THE CDIO FRAMEWORK AND NEW PERSPECTIVES ON TECHNOLOGICAL INNOVATION

Frido Smulders

Faculty of Industrial Design Engineering, Delft University of Technology

Aldert Kamp

Faculty of Aerospace Engineering, Delft University of Technology

4TU.Centre for Engineering Education
Delft, the Netherlands

Clement Fortin

Space Center
Skolkovo Institute of Science and Technology, Moscow, Russia

ABSTRACT

Technological innovation happens on a daily basis all around us. Yet, in our educational programs there is rarely any attention paid to what this is and how this unfolds over time in real life. This is not at all surprising, since there is not one unified and widely accepted body of knowledge on technological innovation that is grounded enough, meaning, knowledge based on research of technological innovation practice. The CDIO-framework is implicitly addressing innovation from the perspective of existing technological knowledge and therefore is not yet equipped enough for the purpose of tech-innovation. This paper therefore aims to initiate a discussion on what technological innovation is and how this could fit within the CDIO-framework. We will provide a definition of technological innovation based on innovation theoretical framework which reaches its readiness when practice is able to apply the new technology to design, engineer, build, maintain and dispose the objects that apply that particular technology. This lens will be used to analyze a well-documented case that reports on the development of a new structural aircraft material that is now widely used in the Airbus A380, hence a technological innovation. It will be shown in this paper that the research activities that support the development of the new technology, follow the logic of innovating as a generic and natural phenomenon. The paper ends by proposing a possible path to bring the subject of technological innovation within the confines of our educational curricula, without too much cutting on the subjects that we are teaching. Its base comes from the idea that what we are teaching today is the result of a technological innovation process of yesterday.

KEYWORDS

CDIO framework, Engineering education, technological innovation, product innovation

INTRODUCTION

This paper provides an additional perspective on the existing CDIO-framework by explicitly focusing on the innovation of technologies. The CDIO-framework advocates conceive-design-implement-operate as the sequence that brings complex products and systems to life in a collaborative setting of involved disciplines. As such, the CDIO-framework aims to teach engineering students what is necessary to become ‘engineers that can engineer’ in the daily practice of organizations. They need an in-depth working knowledge about their discipline, have interdisciplinary skills and understand the process of conceive-design-implement-operate (e.g. Malmqvist, 2017). This framework for engineering education advocates frequent design-build cycles that include a strong focus on teamwork and interpersonal skills, in addition to the deep technical knowledge belonging to the various disciplines. The CDIO-framework is therefore believed to provide a holistic perspective on engineering education that mimics the engineering profession. A profession that by default forms a crucial partner in technological innovation processes.

The CDIO-sequence covers some innovation processes because the conceive-activity covers customer needs, technology enterprise strategy and conceptual technical & business plans (Malmqvist, 2012). The design-activity covers “plans, drawings and algorithms that describe what will be implemented”, and the implement-activity focuses on the “transformation of the design into the product, process, or system” that during the operate-activity is “delivering the intended value” of complex engineering systems (Malmqvist 2012).

We define innovation as ‘changing an existing environment by the introduction of something new’, which is based on the Latin ‘innovare’ (Smulders, 2015). Innovation ranges from incremental to radical changes. Consider for instance the development and market introduction of a new model vacuum cleaner versus the development and delivery to its first customer of Boeing’s Dreamliner. *Incremental innovations* could be defined as new products that apply existing and proven technology. *Radical innovations* make use of new technologies, cutting edge technologies that just passed the threshold of applicability, reliability and safety. Boeing’s Dreamliner is the first passenger plane where the airframe consists of more than 50% composite materials. A radical innovation that to some extent changes the rule of the game by delivering new features to airlines and passengers. Substantial lower operating costs and less maintenance and for passengers more comfort.

As we will further address in this paper, the example of the new model of a vacuum cleaner is representing a large class of what Smulders (2014) termed single-loop innovations, that is new product ideas with existing technology. Very little changes are necessary to absorb the ‘new’ product or system across the value chain, including manufacturers, suppliers, distributors, sellers and users. The second example then forms a much smaller class of double-loop innovations: a new product idea with a new technology. Double-loop innovating activities require many changes for all involved stakeholders, some of these changes could be very drastic or dramatic as the Dreamliner case showed us (e.g. Shenhar et al., 2016).

It is not clear how the development process of products and systems, and the innovation process of technologies are interrelated. Consider for instance the development of new structural materials for the aerospace industry and how composites ended up in the Dreamliner. The first planes that used composite materials were designed by engineers that carried forward the metallic tradition in their engineering process and applied these to the new class of materials (Potter, 2009). The aircraft manufacturing industry for many years used existing knowledge and norms of metallic (aluminium) structures to design parts from carbon fibre, which resulted in what is called ”black aluminium” parts (Tsai, 1993), parts made from carbon to replace existing components without realizing the full potential of the new material. In this manner engineers for decades were not able to design in such a way that took full advantage from the inherent material properties of composites.

The development and introduction of Boeing's 787 Dreamliner marked the situation that enough new engineering knowledge was developed to create a passenger plane of which more than 50% of the airframe is made out of composite materials. The fact that the 787 is the first plane that made extensive use of composites indicates that engineers and managers had sufficient confidence that enough validated engineering and manufacturing knowledge was available for developing such an innovative plane. The knowledge had been developed and validated over the past decades by engineering scientists and specialized companies, that is, knowledge located within the scientific domain of universities as well within the practical domain of specialized companies. One could say, the technology was then ready for full scale application. In other words, composite technology had reached the required level of maturity (Level 6, Fig 1) of Technology Readiness Level (e.g. Héder, 2017).

For the purpose of this paper, we define technology readiness from a business innovation perspective: Technologies are ready if companies are able to design, engineer, manufacture, operate, maintain and dispose the artefacts that use that particular technology.

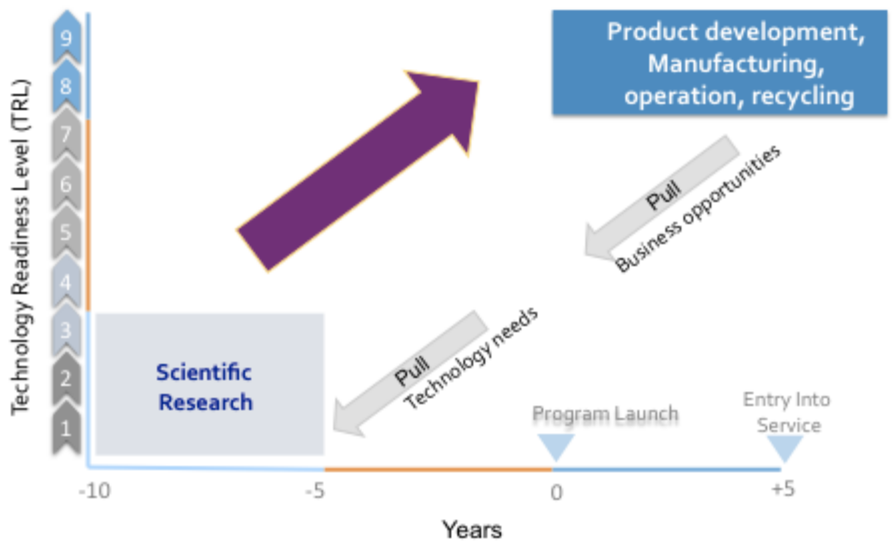

Figure 1: Technology Readiness Levels over time (Fortin).

Back to CDIO: The development of a new vacuum cleaner perfectly fits the CDIO-framework. The case of the Dreamliner at first glance, also fits the CDIO-framework, conceive the new plane, design the new plane, implement the design by using existing disciplinary knowledge and operate the plane. Apart from the fact that the project ended up costing double the planned costs, if not quadruple, and being overdue in delivery of the first plane by 40 months, it is a wonderful example of applied new technology. The question is however, who were responsible for the development of the new knowledge underpinning the new composite technology? Of course, these were engineers, researchers and managers! Whether they worked in science or in practice, engineers focused their development efforts over a long period to bring composite technology to its readiness as we have defined above at Level 6.

This brings us to the core question in this paper: if engineers are responsible for developing new technological knowledge, where do we teach it in the engineering curricula, and must it be at the Bachelor, Master or PhD level? And how does it relate to the CDIO-framework? A paper by Crawley, Edström and Stanko (2013) discusses the Skoltech initiative in Russia. A so-called 'green field' university that is built from scratch. Skoltech's curricula are explicitly aimed at enhancing technological entrepreneurship and innovation. Integrating CDIO-based education, cutting edge research and application forms the base for Skoltech's innovative challenge. It is Skoltech's mission to "… bridge the gap between fundamental science and innovation, to become transformative members of society …" (Skoltech website), hence we should be able to teach the process of technological innovation to our engineering students. In line with the initiative in that paper, we will discuss technological innovation at a more theoretical level that aims to connect CDIO with recent developments in the field of innovation sciences.

Most engineering programs predominantly teach existing validated engineering knowledge. And yet, the design-build projects that are part of their curricula, focus on the application of existing engineering knowledge, not on the development of new technologies, that is, technological innovation. Of course, students must learn first to develop from well-established knowledge; and then at the graduate level, the focus could be applied more on technological innovation, like the initiative of Skoltech.

Over the past decades, there has been an unprecedented growth of new technologies that reached application thresholds and were subsequently spread of the world on the wave of globalization. But, major societal challenges on energy transition, food development and sustainable growth and development require rapid, trustworthy and robust development of new technologies. Future engineers simply cannot afford to develop new technologies that take too much time, fail once these are introduced in practice and cause unexpected side effects on the long run. What 'corporate social responsibility' is for companies, is 'technological societal responsibility' for the engineer. Of course, the engineering codes come with the engineering education, but seen from the challenges society (and the world) is facing, these codes might not be sufficient if our engineers are not sufficiently aware of innovation processes or know how to develop new technologies fast and in rigours manners. Therefore, 'technological societal responsibility' is not limited to technology only.

We see this paper as a means to initiate a discussion on this subject in relation with the existing CDIO-framework. The paper discusses the innovation process of technology from an innovation perspective. First, we introduce a recent perspective on innovation in terms of the IDER-framework, which positions design and engineering apart from each other yet, symbiotically related. This framework serves as a lens to explain what has happened during the development and application of a new class of aircraft materials. Then we connect the CDIO-framework with the IDER-framework and discuss what both frameworks could do for future engineering education and especially for teaching technological innovation.

THE IDER-FRAMEWORK

This section describes the IDER-framework as a generic framework that could be seen as representative for a basic innovation cycle (Smulders, 2014). It refers to the verb of innovating that was defined earlier as 'changing an existing environment by the introduction of something new'. The IDER-framework is derived from the literature on product innovation, which, in line with the definition of innovating, describes a process of changing an existing market environment by the introduction of a new product. The product innovation model presented by Roozenburg & Eekels (1995) served as the base for the IDER-framework that was developed by Smulders, Dorst & Vermaas (2014). The increasing popularity of design thinking formed the motive for these authors to investigate the role of design methods and tools in contexts beyond its traditional application within product development. This led them to set the ‘design’ activity apart from the ‘engineering’ activity and discuss the respective contributions to the product innovation process and by doing this, identify their interrelations. From this core of product innovation, that is, the development of the product, they added the early and final activities to arrive at full-fledged innovation perspective in abstracted terms, the IDER-framework (Smulders et al., 2014).

The framework reads as follows. The first element ‘I’ of *initiating* covers the front end of product development by, for instance, market research and/or ethnographic studies. The second element D of *designing* concerns the development of concepts of the new product or service. The third element E covers the *engineering* and embodiment of the artifact and the associated development of the necessary manufacturing processes and tools. Engineering aims to validate and consolidate what comes out of the D element and to prepare that content for implementation in the totality of the R element. The fourth *realizing* element R aims at inserting ‘life’ in the value chain, that is, ramping up all activities associated with, e.g., purchasing, logistics, production, sales and use of the new product. The R-element is to be seen as a new or adapted socio-technical reality in which actors perform their value adding activities which includes the use of the new product. This situation marks the end of the innovation-cycle (and possibly the beginning of a new one). The four sequentially dependent sets of innovating activities all belong to the overall cycle of innovating as defined here, meaning, the combined activities are all aimed at changing an existing environment by introducing something new within that environment, hence, innovating (Smulders et al., 2014).

By default, the literature on product innovation focuses on the product and its directly related elements like product strategy, marketing, manufacturing and user experiences. Looking from the perspective of the ‘total product’, Smulders (2014) realized that the abstracted framework provides interesting footholds for generalization. The total product includes all elements that add in one way or the other value to the operational chain. Thus, beyond the actors that are directly involved with the product, there are many other actors that need to go through some sort of development cycle to prepare their contribution to fit into the overall operational activities. Such could include parts suppliers, purchasing actors, distribution and sales people, maintenance people, users, etc.

Just to illustrate, think of the department of legal affairs that details the contract with a new supplier, which is very similar to what engineers do when they detail components of the product and decide upon tolerances. And like product development, also contract development first goes to a similar cycle of ‘initiation’ to look for suitable suppliers, ‘design’ to discuss the ins and outs of what will be supplied at what time and in what quantity and quality, its guiding principle so to say. This conceptual base of the contract ends on the desks of legal department. And such changing and adapting to absorb the ’new’ counts for the totality of the social-technical system that is related to the product. In other words, all knowledge necessary for enactment in the R-element becomes available from the knowledge creation activities of all the former activities, meaning all affected objects will have their own IDER-cycle. Retracing upstream in the IDER-cycle, each affected object forms an innovation activity on its own, in coherence with its direct (and indirect …) environment. If the E-element delivers the robust knowledge for its realization within the R-element, then the D-element delivers the solution for its guiding principle, the principle for or architecture of the solution which in its turn is the conceptual predecessor of its whole. The I-element then is responsible for investigating the need and scoping the size of the upcoming development cycle. Cycles are initiated by some kind of surprise (Schön, 1984), doubtful situation (Dewey, 1938), anomaly, serendipitous insights, undetermined situations, troubling observation or strategic wish. The reasoning portrait here points to the universality of the separate IDER-activities that subsequently spread all over the full length of the project as Figure 2 aims to illustrate. This observation makes the activities covered by the IDER-framework heterogeneous and applicable at any level and to any socio-technical object. It is suggested to be a 'process-within-similar process' that follows the metaphor of the nested doll, i.e. the matryoshka principle (Smulders, 2015).

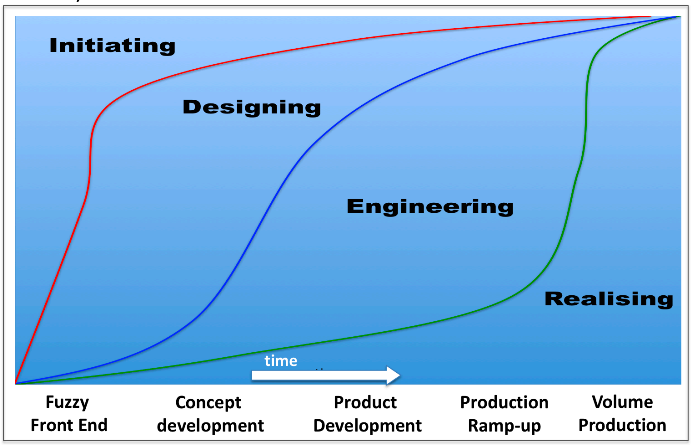

Figure 2: Schematic representation of IDER-elements over duration of innovation cycle. The vertical axis stands for total activities spend in the project, 0-100%, at each cross-section.

Over time and towards the end of the overall innovation cycle less and less objects need to go through IDER-cycles as Figure 1 illustrates. At the same time, more and more knowledge and content ends up in operational processes that progress towards their final performative state. The IDER-framework serves as a lens to analyze the technology innovation process and draw lessons towards educating our future engineers.

CASE: TECHNOLOGICAL INNOVATION

Technological innovation as we have seen in the introduction is posing interesting challenges to the innovating actors. As a reminder, we defined technology by its readiness for application which meant that the innovating actors are able to design, engineer, manufacture, operate, maintain and dispose the artefacts that use the technology. In this section, we will use the IDER-framework to discuss the development of new technologies, something we think should become part of our engineering curricula. For this purpose, we refer to a well-documented case on the development and industrial application of a new class of aircraft materials, Fibre Metal Laminates (FML) (e.g., Berends et al. 2011; Schijve 1993; Van Burg et al. 2008; Van Hengel & Kortbeek 2009; Vermeeren 2003; Vlot 2001). The data for the case study was partially collected during a three-year participation (1985-1988) of the first author in two roles: MSc-researcher Aerospace Engineering at Delft and application researcher within the confines of one of the participating companies (Alcoa). Other data came from the many publications that report on this project and irregular observations and discussions by the author with the innovating actors over the period 1989-2005.

Case narrative

The case concerns the development of an entirely new structural material for airplanes. The development of ARALL (Aramid (= Kevlar) Reinforced Aluminum Laminate) in the early 80's and GLARE (Glass Reinforced Aluminum Laminate) starting in the late 80's until its application in the fuselage of Airbus A380, beginning of this century. These two materials form the first sets belonging to new class of materials that combine the properties of aluminum with those from composites. They increase fatigue resistance of metal sheet materials. After discovery of ARALL (in the D-element of the IDER-cycle) and the early positive test results it was decided to develop the material and prepare it for the market through a certification program. The tests aimed to move into the E-element and the initial successes caused a further move towards the R-element with certification programs and production process development cycles. Positive results of the material tests with the first generation fibre material and the development of feasible production methods led to promising contacts with aircraft manufacturers. At that moment the solution principle of fibres for the new material slowly got frozen, marking the transition from D-dominated development work to E-dominated development work. The project proceeded as foreseen, until in the mid-eighties problematic issues started to surface: fibre failure and fatigue cracks under loading conditions of a fuselage, one of the most promising application areas. It was an indication that either test methods were not adequate, or the fibre metal laminate material concept itself. It proved to be both! Figure 2 illustrates the changeover of activities initiated by the surprise of fibre failure.

The 'surprise' initiated a series of research projects that had to uncover the mechanism of fibre failure. Each of these projects was a small IDER-cycle on its own, where the R of the preceding research formed the I of the next research (Smulders 2014). Ultimately and by the extensive use of microscopic investigations the complex fibre failure mechanism was uncovered (Smulders, 1988). It led to yet another doubtful situation regarding the composition of the fibre material and its application in aircraft fuselages. In parallel a first industrial application of the fibre metal laminate for the cargo door of a military air lifter looked promising at first. But after the first series of doors it was realized that from economic perspective applying ARALL was not the right solution at all. The manufacturing of the panels turned out to be far too labour intensive and costly to make up for its advantages in weight, inspection and maintenance savings. The design and engineering of the production system for these doors had been based on metal philosophy Clearly there had been not enough E-Knowledge available at that time to 'engineer', including production and assembly - this new class of materials in an optimal sense.

The above doubtful situations resulted in new IDER cycles. The new insights initiated development processes that challenged some fundamental assumptions regarding the principle of the fibre material, its D-solution so to say. At the outset, it was assumed that applying the lightest suitable fibres would be most advantageous, but microscopic research after the failures revealed that it had not been a good choice at all (Smulders 1988). This observation gave the material designers requirements to look for different class of (glass) fibres that seemed to better fulfill the requirements, although these were somewhat heavier than aramid. There was an iteration back to the D-element by opening up the seemingly frozen fibre concept and redo all the D, E and R activities that had already been done for ARALL. The result was GLARE, the second generation of fibre metal laminates. The deeper theoretical understanding of the fibre metal laminate culminated in a much more focused GLARE Technology Development program incorporating a different attitude and approach

(Gunnink et al., 2003). It included adaptations of design and, manufacturing methods and a review of maintenance approaches: It was for instance discovered that conventional maintenance and repair methods that were based on metal (D-element) proved to be adequate. This prevented aircraft operators to spend scarce resources on the development and validation of entirely new maintenance methods.

The application of GLARE as dominant structural material for the skin of the fuselage of the mega plane of Airbus, the A380, shows that this time the innovating actors were better equipped to prevent costly iterations as had happened around ARALL.

The above scenario also shows that the social structure of innovating actors is far more complex than just the actors within one organization. The knowledge developed in interrelated IDER-cycles by many different actors across many different organizations resulted in a new socio-technical system of integrated knowledge elements that provided a robust base for initiating, designing, engineering and realizing new FML applications (Van Burg et al. 2008), hence, a new technology as defined above was born.

Case analysis: Technology Development

The development of the new fibre-technology, as represented in Figure 3, experienced an unexpected iteration regarding its core principle: the fibre chosen. From the perspective of the IDER-framework, one could say that an additional technological research cycle was needed to develop the new E-knowledge specifically for this new class.

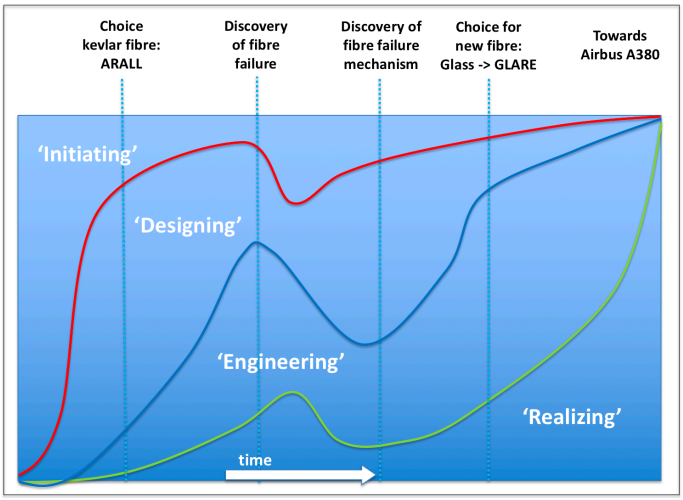

Figure 3: Schematic representation of the iterative trajectory developing FML-technology

What exactly constitutes E-knowledge and how does this come about? One could describe the notion of E-knowledge as follows: E-knowledge allows the user to design and engineer new products within the confines of a given and validated body of knowledge covering the field of that particular class of products. This is what most engineering curricula teach: how to design and engineer products related to a certain disciplinary class of products (bridges, dikes, ships, planes, etc.). Let's have a quick look at what scientific research within the engineering sciences actually aims to achieve. Scientific researchers, as discussed by De Groot (1994), Dorst (2008) and others, embark on activities that, roughly, follow the sequence: observe, describe, understand, explain, predict and prescribe, hence validated engineering knowledge. Figure 4 provides a schematic overview of this sequence from left to right (Smulders & De Bont, 2013).

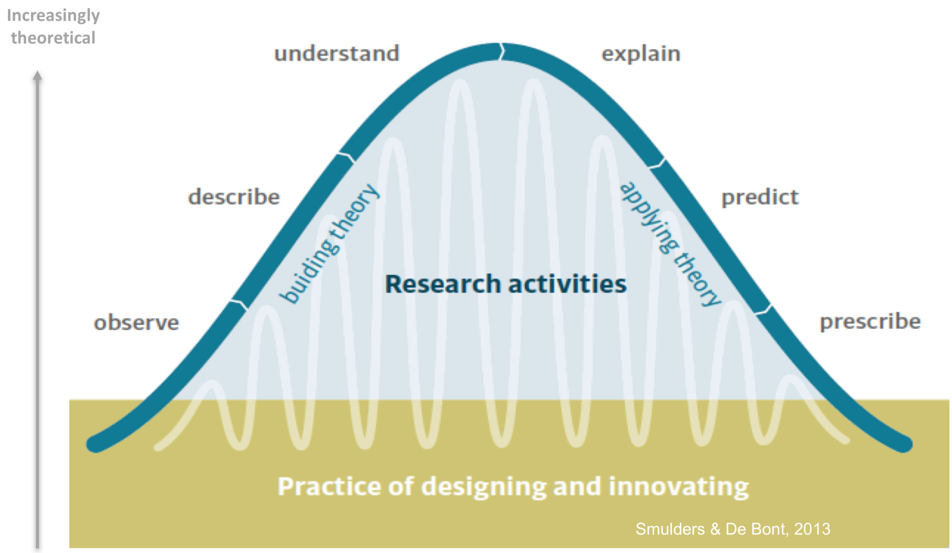

Figure 4: Schematic representation of the empirical trajectory of science (Smulders & De Bont, 2013)

The research activities aim to form theoretical explanations of real world phenomena and, based on these, developing methods and tools that are of value to those applying them in society, business, or engineering. For instance, scientific research in a lot of the engineering fields has resulted in handbooks with methods for dike design, aircraft design, bridge design, et cetera that prescribe (right side) the way these objects should be designed and engineered. These handbooks provide prescriptions like, ‘if you are in situation x then do y for resolution’. In Figure 4, the research activities on the left side of the curve have a fundamental orientation, whereas the research activities on the right have an applied orientation. In general, on the left side the aim is to build theories and on the right side to test and apply them. Depending on goals and situational factors, researchers choose a suitable research approach from a large array of research methods. For instance, the situation of fibre failure was not ‘predicted’ as such and could not be ‘explained’ by the existing theories in the field. Such required a more fundamental and ‘grounded approach’ that followed the trajectory of observing, describing, understanding towards explaining the phenomenon of fibre failure. Once this was explicit, predictive experiments could be performed to prove the mechanism (Smulders, 1988). The changeover from aramid to glass fibres then pushed the research activities - for the second time – to the right side of the curve. The trajectory of technology development. Like that for the fibre metal laminate materials, typically aims to arrive at the right side of the curve where the new E-knowledge has been transformed into predictive and prescriptive forms.

The relation between the IDER-framework and the research perspective is explained as follows. The I-element typically is closely related to the curiosity of the researcher or to similar things as described above, surprises, anomalies, etc. In the case of technology development, it is the need for developing new robust E-knowledge. The D-element then covers the choice for the right research approach and depends on the research question. The E-element is formed by the application of the existing research methodology in order to arrive at falsifiable research results. The resulting conclusions are to be seen as new knowledge that belong to the R-element and possibly bear thoughts that initiate a subsequent research cycle. In recap, over the course of the full trajectory of the new fibre-metal technology development, many smaller and larger IDER-cycles delivered new knowledge, insights and formulas, that in total resulted in the new technology, validated to the standards in aviation and therefore crossed the threshold of applicability in the Airbus A380. All the individual research and development projects are to be seen as innovation cycles that each follow the IDER-sequence and contribute to the overall innovation cycle. This brings us to the final section in which we compare CDIO framework with the IDER-framework to arrive at some thoughts for the future of engineering education that could include technological innovation.

HOW TO EDUCATE FOR TECHNOLOGICAL INNOVATION: IDER & CDIO?

How do the CDIO and IDER frameworks contribute to engineering education for the case of teaching the fundamentals of technological innovation? Let's first reflect on what we have seen so far. Initially we defined technological innovation by its readiness for application in business. Based on what we have seen in this paper we could go one step further and define the verb not just its end result: innovating for new technologies. From this perspective, single-loop innovating concerns the realization of new (class of) products with the use of an existing body of E-knowledge. The development of new technologies for a new class of products is then to be regarded as a double-loop innovating process: the first loop concerns the new class of products and the second loop concerns the new E-knowledge that is required to bring the new class of products to live (Smulders, 2014). Although Smulders sees innovating as situational, which means that discriminating between these forms of innovating must be seen from the perspective of the actual innovator, within this paper we take a more aggregated perspective at the level of the actors within the technology development process. All innovating actors in coherence with each other go through a double-loop innovating process, whereas the individuals might be involved in a single- or double-loop innovating activity. It depends on their personal situation and context.

And so, the verb of technological innovating covers the series of development activities that aim to create a new or adapted body of (E-) knowledge that allows the users to deploy such for the purpose of initiating, designing, engineering and realizing new objects within a new class of objects. The development of a new technology is a double-loop innovating process that is followed by a longer series of single-loop innovating processes that create new objects within the confines of that particular technological body of knowledge.

Apart from some semantic issues, both frameworks seem to support the single-loop innovating activities. Remains the question, how could these frameworks contribute to the development of a new body of E-knowledge? We have described the relationship between IDER-framework and the research activities that aim to develop new E-knowledge. It shouldn't be too difficult to use the CDIO-framework for the same purpose, however, that would require a similar abstracted perspective on the constituting CDIO-elements.

Let us return to the first paper on the IDER-framework by Smulders et al (2014). Since they were interested in the application of the D-element beyond its traditional domain, they also addressed the socio-interactive dimension among the elements. Issues like transfer of knowledge and insights from one group of actors to another sequentially dependent group, for instance from actors dominantly working on D-like activities to actors with an E-dominance. Scientific work on the socio-interactive dimension finds itself still on the left side of the science model (Figure 4), whereas the engineering sciences of existing technologies have reached the prescriptive state on the far-right side. Setting these thoughts apart for a minute, the interesting observation here is, that starting from the IDER-framework rooted in innovation sciences, we were able to go beyond the CDIO-framework to initiate a discussion on technological innovation. The perspective on technological innovation as introduced here shows that both frameworks seem to cover in abstracted sense a generic and cyclic process of developing new objects, either through practical development activities, through fundamental research cycles or in a Deweyan sense through both, combining deep specialized practice with deep fundamental science (e.g. Stompff, 2012). This brings us back to the question: how can we apply these insights for educational purposes?

It is not realistic to build dedicated educational programs that let engineering students experience what it is like to develop new technologies. But, at present we only teach them the scientifically validated technologies and let them, by means of the CDIO ideas, experience how to apply these in multi-disciplinary settings. What should we teach them to experience or learn about the process of technological innovation?

What we are teaching today is actually the result of a technological innovation process in the past. The existing technologies similarly will have gone through many iterative cycles of trial and error, in both domains, science and practice and with the involvement and contributions of many disciplines and stakeholders. Uncovering the history of the technological innovating activities through the lens of a suitable innovation framework (CDIO, IDER, Dewey, others) and integrated within a socio-interactive lens. Not storytelling on facts and dates, but as a technological innovation narrative using a dedicated vocabulary that spans the full width of what has happened, yet is generic enough to be applicable for all technological innovation processes. Paying explicit attention to the perspective of the involved innovating actors will bring the story to life. What troubles did they encounter? What assumptions were needed to go and how was did accepted? How did they conquer resistance to change? Basically, building a case through an innovation theoretical lens combined with a socio-interactive lens. The didactic form in which this could be taught is yet another challenge. The full range of didactics opens up here, ranging from mini projects to serious gaming, from making a movie based on the narrative to creating a new narrative on tech-innovation of not too complicated technology.

REFERENCES

Berends, H., Van Burg, E., and Van Raaij, E.M. (2011). Contacts and Contracts: Cross-Level Network Dynamics in the Development of an Aircraft Material. *Organization Science*, Vol 22(4), pp. 940-960.

Crawley, E.F., Edström, K., and Stanko, T. (2013). Educating engineers for research-based innovation-creating the learning outcomes framework. *Proceedings of the 9th International CDIO Conference,* Massachusetts Institute of Technology and Harvard School of Engineering and Applied Sciences, Cambridge, Massachusetts, June 9-13.

Héder, M. (2017). From NASA to EU: the evolution of the TRL scale in Public Sector Innovation, *The Innovation Journal: The Public Sector Innovation Journal,* Volume 22(2), 2017, article 3.

Marissen, R. (1988), *Fatigue Crack Growth in Arall, a Hybrid Aluminium-Aramid Composite Material*, PhD-thesis, Delft, Delft University of Technology.

Potter K.D. (2009), Achieving low variability, rework and scrap rates in the production of advanced composite parts, *SEICO09, SAMPE Europe 30th*, 265-270.

Roebroeks, G. (1991), *Towards Glare. The development of a fatigue insensitive and damage tolerant aircraft material.* PhD thesis, Delft, Delft University of Technology.

Shenhar, A.J., Holzmann, V., Melamed, B., & Zhao, Y. (2016). The Challenge of Innovation in Highly Complex Projects: What Can We Learn from Boeing's Dreamliner Experience? *Project Management Journal,* 47(2), 62-78.

Smulders, F.E. (1988), *Fibre failure mechanisms in ARALL laminates*, Unpublished MSc-thesis, Delft University of Technology.

Smulders, F.E. (2014). The IDER-model: Towards a vocabulary to describe innovating. *Proceedings of the 15th International CINet (Continuous Innovation Network) Conference,* Budapest, Bulgaria, September 2014, 815-831.

Smulders, F.E. (2015). Heterogeneous designing & engineering: Antecedents and indicators to innovativeness. *Proceedings of the 16th International CINet (Continuous Innovation Network) Conference,* Stockholm, Sweden, September 2015, 880-890.

Smulders, F.E. (2017). Heterogeneous engineering: Essential bridge implementing creative design. *International Conference on Engineering Design (ICED).* University of British Columbia, Vancouver (Canada).

Smulders, F. & De Bont, C. (2013). Design research: purpose, dynamics and progress. In C. de Bont, F. Smulders, R. Schifferstein, M. van der Voort & E. den Ouden (Eds.), *Advanced design methods for successful innovation*, Design United, 211-235.

Smulders, F., Dorst, K., & Vermaas, P. (2014). On applying Design Thinking elsewhere: Organizational context matters. *Proceedings of the Academic Design Management Conference*, London, Sept 2014, 2798-2817.

Stompff, G. (2012). *Facilitating Team Cognition. How designers mirror what NPD teams do***.** PhD thesis, Delft, Delft University of Technology.

Tsai, S. W. (1993). Rules of Composites Design: a Review. In Metal Matrix Composites: Proceedings of the Ninth International Conference on Composite Materials (ICCM/9), Madrid, 12-16 July, 1993 (Vol. 1). Woodhead Publishing.

Van Burg, E., Van Raaij, E. and Berends, H. (2008), The fibres that hold an innovation network:1 an analysis of knowledge sharing in the Glare network. In A,P. de Man (ed.), *Knowledge management and innovation in networks*, Edward Elgar, Cheltenham, UK: 145-173.

Vermeeren, C.A.J.R. (2003), 'An historic overview of the development of Fibre Metal Laminates', *Applied Composite Materials*, 10, 189–205.

Vlot, A. (2001), Glare. *History of the development of a new aircraft material*. Dordrecht, Kluwer Academic Publishers.

BIOGRAPHICAL INFORMATION

Frido Smulders, PhD. is Associate Professor, Design Innovation & Entrepreneurship at the School of Industrial Design Engineering of Delft University of Technology. In addition, he is TU Delft Educational Fellow. He holds a PhD in Innovation Sciences at Delft and BSc & MSc degrees in Aerospace Engineering also from Delft. His MSc-research in the material sciences resulted in Glare, the material now applied in the fuselage of Airbus A380. His present research focuses on the phenomenon of innovation and more recently also on the related topic of entrepreneurship. He has an almost utopian aim to uncover the fundamental building blocks/molecules of what (technological) innovating really is. He has authored and co-authored 80+ articles and book chapters including some publications in the field of education. His career in business prior to rejoining academia spans from concept engineer in the Offshore Industry (SBM Offshore) to materials specialist in Aerospace Industry (Alcoa), and many years as a management consultant in the field of innovation and technology.

Aldert Kamp is the Director of Education for TU Delft Faculty of Aerospace Engineering since 2007 and Co-director of the CDIO-initiative. He is deeply involved in the rethinking of higher engineering education with a horizon of 2030. More than 20 years of industrial experience in space systems engineering, 15 years of academic teaching, educational management and leadership, and an in-depth study of trends in society, engineering and higher engineering education, have given him good insight in the competencies engineering students need at graduation for a successful career in the rapidly changing world. He is the author of the report “Engineering Education in a Rapidly Changing World – Rethinking the Vision for Higher Engineering Education” and fervent blogger about “Adapting Engineering Education to Change”.

Clement Fortin is Interim Provost and Dean of Faculty and Post-doctoral Affairs at Skoltech in Moscow. His current research interests focuses on concurrent system and product development and their integration with technology development and PLM systems. At Skoltech, he is also working on the further development of the CDIO principles to the graduate studies level.

Corresponding author

Dr. Frido Smulders
Delft University of Technology
15 Landbergstraat
Delft, 2628CE, The Netherlands
31-614-325-265
f.e.h.m.smulders@tudelft.nl