INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
8 & 9 SEPTEMBER 2016, AALBORG UNIVERSITY, DENMARK

TRIPLE-LOOP-LEARNING: AN INSTRUMENTATION MODEL FOR ENGINEERING DESIGN INNOVATION EDUCATION

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ABSTRACT
This paper presents a framework for engineering design innovation education. This is discovery research in a purely qualitative sense. The authors, both highly experienced educators, are reflecting upon their practice of delivering team-based new product development courses at the master's degree level at deeply different universities in Sweden and the United States of America. In both cases, industry partners bring real-world projects and funding to the curricula. They have, as their primary objective, the development of talented new product development leaders. In both cases there is no intellectual property attachment to the funding. This paper seeks to make important distinctions about common language and practices within different regional and academic cultures. We are hopeful that our observations and the presented framework will draw others to deepen our understanding through next generation quantitative studies.

Keywords: Innovation, course instrumentation, learning elements, project-based learning.

1 WHY ARE WE DOING THIS?

Creating and implementing innovation in an academic context is not easy. This paper outlines a learning instrumentation strategy that has successfully overcome academic obstacles to innovation. The engineering education literature is replete with storied attempts and notable failures. Innovation in engineering education research juxtaposes insights from the learning sciences versus practices by faculty peers in engineering. Crossing disciplinary boundaries is always risky. Our experiences suggest ways to delineate the risks and opportunities of important steps needed to take. Based on previous research [1], innovation in engineering education binds together authentic practices with forms of evidence based approaches to change. From a teacher's perspective such change is only possible if the value of adopting new practices is positively impacting student learning.

Amongst our peer faculty shared strains of research lead to widely different implementations. For example, drivers for change stem from individuals succeed differently of the impact of change due to shifting circumstances [2][3]. To approach innovation at similar level is therefore very context dependent. In our scenario curriculum innovation is dependent on both the faculty and student sides of the equation. Recent research frames thinking and beliefs about problem solving as emergent and heavily dependent on implementation processes, e.g. [4][5]. Curriculum innovators need to increase the transparency of their intentions and values, not just their methods. Previous research states that engineering education addresses how critical the building blocks of learning are to support value over time as a practicing engineer [6][7]. In summary, as changes occurs even more frequently today than before we are destined to search for influences that can help instrumenting the learners. It is our goal to explore and define what we label as learning elements that can promote innovation and support re-design of curriculum activities. On a higher level our goal is to influence courses across the engineering education spectrum to release student creativity and increase the probability of innovation.

2 WHAT WE HAVE DONE?

The paper is built on 5-years of longitudinal observation in two project-based learning (PBL) courses. One course is given at the KTH Royal Institute of Technology Stockholm and the other at Stanford University. In both cases the courses are given within the departments of mechanical engineering at the masters' level. During these 5-years the instructors have shared practices, literature, and point-of-views on innovation in engineering design education together with dissertations [8] as basis for input. We witness that within the different contexts our students face distinctly different challenges (contextually) when dealing with largely the same assignments. In both programs the emphasis is on new product development for future markets and new business models. We invite the reader to expect a discovery-research position paper versus a hypothesis testing data set. A key reason for this is the reflective and retrospective nature of the paper addressing insights from past research studies made.

3 WHAT CONSTITUTES INNOVATION IN ENGINEERING DESIGN EDUCATION?

Innovation in engineering education has become the driving theme of many conferences across the discipline. As recently as 2007 [9] only considered innovation to be "an emerging contemporary theme". Notably, innovation has been difficult to trace from program-level discussions down to individual course elements. Typically, innovation is discussed indirectly as a concept, something that "includes a deep conceptual understanding of fundamentals, the skills to exploit ideas, and a sense of self-empowerment from learning" [9]. If action towards innovation is to take place, curriculum re-design is a necessity. Both the rationale for change and instrumentation for measuring impact must be in place [4]. Therefore, instrumentation is a necessity for systematic innovation. One respected instrument is *reflective practice* [10], as captured within student documentation of their projects. This builds on the foundational work of Kolb, [11]. Reflective practices and learning loops are dealt with differently depending on the context in which they are occurring. Research shows that different stakeholder objectives influences how reflection and learning is established [12]. This means that a challenge provider's objectives have major influence on the nature of new product development and the strategy for how innovation is approached.

Building on literature that emphasis reflective character, e.g. [10][13][14] this paper stresses learning-in-action, doing, and knowledge applied. Our focus on reflective practice and introspection aims to move beyond learning the facts to understanding the meaning of data and experience. To approach the complexity of engineering design innovation education attention is put at the systematic structures as the means for implementing change. Learning elements of outcome-based innovation and problem-solving capabilities have altered our approach and forced continuous exploration. Our courses are in a continual state of re-design [15], a fact that further complicates the notion of *controlled studies*. Previous research [4][5] forces us to challenge our beliefs about what engineering education should be and accomplish for our students.

4 WHAT WE HAVE LEARNED?

The way context influences the learning process may dramatically shift in-between geographical locations. Based on ethnographic studies designer behaviour at different locations express only modest cultural differences. Following the pattern of differences presented in cases from in Palo Alto, California, USA; Shanghai, China; and Munich, Germany there were notable differences in the behaviour and needs of the challenge providers in these three regions. We found a related effect when comparing our PBL courses in Stockholm to Palo Alto. In relation to how Hinds et al. [12] denote stakeholder influence to the innovation process, we found evidence that the clients in different regions held deeply different expectations for what they needed. For example, clients in Munich sought "precision innovation" while clients in Palo Alto sought "break-through innovation." Regional differences like these were found in our courses. In Stockholm, students expect to take a career long position in a large, well established company. In Palo Alto the notion of doing a start-up is a viral expectation. Does the same learning experience work for both expectation scenarios?

Our findings show that students are more focused (in a linear sense) when engaged in a clearly delineated learning objective. At the same time, missions with ambiguous outcome requirements fostered creativity and discovery. Linear experiences were "comfortable" while discovery experiences were "stressfully-exhilarating". It was found that by adopting learning elements that challenge existing paths of action, a set of key course characteristics emerged as learning accelerators, including learning things that neither the student nor instructor had anticipated. Reality was the guide, not the text-book.

We find that the triple-loop-learning model (Figure 1) is observable and potentially quantifiable in both courses. We are keenly aware that students and faculty understand the model differently according to regional culture differences. In this representation the focus is on feedback paths that should inform the project team's awareness of their own work-flow. The pathways include: 1) design team activity **observation**; 2) technical progress in **action**; and 3) **reflection** on the impact of process (human variables) and product (technical) variables within shifting global market, manufacturing, and distribution variables.

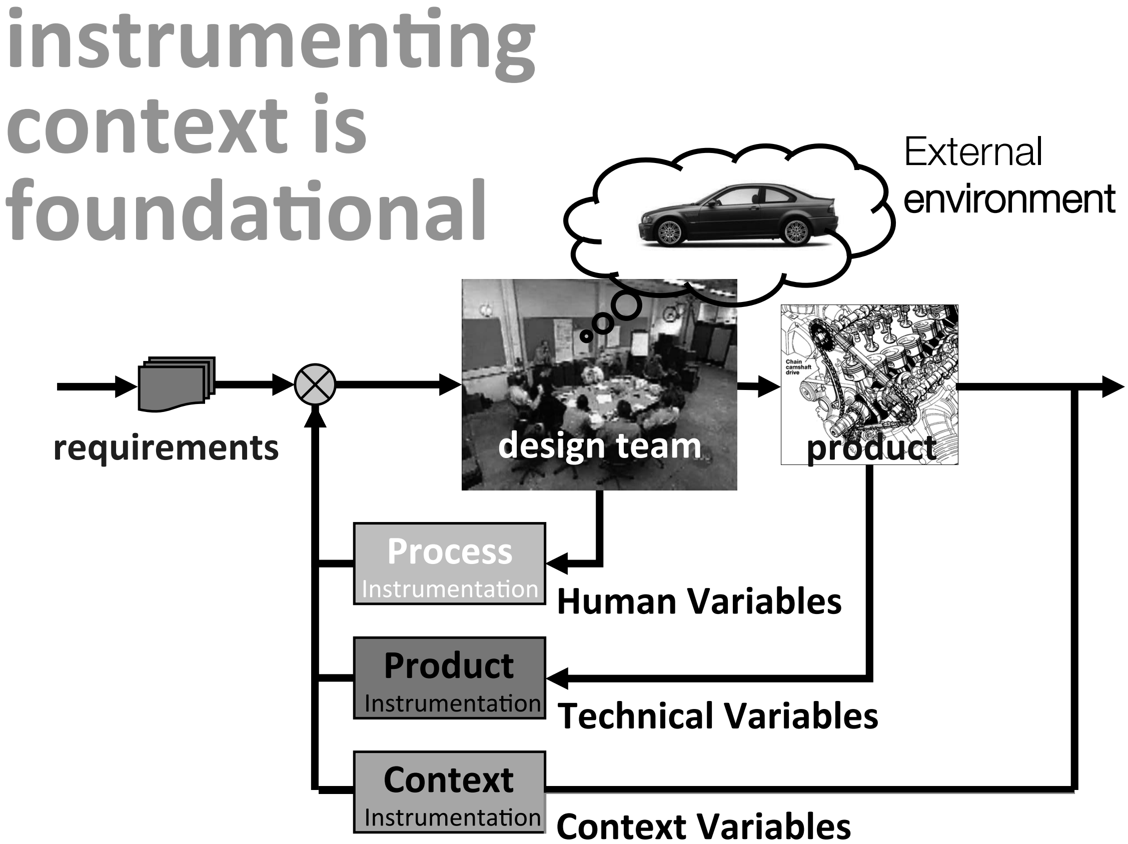

Figure 1. The Context-based triple-loop-learning model

In use of a control system metaphor "product" variables are now emphasized by focus to the human variables (Figure 1). Within the past 5 years the impact and importance of context variables has forced continuous re-design for all three instrumentation feedback loops. This make all design encounters highly responsive for new learning and insights as context influence is accelerated by team level interaction and technical expertise.

Innovation in engineering education does not need to be complex or difficult. It is important for educators to push forward elements that make abstract concepts accessible to pragmatic hands-on exploration. This paper builds on the experience of how enabling learning formats for innovation is matched through a practice-oriented and human-centric approach. Providing a systems perspective the triple-loop learning model is simultaneously attentive to technical, behavioural and context variables. These variables must also be present in the curriculum implementation environment. Designing environments conducive to learning through discovery while engaged in an externally defined problem challenge is inherently scary and invigorating. New ways of thinking are required at the individual and team level. In many cases the teaching team must also be learning and adapting in near real time. Learning about innovation in engineering education can be served by three guiding questions:

- *How might we augment idea generation and prototyping activity that could triggers innovation beyond simply educating engineers?*
- *How might we bring individually educated students together as teams whose tangible collective innovation potential is greater than the sum of their intelligence and knowledge to date?*

- *How might our radical curriculum experiments be integrated with current curricula to better mature the thought and practice skills of the intent-to-innovate mind-set?*

Apart from the students' personal motivations, educators face the challenge of providing a setting that allows for diversity in, for example, technologies, opportunities, and perspectives. The importance of a systematic approach, planning efforts, and freedom that allows iterative testing and debriefs should be appreciated. The emphasis is on facilitating environmental issues so as to ensure improvements in students' intrinsic and extrinsic motivations while also allowing them to face continual challenges. Acting in such a setting, students are challenged to explore, test and refine. Students should be able to adopt an open approach to engage in distinct disciplinary challenges as well as by developing the "intra", lateral way that they reason with peers and colleagues. Distinct learning elements constitute a basis for sharing accepted beliefs and new knowledge and for making them functional. Our findings suggest a range of inputs in which perspectives and needs are the originating sources governing which piece of knowledge becomes attached to a particular meaning. Initial statements capturing "to whom" and "for what" link actions, or at least the thought of actions, to the challenge of ensuring student commitment to learning the existing curriculum. Allowing innovation as a catalyst in the educational approach also entails adjusting existing beliefs and values. Rooted in traditional practices, an act towards innovation allows a first step whereby attitudes are confronted and formed through ongoing experiences. Burton el al. [4] frame transformation of values and beliefs as a necessary step towards innovation. Our insights confirm that change practice rooted in fundamental individual core values is crucial when trying to establish new ways of thinking and prioritizing.

This paper argues that efforts to incorporate innovation at a fundamental level needs to aim at a systematic change that moves beyond the direct effects of changed practices. This research converges with Kolb's [11] cyclic looping, according to which student learning is shaped by evolving through stages, such as experiencing, reflecting, thinking, and doing. Similar to how shared beliefs can be communicated by using artefacts [15], perceived knowledge-based value in the iterations become crucial. This means that explicit and implicit expectations and needs should be kept at a level that includes flexibility in its design. Tolerance to change is needed from the supporting structure, e.g. faculty, system and organisation. Recognizing and promoting faculty involves engagement by faculty that wish to challenge and revise existing curricula. It concerns follow-up on efforts made and disseminate good examples so that a community of faculty change makers can find a forum for inspiration and sustainability. To build on sharpness, disciplinary knowledge is vital in establishing knowledge that captures both depth and applicability in the specific domain of engineering. This does not conflict with diverging attempts whereby functionality is tested and iterated across a spectrum of alternative domains. Learning elements need to be flexible in terms of *how* they are introduced, and more or less control will be needed depending on the maturity level of project groups and participants. To sufficiently meet needs and excel in the exploration of innovation, the timing, that is, *when* to introduce such efforts, should be handled with delicacy. This means that the educator should focus on providing a balance between control and self-regulation, depending on students' prior knowledge and each enabling activity's purpose.

5 WHAT CAN WE CONCLUDE?

This paper integrates lessons-learned from several independent research studies over the course of five years in two widely separated schools of engineering. Based on insights from our engineering design courses we conclude that innovation is best perceived as an embedded starting point for course design. This means that learning elements that could trigger innovation play an important role while being facilitated through the context-based triple loop cycle. Instrumenting innovation along the axis of iterative feedback loops makes the shift to go beyond the curriculum, course, and program without jeopardizing loss of rigor in classic, mandatory courses. Disciplinary knowledge has been upheld and strengthened hand in hand with the integration process. By rethinking and possibly redesigning current curricula and courses applicable innovation knowledge put a value added perspective on the individual student. The individual builds knowledge based on empathy, creative exploration and collaboration. Human variables build on how individuals allows for a team to excel through process learning. This individual level comprises expectations also on how technical expertise is brought in to actively engage and strengthen the collective knowledge in the design team. Figure 2 visualizes the individual, contextual, and educational learning imperatives to innovation in engineering education. It builds on the context-based triple loop highlighted (in yellow) as aspects covering the individual, technical expertise and the dynamics of the surrounding context. The outer layer (dashed line) relate to how well educational transparency can be made. This means to what extent a learning situation, learning element, practice and similar can be translated in to another setting. How to learn innovation in a new course offering or as an implementation feature in an existing program exists on Meta level. On Meta level student learning is addressed as part of a course offering or program, which needs to determine change benefits and efforts needed to be made. The learning transparency in this case builds on the emphasis of 'how' and 'to what extent' learnings can be translated and adopted in other programs or courses.

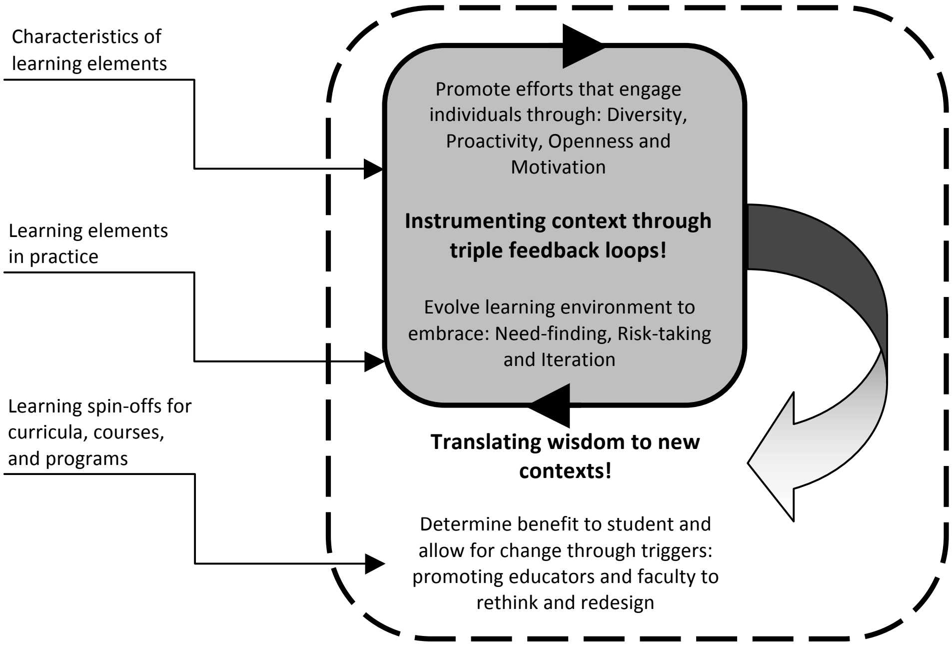

Figure 2. Engineering design innovation education in principle

6 WHAT MIGHT YOU "TAKE AWAY"

The paper's intention is to delineate the linkage between student learning and instructional elements that promote innovation in ways that can be reformulated and tested in other contexts. Generic student skills provide a basis from which innovation can evolve. However, skills covering both breadth and depth need to be framed explicitly so that learning activities can be matched with diversity, proactivity, openness, and motivation. To trigger students to engage in situations that stresses them to be proactively feedforward a sense of control over any distinct learning situation. Educators have many opportunities to increase attention to innovation. Instructional innovation is a preemptive move by instructors to inspire innovation by students. The learner mimics the instructional leader. This implement one of the most important tenants of the learning sciences, that the human capacity to learn is best implemented through mimicry.

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