theory for effectuation in 2001 juxtaposing it with causation theory for entrepreneurial decision-making processes, this approach has been adopted and validated internationally in various education and business contexts. In essence, while in causation theory the focus is on achieving a desired goal through a specific set of given means, effectuation theory puts the focus on using a set of evolving means to achieve new and different goals and thus evokes creative and transformative tactics [24]. Put differently, "*effectuation differs from the causal logic, where there is a predetermined goal and the process to achieve it is carefully planned in accordance to a set of given resources*" in that in 5.1, "*you identify the next best step by assessing the resources available in order to achieve your goals, while continuously balancing these goals with your resources and actions*." Effectuation is an attractive approach that can also be integrated in other than strict entrepreneurial courses because it "*can be used in to support self-efficacy and process understanding by letting the students identify the next, best step in order to solve the problem that they work with*" [25].

The effectuation method consists of four basic principles and an underlying worldview called the "Pilot-in-the-plane," which describes the future as something you can influence through your own actions, meaning that you can create your own opportunities. The four principles of effectuation [24, 25], namely "bird-in-hand," "lemonade," "crazy quilt" and "affordable loss," can be used to plan and execute the next best step and to adjust direction according to the outcome of one's actions at each step as an iterative process for decision making in a project or entrepreneurial process.

This is seen as an inspiring example of how far-reaching and transformative for students this method can be to empower students to take ownership of their lives and careers and demonstrated successfully how to cultivate an entrepreneurial mindset with students even when starting out with only the "*bird in hand*" [26].

5.2 Design Thinking

Another meta-approach that is closely related to the shift from the planning and prediction approach to an approach focusing on creating value and opportunities having a user-centric perspective, is design thinking. Design thinking is an innovative, human-centered approach to defining and solving complex problems and while originally intended to energize business innovation, it has also had considerable impact on education, probably because the process of design thinking fosters creative confidence [27]. The methodology is interactive and participatory and with its central emphasis on human needs it fosters student-centered learning, providing a proven alternative to the traditional university lecture style of learning [28], which has proven to be unsuitable for developing an entrepreneurial mindset [22]. Probably, the most powerful feature of this approach, not unlike the effectuation approach, is that it fosters a belief in "*one's ability to create impactful change*" [27].

With respect to the origins of design thinking, it was developed by California-based design agency IDEO David Kelley in collaboration with Larry Leifer, head of the Center of Design Research, and Terry Winograd, head of the Human–Computer Interaction Group at Stanford University. With funding from SAP founder Hasso Plattner, they set up the Hasso Plattner Institute of Design at Stanford, now widely known as the "d.school." The approach has proven itself through the high rate of spin-offs from the d.school as well as through its commercial success resulting in adaptation by companies and institutions around the world [29].

Quite similar to the effectuation approach, the process of design thinking, while consisting of five distinct steps, is in essence a nonlinear and iterative process, which requires the students to be able to "*define the parameters of a problem, identify needs, deal with varying levels of ambiguity, actively solve problems, and make connections between their lives inside and outside of school*" or university settings [27].

The five key phases of the design thinking process are defined as empathize, define, ideate, prototype and test according to the d.school guide [30]. Because iteration is fundamental to good design, while the process is described in a linear fashion, the design process is not meant to be linear. Rather, it is intended to take multiple cycles through the design process steps until the scope narrows from broad concepts to nuanced details.

Aside from its success in the business world and in design schools and entrepreneurial courses, as a methodological approach, design thinking has a high relevance to engineering as well. Considering that "*the core of engineering is not simply applied science, but the application of design and creativity to science*," as Kamp puts it, design thinking seems to be a suitable path to achieve this. In addition, there is a call for more emphasis in engineering curricula on "solving unstructured real-life problems by combining data analysis and highly subjective and even intuitive judgements about aspects of a problem" to make the students more familiar with the uncertainty of real problems, which is well reflected in the design thinking approach [31]. As engineering problems are becoming increasingly complex and their solution require skills and methods other than the rational problem-solving methods currently emphasized in most engineering curricula, design thinking provides a new path for tackling real-world problems in a creative, innovative and entrepreneurial way.

6 Good Practice Case Studies

The following case studies present selected examples for implementing value creation approaches to entrepreneurial education within engineering curricula. The first case study shows how an entire (private) university program is based on an active learning by value creation approach while also integrating design thinking as a fundamental concept into the entire curriculum. The second case study shows that implementing far reaching changes across disciplinary boundaries to integrate entrepreneurial and design elements is possible at a public university as well. Hence, Chalmers University of Technology, a public university in Sweden, is currently undertaking the biggest investment in the history of the university to incorporate broad changes and curricula adaptation. The third case study shows how changes have been implemented on a departmental level to integrate entrepreneurial education into engineering curricula on a program level. The fourth case study shows how changes can be made on a course level by showing how the effectuation approach was applied to the entire course design of an interdisciplinary course on entrepreneurship and partnerships.

6.1 Olin College (USA)

Established in 1997, Olin College of Engineering is a small private university in Needham, Massachusetts, focusing on undergraduate engineering education with a radically student-centered approach underpinned by experiential learning, where students draw inspiration from across a wide disciplinary base to tackle design-based challenges. The themes of entrepreneurship, self-directed exploration and social responsibility are evident in the educational approach [32].

Olin begins with hands-on challenges from day one culminating in a two-semester Corporate Capstone project (SCOPE) where teams are engaged on impact projects with corporate partners, government research laboratories, NGOs and start-ups. While basic fundamentals of engineering sciences are learnt on a need-to-know basis rather than a full framework of mathematics, physics and engineering sciences, the focus is on how to build upon the fundamentals, how to ask the right questions and acquire and validate new knowledge from the abundance of information that is available on the internet, from YouTube to Instagram to online courses. Almost all classes are project-based, and while academically interesting a special focus is placed on them always adding value to companies, organizations or communities. In addition, the educational programs are very human-centered, with high customer involvement and extensive collaboration, empathy and talking in line with the design thinking methodology [1].

According to a global benchmarking study by Graham [32] from MIT, Olin College is "*cited by the majority of thought leaders to be the 'current leaders' in engineering education, with other highly-regarded universities including Stanford University, Aalborg University and TU Delft.*" Obviously, not every university has the resources and possibilities for redesigning the entire curriculum and engage companies to fund student design challenges with tens of thousands of dollars per team. It is to be noted that this approach may not be suitable or desirable for all students and/or programs. However, this example shows that it is possible to re-engineer engineering programs.

6.2 Chalmers University of Technology (Sweden)

Another pioneering and leading example for combining entrepreneurship with modern learning environments is currently being realized at Chalmers University of Technology in Gothenburg. Even though Chalmers University of Technology has implemented various strategies for giving all students an entrepreneurial flavor according to the comprehensive concept of entrepreneurship education, a new educational model is currently being developed on campus. The so-called Tracks initiative [33], constituting the biggest investment in the 190-year history of the university, is characterized by a combination of challenge-driven courses, where students work together in teams across programs, and a modern and flexible learning environment. The courses are created as project courses from five different global themes and are being elected by students from different disciplines. The teams comprise different competences, and they thus work across disciplinary boundaries right from the beginning. The learning environment will contain a huge variety of resources such as modern tool chops for all kinds of materials and spaces where students can build and create innovative artifacts but also a media studio and computer resources for machine leaning and artificial intelligence. The purpose is to create and test a new educational model in order to:

- Give students the opportunity to create inter- and cross-disciplinary competencies;
- Meet the students' expectations and need for a more individualized study plan; and
- Shorten the lead times for including new technologies and new materials in curricula.

In addition, as part of the results of a six-year project funded by the KIC EIT Raw Materials on how to integrate the principles of conceive–design–implement–operate (CDIO) into mining engineering curricula [6], a suite of student collaboration projects was launched where students at Chalmers University and the Institute for Advanced Mining Technologies at RWTH Aachen University worked with real-world industry projects from the mining and raw materials industries applying their knowledge and skills in order both to practice to do something of value with their education as well as gaining inspiration for the continuation of their studies [34].

6.3 University College London (UK)

University College London showed that it is possible to implement far-reaching reforms across all engineering programs focusing on design thinking. In 2014, the School of Engineering at University College London (UCL) implemented the Integrated Engineering Program (IEP). At the core of this department-wide curriculum change lies a series of discipline-specific 'scenarios' throughout the first two years, operating in five-week cycles, where students spend four weeks acquiring a range of knowledge and skills that they then apply in a one-week intensive design challenge. These are complemented by a series of cross-disciplinary, team-based projects often framed around themes in social responsibility that bring together students from across the engineering school. At UCL, in addition to the design focus, multidisciplinary learning plays a significant role, reflected in subjects such as Engineering and Public Policy, Tech Journalism, Sustainable Building Design and Connected Systems in undergraduate studies [32].

6.4 University of Copenhagen (UCPH)

A good example for adapting the effectuation approach to an entire (entrepreneurial) course on "entrepreneurship and partnership" comes from the University of Copenhagen (UCPH) in Denmark. In this course, the students have to create partnerships in relation to an actual entrepreneurial project, which could be a cultural project, a social project or starting up a company. The course design is inspired by the insight that entrepreneurship today is much more than management thinking and ideas about economic growth. The course has a clear value creation approach, which includes cultural and social as well as economic value. The learning objectives of the course are defined as 1) knowledge of how to manage communication and knowledge sharing; 2) the ability to think and act creatively and innovatively; and 3) the ability for the students to put themselves and their professional skills into play. The method Open Space is used for group formation and the students' project management is coupled with the underlying approach of effectuation. The lecturers of the course, who act more as sparring partners for the students in this course said about the course that "*we find that students are challenged compared to traditional teaching, but it is also very stimulating for them. We also see that the tension between a practical project and a traditional academic assignment is quite fruitful*" [35].

7 Role of Rooms and Infrastructure in Entrepreneurial Education

As stated in the good practices above, the establishment of entrepreneurial education requires a complete redesign of courses or even of the entire curricula. These redesigns always contain learning elements where the practical application of knowledge and skillsets in design thinking elements toward business creation and active-learning by value creation approaches plays a key role. It is obvious that the utilization of such methods for teaching and self-learning has completely new requirements regarding the usage of rooms and spaces. In classical lecture halls, proper auditorial seating, beamer and/or board are mandatory. The realization of, e.g., effectuation or design thinking methods, business planning or the actual engineering creation process has completely different requirements regarding rooms, spaces and laboratories. Spaces corresponding to the task are not only a necessity but also have a supporting effect on creative and production processes.

Audretsch et al. [36] conducted one of the first studies to examine the link between infrastructure and entrepreneurship. A hypothesis was developed by the authors that start-up activity is enhanced by infrastructure. However, the authors mention that not all types of infrastructure have a homogeneous impact on the entrepreneurial decision. Thus, they developed a second hypothesis indicating that "*certain types of infrastructure which facilitate connectivity and linkages among people are more conducive to startup activity.*"

Academia plus Business (AplusB) centers is an initiative of the Austrian Ministry for Transport, Innovation and Technology and is responsible for encouraging entrepreneurship for higher education institutions. One of the services offered by them is the provision of infrastructure such as laboratories, offices and meeting rooms [37]. The study claims that entrepreneurs cannot develop their businesses within the environment which does not support them [38].

One excellent example, also part of the good practice studies above, for an entrepreneurial supportive environment can be found at the Chalmers University of Technology about their flexible learning environment [33] as part of their so-called Tracks initiative. Large investments in the learning environment were made. The developed environment includes a flexible learning environment where project spaces can be formed. Provided physical and virtual components utilize a high degree of interaction, also with industry partners and other parts of society. The environment also includes a modern workspace, e.g., resources for machine learning and artificial intelligence, as well as labs for prototyping and testing. Further, it includes areas for creative group work and informal working modes.

In summary, it can be said that the there are multiple examples that indicate that infrastructure are not only mandatory but can have a significant effect on the creativity of retain processes and therefore are a key supportive element in entrepreneurial teaching. The stated examples clearly provides environment for the support of the different working modes, meeting the general need for entrepreneurial education. However, there was a lack of examples of such infrastructure or environment and utilization of a supportive environment in the mining engineering discipline.

8 Bringing Entrepreneurship into Mining Engineering

The good practices briefly described earlier in the paper show that changes are underway in the engineering discipline on different levels. In some universities, courses are being adapted to new methods, while in other cases entire programs and curricula are being adapted within a department or even across departments.

However, when it comes to mining engineering in particular, good practices for implementing entrepreneurial education across courses and curricula are still a rare find. One place where a transformation is currently taking place to adapt and transform mining engineering education in a comprehensive approach, is at the Institute for Advanced Mining Technologies (AMT) at RWTH Aachen. This transformation incorporates the establishment of spaces and environment designed for the practical integration of research, education and transfer as enabling component for the establishment of entrepreneurial teaching and learning, not only using theoretical methodological approaches but combining with the physical elements. As basis for bringing entrepreneurship into mining engineering the world's first Learning Factory Mining 4.0, which is currently being established on RWTH Aachen premises can serve as a benchmark project for mining engineering schools.

Following the concept of a Learning Factory for industrial production systems, which has been used in production technology for some years now, the Learning Factory Mining 4.0 is a "hands-on" approach to learning, in which the technological elements of a Mining 4.0 environment are made available in real and/or digital form. This enables a "learning-by-doing" approach, especially in group work, and all "learning types" (auditory, visual, haptic, communicative) can experience the best possible promotion of their skills. Beyond the learning experience, the Learning Factory fosters project driven creative actions, prototyping and testing of new ideas and is an enabling element for the support of entrepreneurial teaching activities that also allows for an active exchange of ideas among students with researchers, industry partners and society due to its shared nature.

The specific characteristic of the Learning Factory is its holistic approach, in which the three pillars of research, teaching and transfer are equally integrated and purpose-oriented innovation spaces are created through the useful and methodical combination of humans, space and technology.

The infrastructure, which is currently under development and construction, will consist of two core elements:

1. Multifunctional, multi-sensory and modular innovation environment as a basic physical element; and

2. Flexible modular teaching and learning elements based on cyber-physical modules with basic engineering and mining specific application modules

Methodologically, the environment is embedded in various teaching activities along the entire curriculum of the study program Sustainable Raw Materials and Energy Supply (BSc) and Mining Engineering (MSc). The majority of courses in this curriculum are project-based and thus offer opportunities to integrate entrepreneurial activities into existing courses and embed the entrepreneurial mindset within the established curriculum. Courses offered by the AMT cover both the engineering fundamentals in mechanics and electrical engineering as well as applied courses and specializations in the field of mining machinery. The initial three semesters focus on the exploratory and curiosity-driven learning through independent practical experiments, while the more advanced courses increasingly focus on project- and innovation-based approaches applied in a capstone project with a high degree of application relevance and real-life orientation.

The aim is to ensure that the future, responsible and competent graduates receive excellent training in the sense of a holistic and modern competence-oriented university education and are thus best prepared for the diverse and complex challenges and tasks in professional life ("Educating engineers, who can engineer"). The AMT Learning Factory Mining 4.0 integrates and combines research and teaching, focusing in particular on the activities related to empathize, define, ideate, prototype and test [39].

As this environment strongly supports and fosters entrepreneurial action levels of “creation” and “value creation” for students and researchers within existing courses and industry-driven research projects, it creates a potential to connect these activities toward “venture creation” and also “sustainable venture creation.” To realize this potential and connect it toward existing venture creation programs, the AMT is part of the activities of the “Excellence Start-up Center.NRW” (ESC.NRW) project, which is currently being established at RWTH Aachen University by its technology transfer institution, RWTH Innovation. ESC.NRW is funded by the state North Rhine-Westphalia and has its focus on the expansion and further development of existing university start-up networks in a regional ecosystem directly connecting to institutes of different faculties in order to increase the start-up potential at universities with strong transfer and research capabilities. The core measures of ESC.NRW include raising awareness of entrepreneurship within the university, qualifying future founders, supporting start-up projects and sustainably integrating the activities in research, teaching, transfer and administration within the university. As part of this project, the AMT is involved in the setup of a theme-oriented incubator in the field of raw materials incorporating activities in mobilization, ideation and incubation of ideas within and for the mining sector. For these activities, the infrastructure of the Learning Factory will play an integral role as it provides a framework and playground for boosting entrepreneurial thinking and mindset and fostering start-up creation based on the potentials created by entrepreneurial education in the respective field. [40]

9 Conclusion

Starting off with an overview of core concepts and definitions as well as classification schemes for entrepreneurial education, this paper intended to show concrete examples for applying these concepts to engineering education and, in particular, to the discipline of mining engineering. It was argued that entrepreneurship education can also be a valuable pedagogical approach to foster the skills and competencies outlined in the CDIO framework.

It is mandatory but not sufficient to redesign the curricula. Entrepreneurial teaching has completely different requirements for teaching, learning and creating environment in comparison with standard lecturing. To fully implement and support the use of innovative methods for entrepreneurial teaching, a redesign toward method supportive environment and spaces is also mandatory to support the different working modes.

Some of the current issues in mining engineering education were discussed to show the necessity of adapting programs and curricula to the changes and transformation affecting the industry at this time. On the one hand, the mining industry is changing through digitalization and automation, changing the job profiles of mining engineers. On the other hand, mining operations have to increasingly accommodate demands from various stakeholders with respect to improving sustainability and maintaining their “social license to operate.” These factors highly impact the future job profiles of mining engineers. One can argue that the pedagogical approach of entrepreneurship education, which places value creation for others at its core, is of particular relevance and importance to future mining engineers if they are to successfully manage and lead the mining operations of the future.

Since practical examples for integrating elements of entrepreneurial education in mining engineering are still a rarity, the emerging Learning Factory Mining 4.0 at RWTH Aachen University was presented as a benchmark project for making much needed changes a reality. Further, this learning environment is also connected to the local development of a Start-Up Center that will facilitate through entrepreneurial teaching programs mobilized students and other entrepreneurs toward “sustainable venture creation.”

In conclusion, it has become clear that students can become highly motivated and engaged by creating value for other people outside the campus by applying the knowledge they acquire and that this can enable deep learning experiences. This not only illustrates the practical relevance of the concepts discussed but also implies the necessity for engineering schools to find ways to adapt. Integrating entrepreneurship education, based on its wider conceptual definition, can help engineering programs to remain attractive to the next generation of students and fulfill their responsibility in preparing them for the demands of their engineering careers in world of accelerated change. The world of mining is undergoing profound transformations and entrepreneurship education can provide the necessary tools and opportunities to enable future mining engineers to successfully ride waves of change in the decades to come.

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