The creative process in engineering

Teaching innovation to engineering students

Stéphanie Buisine (IRISE-CESI) & Samira Bourgeois-Bougrine (LATI-Univ. Paris Descartes)

Abstract

This chapter reports on 3 pedagogical experiments related to training engineering students to innovation. We first introduce the basic epistemological foundations and business strategies accounting for the differences in engineering process we observe in today's innovative companies. We also review the most frequent methodological blocks that are found in the engineer's toolbox to innovate. Study 1 subsequently aims to analyse the relations between engineering process, methods, and creative performance. This experiment was conducted with 27 students during a 10-session individual innovation project. The results suggest that a constructivist process with a strong focus on user needs and a weak focus on technical constraints should be fostered to increase students' creativity. Study 2 implemented these recommendations with 30 students organized in groups of 6 and assigned to real or realistic innovation projects for 5 weeks. Students' feedback on this process highlighted a new set of key drivers to innovation: creativity methods, but also mentorship, group composition and user studies were judged as pivotal to their performance. However, it also appeared that the chosen process and methods were insufficient to take full advantage of user studies and reach proven successful strategies such as Need-seeker. Consequently, we designed an original Need-seeker method and tested it with 55 students (Study 3) during a short pedagogical project. The results were encouraging since students managed to identify basic unmet needs to focus their creativity on. The 3 experiments result in a set of insights on engineers' creative process and on innovation training for students.

Introduction

To face innovation challenges of the 21st century, many companies rely on their engineers to fuel the creative process and set out the roadmap of future technological innovation. Creativity has therefore become a requisite skill for engineers and a part of their basic training. However, there are many ways to implement engineers' creativity and innovation process according to different epistemological approaches. Contrasting philosophies, in particular positivist and constructivist worldviews, determine different design reasoning models and business strategies (Liem, 2014). Positivism refers to a scientific and structured method focusing on identifying the causes influencing outcomes. It is an analytical, problem-centred approach that invests high on the fuzzy front-end of innovation and leads to a waterfall sequential process in which creativity takes centre stage. Herbert Simon's (1973) seminal research contributed to shape this sequential engineering process based on three major steps: problem setting, (creative) problem solving, and evaluation of solutions. This view gave rise to many sequential design practices, like the General Design Theory (Yoshikawa, 1985; Tomiyama et al., 2009) and industrial engineering processes organized as a series of stages and gates (Aoussat et al., 2000; Pahl et al., 2007; Cooper, 1990).

In contrast, constructivism is associated to postmodernism and rejects absolute truth. It considers that reality is a social construct depending on the context: it is a solution-focused approach in which the problem is iteratively co-constructed with the solution (Visser, 2009). This worldview leads to circular rather than sequential design process, with creative thinking throughout the project. This approach is implemented in many recent design trends, such as information technology (Boehm, 1988), user-centred design (ISO 13407, 1999), agile software development (Beck et al., 2001), design thinking (Cross, 2011), or lean startup (Ries, 2011). Basically, both positivism and constructivism may produce successful outcomes: choosing a process may depend on the project, on the nature of the product to be designed, and most importantly on corporate culture.

Some researchers use an evolutionary metaphor to characterize different business styles and corporate strategies (Picq, 2014): K-type companies are analogous to species that follow a qualitative humanlike reproduction strategy (few descendants; high investment in gestation and education; high success rate). In contrast, r-type companies use a quantitative and opportunistic strategy similar to dandelion-like reproduction (many seeds disseminated; low investment; low success rate). K-type approach may be read as positivist engineering with high investment on the fuzzy front-end, waterfall process, convergence, few new product but high success rate. This kind of strategy can be found in large groups and in traditional industrial sector. Conversely, r-type strategy corresponds to constructivist engineering with lower temporal and financial budget, iterative or circular process, divergence, many ideas but high risk of failure, like in startup companies. In natural ecosystems, K-type strategy tends to outperform r-type strategy when the competition increases (Picq, 2014). This is why a successful r-type startup company with a constructivist approach may progressively turn its strategy into K-type positivist approach when growing and gaining investment capacities.

Besides, the innovation process is structured by basic methodologies to be selected and arranged in a customized way (sequential, iterative…) for each project. For clarity's sake, we present these methodologies below as a sequential process divided into the four stages of New Product Design process (Aoussat et al., 2000), knowing that each method can be extracted and used independently or integrated into a constructivist process as well:

- The first stage of New Product Design process, *Translation of needs,* aims to define functional specifications of the future product to design. This stage involves methods and tools allowing the team to better understand the users, the market, and competitors' products. They include surveys, technological watch, trends analysis, field observations and user studies. Some communication tools exist to share the results of these studies, for example product mappings and inspiration boards to illustrate the state of the art and capture design trends (Bouchard et al., 1999), or Personas to represent archetypes of customer segments (Pruitt & Adlin, 2006). The data collected is finally synthesized through value/function analysis, which results in a list of functional specifications, associated to key performance indicators and target values to be achieved by the future product.

- The second stage, *Interpretation of needs*, draws on the results of the first stage to search for new concepts and new solutions that will meet function specification and key performance indicators. This is the main creative stage of the process. To successfully conduct it, engineer's toolbox includes basic creativity techniques such as Brainstorming (Osborn, 1963) and its declinations brain purge, analogies, or problem reversals (Van Gundy, 2005), mind-mapping (Buzan, 1991), etc. Engineers are used to conducting collective creativity sessions in order to maximize divergent thinking through multidisciplinary team and, when possible, integration of users in the session. The creative phase results in a pool of ideas and concepts that are then sorted and ranked using multi-criteria matrices which include the key performance indicators from function specification. More specific and convergent creativity methods, such as those from the TRIZ framework (Altshuller, 1996; Savransky, 2000), can also be used to model technical/physical problems and find inventive solutions. The second stage ends when a satisfactory concept is selected by the project team to serve as a basis for the new product. In constructivist process, several different leads from the creative phase(s) might be explored in the project.

- The third stage, *Product definition*, is dedicated to detailed design and materialization of the concept: product architecture, which is sometimes modelled using SADT (Structured Analysis and Design Technique) and/or FAST diagrams (Function Analysis System Technique), choice of technical components and materials, mock-up design, product-process link, Computer-Assisted Design, etc. Intermediate user tests can be conducted on representations of the product concept (3D picture, high- or low-fidelity mock-up, storyboard…). Finally, the product solution, the associated processes and production means can be assessed through FMECA (Failure Mode, Effects, and Critically Analysis).

- The final stage, *Product validation*, aims to validate product design by (1) building an industrially reproducible prototype and (2) having it user-tested. In constructivist process, the industrially reproducible prototype is not required and user-tests are preferably conducted on low-fidelity mock-up or minimum viable products (Ries, 2011).

The aim of this chapter is to provide insight on what methods engineering students should be trained to, and how, and the subsequent impact on their creativity in the context of simulated or real innovation projects. To this end, we draw on three pedagogical experiments conducted in three different schools of engineering.

Study 1

The first study took place in a generalist school of engineering in Paris (Arts et Métiers ParisTech). The participants were students who were introduced to the abovementioned New Product Design process (Aoussat et al., 2000) and the related methodological blocks through a 150-hour class entitled "Product Engineering".

Method

Participants

The sample included 27 students in their final year of engineering studies (4 females, 23 males, *age* = 23 years ± 1). They were rewarded course credits for their participation.

Procedure

The participants engaged in an innovation exercise that they had to perform individually outside of class hours over an 8-week period. To validate the exercise, they had to dedicate 10 working sessions to this project. The goal was to imagine a kitchen for a minivan with the following requirements: Enable cooking, storage of water, dishes, fresh food; be adaptable to most minivans with no modification of the car; occupy no more than 30% of the trunk; be installed in less than 15 min; weight less than 20 kg; comply with security standards, etc.

The participants were provided with a blank booklet to track their process: for each session they had to fill in a self-report of the stage(s) of the creative process addressed (Table 1) and an open-ended section to describe the methods used and the intermediate ideas and productions. This methodology of repeated measures was previously tested in emotions research (Diener et al., 1995; Vansteelandt et al., 2005; Zelenski & Larsen, 2000).

1	*Definition of the problem*	Focus, explore the theme, the aims, need to create, need to express, challenge
2	*Question*	Ask, interact with the work, understand
3	*Documentation*	Capture and search for information, be attentive, always have the project in mind, store information, accumulate, be impregnated, receptive, available, observe, show sensitivity and awareness
4	*Consider the constraints*	Define constraints, identify a customer's request, set constraints for oneself and define one's rules and freedom
5	*Insight*	Have an idea, experience the emergence, the sudden appearance of an idea
6	*Association, associative thinking*	Resonance, play with forms, materials and significations, imagination, daydream, analogy

7	*Experimentation, exploration, divergent thinking*	Try, modify, manipulate, and test
8	*Assessment*	Be self-critical, stand back, analyze, reflect, check the quality of a result
9	*Convergent thinking, structuration*	Crystallize, make a prototype, visualize and structure, establish order, sequences, control and organize
10	*Hazard benefit*	Luck of the environment, aleatory processes, be open to the hazard, to take a walk, to accept accidents and chaos
11	*Implementation*	Transpose, make, illustrate, produce, compose, give shape, apply
12	*Finalization, ending*	Edit, develop, complete, justify, explain one's work, exhibit
13	*Break*	Rest, digest an idea, let time pass, do something else

Table 1: The thirteen stages considered in the booklet.

At the end of the project, the participants were instructed to provide:

- Six different idea sheets corresponding to 6 kitchen layouts: 2 for short-term implementation (< 1 year), 2 for medium-term (between 1 and 10 years) and 2 for long-term implementation (>10 years).
- The booklet retracing their process (creative stages, methods used and intermediate productions).

Evaluation of the creative performance

A multidisciplinary jury of five teachers from the school, all specialized in innovation, evaluated independently the 162 layouts for a functional kitchen produced by the 27 students on 7-point Likert-type scale (1: not at all creative to 7: extremely creative). The judges received the layouts to be evaluated in random shuffled order, with no information about the students and no access to booklets. Inter-judge agreement amounted to .80, which is very satisfactory.

Besides, in-depth analysis of the 162 kitchen layouts was conducted according to 4 criteria: originality or uniqueness, flexibility or variety, elaboration and integration of technology. An original kitchen concept was unique, surprising, move away from the obvious and commonplace. The focus was on the uniqueness of the concept e.g. proposed by only one student. Flexibility or variety refers to the number of different kitchen concepts proposed (e.g. at least two different concepts among the six designed kitchen). Elaboration measures the amount of detail associated with each kitchen idea. Elaboration has more to do with focusing on each solution/idea and developing it further and adding details. Integrated technologies included green energy, smart or connected kitchen…

The booklets were analysed as well in order to assess the creative process stages and the methods used by the participants.

Results

Output and creative performance

All students managed to produce six layouts for an integrated kitchen. The booklet analysis revealed that the most common aspects considered by students were the reduction of cost and size of the kitchens, the spatial position inside the car, the modalities of use (outside and/or inside the car, while driving), the modularity (functional units as basis of design), practicality (easy to store, deploy and to carry) and technology integration (energy production, water and waste recycling…). The most creative students came up with original unique concepts of kitchens, different from classic home kitchen, which could allow new experience for the user such as all-weather kitchen, inflatable or ecological kitchen, remote control food cooking using smartphone, dehydrated food, magnetic levitating modular kitchen, smart or connected kitchen e.g. touch screen, electronic recipes, automated food preparation according the weather and the journey information as well as the available ingredients…

The layouts produced were more or less creative according to the assessment made by jury members. The average jury creativity mark was 4±1.6 with a maximum of 6.2 and a minimum of 2 (1: not at all creative to 7: extremely creative). To investigate the inter-individual differences, the sample was divided in two groups, C+ and C-, respectively above or below the average (4 ± 1.6). Fourteen students obtained a creativity mark above the average (named C+) and thirteen below the average (named C-). The participants were attributed an alphanumeric code according to their rank: S1 for the student with the highest average jury mark (6.2 ± .8) and S27 for the lowest score (2 ± 1.4).

Creative stages

The booklet completed over the 10 sessions revealed the “path” followed by each student to complete the task and solve the problem. The differences between C+ and C- were observed mainly during the last five sessions: C+ were more likely to have "Illuminate, evaluate, associate, experiment and implement" while C- continued to “Question, converge, and consider constraints”. C+ students used creativity tools up to the very end (7 uses of creative tools in the last session in C+ group vs. 1 use in C- group). The analysis of free comments in the booklets also suggested that some C+ students sought to "summarize" design constraints in some key limitations and seemed to disregard several other constraints. They showed a flexible and even a bold attitude towards the constraints: they did not hesitate to criticize, reinterpret, reformulate and even circumvent some constraints. On the opposite, C- students were continually preoccupied by constraints such as the size of the trunk, the weight and the volume of the kitchen, energy issues, etc. More importantly, they generated new constraints in addition to the initial specifications and tried to find solutions that were feasible within these constraints.

Creativity and engineering methods

The analysis of the open self-report part in the booklet, in which the participants recorded their progress, shed a light on the development and creativity techniques used during the creative process. A total of 13 tools were applied by students to solve problems and generate ideas, including: individual and collective brainstorming, brain purge, problem reversal, mind mapping, analogies, TRIZ, FMECA, Personas, FAST diagram, SADT, and APTE framework for value and function analysis.

C+ students employed 4.2 tools in their process (± 1.6; min = 2; max = 7) while C- used only 2.2 tools (± 1.9; min = 1; max = 6). Personas, mind mapping, brain purge and problem reversal were employed by few students all of whom were among the most creative (C+). Brain purge is a creativity tool that helps participants empty themselves of their preconceived ideas or any idea they hold dear. This technique was used only once at the beginning of creativity process by a female student (S1) who received the highest creativity mark (6.2 on average). The purge started by a brief documentation on existing kitchens in small flats, boats, camper van etc.; then she wrote down the specifications as well as a drawing of the classical kitchen to absolutely avoid reproducing. Indeed, her six alternatives layouts had little in common with the classical kitchen. Four of them were unique, highly original, diverse and included state-of-the-art technologies. It is worth to mention that S1 applied frequently tools such as mind mapping, brainstorming, personas and analogies during the 10 sessions. The quality of execution and output of these techniques were at high standards and allowed the student to experience a stimulating divergent thinking. Interestingly, S1 did not use any of the analytical rational techniques such as value / function analysis.

The Persona technique included narrative about different emotional customer experiences and scenarios of use that helped the students to develop some empathy with target customers such as: explorer in Arctic regions or Amazonian forest, nature lovers (ecological kitchen), tradition seekers, elegant and purist design adepts, technological geeks… Surprisingly, some students did not fully develop the personas; others did not integrate the output of these creative sessions or failed to produce elaborate details into their final layouts. This could be linked probably to an insufficient training or a lack of trust in the benefits of this user centred design technique.

Value / function analysis was the third most frequently used technique during the early stages of the creative process (the three first sessions). It mainly consisted in reformulating the initial specifications: no new ideas were generated but students felt they gained a better understanding of the problem and declared they were ready to get started. However, among the 11 students who applied function analysis, 8 (73%) did not come up with any unique or original idea. FAST diagrams, which display functions in logical sequence and prioritize them, were used by only one student (S25) during the 4^{th}, 5^{th} and 6^{th} sessions. The creative performance of this student was in the bottom three (average creativity mark: 2.2 ± 1.3) despite a very structured approach and the use of a total of 6 engineering methods.

Discussion

This study provides several insights on the relation between engineering methods, how / when they are used in the process and the subsequent creative performance. The main features of the creative process of C+ students were: their lightweight processing of constraints, their use of creative/diverging tools until the very end of the project (constructivist process), and their reflexion on user needs through personas.

We observed that students who both alleviated technical constraints and adopted users viewpoint produced the most creative outcomes. This result should be read in conjunction with recent analyses of corporate innovation strategies worldwide, in particular the 2014 study Global Innovation 1000 (Jaruzelski et al., 2014). It shows that three basic strategies can be found in innovative companies: Technology-driver (whose priority is to develop products of superior technological value), Market-reader (which focuses on creating value through incremental innovation and customization of products), and Need-seeker (which aims to find unstated customer needs of the future, and to be the first to address them). Although the three strategies all possess their own success stories, a long-term analysis clearly shows that Need-seeker outperforms the two other strategies in terms of financial return on investment (Jaruzelski et al., 2014). In line with this global trend, our results suggest that focusing more on users and less on technical constraints leads to more creativity, and that engineering students should be trained to do so.

This way of managing innovation project is not self-evident, particularly in France. Indeed, Technology-driver remains the dominant model in France (60% of innovative companies; Péladeau et al., 2013) and Need-seeker struggles to emerge (17%). In contrast, Silicon Valley firms are the most likely to follow a Need-seeker model in the world (46%). Innovation analysts therefore recommend developing Need-seeker strategy in France in order to stimulate innovation and thereby economic growth (Péladeau et al., 2013). In this respect, the Persona method is a convenient, low-cost approach to support engineers' empathy with users, but the benefits might be even stronger if engineers were used to integrating real users in the innovation process, through e.g. interviews, field observations or user tests. Our sample students were actually taught these methods in the Product Engineering class, but they did not use them in this project.

We drew on this set of results to build a new training program for teaching innovation to engineering students, with the following characteristics:

- We decided not to integrate value/function analysis in the innovation process, in order to avoid too much focus on technical constraints and on evaluation criteria.
- We integrated field and user studies as mandatory steps, with dedicated sessions planned in the program.
- We designed the program so as to foster a constructivist process including several rounds of

analysis, creativity and design throughout the pedagogical project.

- As corporate innovation projects are always conducted in teams, we also decided to make students work in groups rather than individually.

Study 2 reports on the implementation of this second training program.

Study 2

This study took place in another generalist school of engineering in Paris (Ecole d'Ingénieurs du CESI), which is known for its innovative pedagogy: this school is class-free and learning exclusively relies on active pedagogy through projects. The participants were students who had chosen the "Innovation" specialty for their final year and engaged in a 210-hour innovation program including 175 hours of group project and 35 hours of personal work.

Method

Participants

The sample included 30 students in their final year of engineering studies (9 females, 21 males, age = 24.3 years ± 1.6). Their participation partly validated a semester of their engineering curriculum.

Procedure

Five groups of 6 students were composed on the basis of an initial deliverable in which the students had to describe their motivation for the Innovation program and to list examples of products they would like to study, to improve or to create. The groups were composed by the experimenter and attributed five different projects (one project for each group) in accordance with students' interests. The sample projects included 2 assignments provided by partner companies, 2 entrepreneurial projects provided by students, and a fictitious project provided by the experimenter on the basis of the group members' interests. The projects were focused on different products (3 goods, 2 services) and therefore had different specific goals but they all consisted in starting with a concept and making it become a concrete reality at the end of the project. This required refining the response to users needs and expectations, refining the concept, strategically positioning the product with comparison to existing ones on the market, elaborating a detailed design, and developing a business plan.

The groups had 5 full-time weeks (i.e. 175 hours) to achieve their project. To this end, they were guided through an innovation process (Table 2), had to produce daily deliverables and were provided with mentorship from several experts.

Weeks	Methodological steps
1	Technology watch Use analysis (field study) Creativity
2	Creativity Materialization of ideas Mentoring committee
3	Materialization of ideas User tests (field study) Creativity Patent watch
4	Creativity Mentoring committee Marketing Business plan
5	Intellectual property Creativity

	Business plan Mentoring committee User tests (field study)

Table 2: The methodological steps imposed along the 5 weeks.

Feedback on creative performance

Twelve experts from the school and from partner institutions participated in the mentoring committee that met three times during the project duration. The experts represented different specialties such as technological innovation, user-centered innovation, industrial design, finances, strategy, etc. The experts gave qualitative feedback on each project and delivered customized advice to each group.

Students were also invited to give an individual feedback on their experience as apprentice innovators. At the end of the project, they had to self-assess the contribution of each methodological step on their creative performance (on Likert-type scale from 1: not important at all to 7: very important), and to indicate what had been most striking to them in this pedagogical project (open-ended question).

Results

The five projects were very different from one another but all groups managed to gain one or several supporters within the experts' committee. For example, one group proved very flexible in the solutions imagined and also achieved a high degree of elaboration. Another group produced a very original business model. A third group combined existing technologies to provide a new solution to unmet societal need, etc. All groups' production was acknowledged as creative and attested by a Soleau envelope (proof of priority for invention) applied for at the French National Industrial Property Institute. Moreover, one of the projects resulted in a patent application, currently in progress, and another one resulted in a startup creation. Experts' opinions were nonetheless much contrasted, some of them being more receptive to technological innovation, some to business plans, and some to response to user needs.

Regarding students' feeling of which methods were pivotal to their creative performance, the results show that training on creativity methods was ranked first, then mentorship, group composition, and user studies (Figure 1).

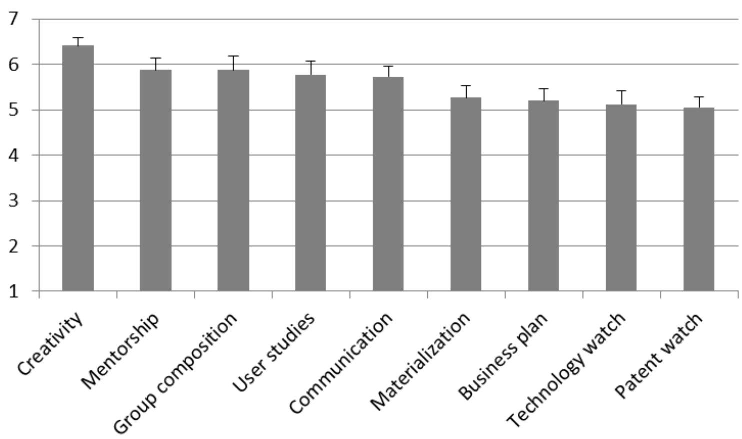

Fig. 1: Subjective evaluation of the impact of methodological steps on students' creativity. Likert-type scale from 1: not important at all to 7: very important.

Discussion

Our results did not enable us to distinguish between the 5 projects in terms of creative performance, since each project had its own specificities, strengths and weaknesses, and got support from at least one expert from the mentoring committee. The overall constructivist process seemed natural to students and none of them reported any redundancy between e.g. the 5 iterative creative steps organized throughout the project. Some of them even suggested that the business plan, which was introduced in the fourth week, should have been initiated from the very beginning of the project.

Students judged creativity methods as central to their performance and 21 students out of 30 cited them as one of the most striking learning outcomes of the program. They were actually introduced to basics of the following methods: brainstorming, mind-mapping, visual projection, Kent & Rosanoff list, problem reversal, analogy, trends, and discovery matrix. Informal comments collected during the project suggested that brainstorming and problem reversals were the most widely used techniques and that each group also had its own favourite techniques in addition to these musts. For instance Kent & Rosanoff list, which consists in forcing unnatural associations on a bissociative principle (see also DesMesnards, 2011), was highly appreciated by some groups and found unfruitful by other groups.

Mentorship was also reported as highly impactful on the creative performance of students. In this respect, we think that collegial sessions were particularly formative for students: during mentoring committees, up to 7 experts were gathered around the table and openly discussed with each group for an hour. This enabled the experts to deliver detailed advice to the students and also to discuss among themselves and confront their complementary views. Therefore, students had the opportunity to understand that there was neither a unique approach to innovation nor straightforward answers to their doubts and questions.

Group composition obtained the same importance score as mentorship to account for creative performance. In the open-ended section of the questionnaire, many students commented on this effect with highly positive terms, explaining that they had experienced powerful group cohesion on the occasion of this project. It was a striking experience for 13 students out of 30. Some of them underlined that they had learnt to better work in group and take advantage of their differences. Although students in this school were already used to working in group, they had never experienced such long (5 weeks, full time) collaboration. We may point out that both group composition and project assignment were imposed by the experimenter on the basis of a 1-page deliverable produced by the students. Although unusual and risky, this procedure seemed effective, as attested by students' evaluations and by further indirect evidences: on the first day (project launch) when we circulated group composition and project assignment to the students, we allowed one permutation by group, but observed that only 3 students out of 30 actually changed groups. Likewise, after 2 weeks and a half of group work (mid-term project review), we offered a new opportunity to change groups and once again only 3 of them decided to change groups, which suggests that the majority of students were satisfied with their group.

Finally, user studies were the fourth method acknowledged as important for creativity. In this respect, we achieved our goal of promoting user integration in engineers' innovation process. Three days of the training program were dedicated to field studies and students had a special authorization to "get out of the building" on those days. They could observe uses, meet potential end-users of their products and interview them, get feedback on their concepts and better capture user needs and expectations. However, we would describe the results obtained as a Market-reader rather than a Need-seeker process. Students could indeed greatly improve and refine their concepts, but they did not come up from user studies with disruptive ideas (or, at most, only one group did). In contrast, Need-seeker approach is assumed to turn into radical innovation, make future needs arise and generate undreamed of concepts. Examples of companies known for their Need-seeker strategy include Apple, Tesla or Procter & Gamble (Jaruselski et al., 2014) – we suspect that our students did not live up to these prestigious references. This is why we decided to further improve the previous innovation process and guide students through a stronger Need-seeker-like approach.

Need-seeking represents today the pinnacle of innovation and is often attributed to geniuses or visionaries; hence there are relatively few known methods for structuring it. The Lead-User method (Franke et al., 2006; Von Hippel, 2005) may be the most effective one to date: by definition, lead users are precursors, and are at the leading edge of important trends in the market. Involving lead users in an innovation project may grant access to needs that will later be experienced by many users and therefore may open successful innovation opportunities, like in companies such as 3M. However, this method seems hardly applicable in a 5-week pedagogical project since lead users are difficult to find and may require up to several months to be identified (Von Hippel, 2005) before being eventually integrated into the innovation process. In contrast, the low-cost Persona method used by some participants in Study 1 enabled them to generate creative ideas because it involved "extreme" (although fictitious) users, for example explorers in Arctic regions or Amazonian forest. We decided to elaborate an intermediate Need-seeker method between the Lead-User and Personas that would involve "extreme" users, although not so unique as lead users and not so fictitious as Personas. Study 3 reports on the testing of this original method with a new population of engineering students.

Study 3

This study took place in an engineering school specializing in biology and biotechnology oriented towards the pharmaceutical, cosmetic, food and environmental industries (Ecole de Biologie Industrielle). The participants were students who had chosen the "Engineering design" option for their final year. The present study was conducted as part of a 9-hour "User-Centered Innovation" class in this option. Given its limited timeframe, the pedagogical project focused on the Need-seeker step only and did not address the whole innovation process.

Method

Participants

The sample included 55 students in their final year of engineering studies (50 females, 5 males, age = 23 years ± 1). Their participation contributed to the validation of their option.

Procedure

Students composed six groups of 9 to 10 members and each group chose an existing product as the starting point of its project. Most of the students in this school are experts in and passionate about cosmetics and strive to pursue careers in this industry. Therefore most of the groups chose a cosmetic product (e.g. nail polish, eye liner, powder foundation), which incidentally offered a very nice challenge to this experiment. The goal of the project turned into finding out new unmet needs related to existing products from a hyper-competitive market with intensive innovation activity.

The Need-seeker method elaborated for this project was inspired by Universal Design (Vanderheiden, 1997; Vanderheiden & Tobias, 2000; Buisine et al., 2011). In many aspects, universal design meets usability principles (ISO 9241-210, 2010; Nielsen, 1993) but generalizes the approach to *all* users (be they young, old, disabled, tall, small…) and not only to target users of a given product (sometimes corresponding to very narrow market segments). In line with this principle, our method named "Off-target user" mainly consists in testing a product outside of the target user population. We hypothesized that focusing on users with special needs would feed the much-vaunted Need-seeker strategy by renewing the look we take on a product, revealing latent needs that are not expressed by target users, and highlighting new original needs. For example, if we study children needs (e.g. beginner readers, narrower vocabulary, shorter stature, weaker force…) while designing a product for adults, this may result in a more intuitive product, with higher usability for adults, elderly people, disabled, foreigners who hardly speak the language, etc. The same reasoning applies to senior needs (i.e. viewing and hearing disorders, lower dexterity, memory disorders, etc.), which are likely to help us design more intuitive products for able-bodied users.

The pedagogical projects were therefore aimed to identify unmet, latent or unknown needs related to the products of interest. To this end, the groups had to conduct user tests with 5 target users and 5 off-target users, confront the needs identified in the two conditions and select an innovation challenge for this product for the next 10 years.

The course of the project was designed as follows: students attended a 4-hour class introducing them to user-centered innovation, Need-seeker strategy and finally the original Off-target-user method to implement. Then they had two hours for (1) composing the groups, (2) choosing their product of interest and (3) setting out their protocol for target and off-target user tests. They subsequently had 2 weeks to conduct the tests outside of class hours, analyze and synthesize the data. The final 3-hour class was dedicated to project defense.

Results

Instead of reporting each group findings, we describe in this section the detailed results of the group that worked on nail polish. We chose this group because it exceeded the initial instructions and conducted a more complete need-seeking process, with a brain purge creativity session, technology watch and market research in addition to the methods required in the exercise. For this reason, their project gives a wider picture of the contribution of off-target user testing for need seeking. This group also published its study (Mear et al., 2015).

The initial brain purge was conducted with group members only, which was a very homogeneous group of 10 women, aged 21 to 24 years, with the same training background, all nail polish users (and some of them expert users). The brain purge was dedicated to finding ideas for improving existing products. The main improvement avenues that were identified were e.g. avoiding formula drips, improving application accuracy and reducing drying time. Technology watch then enabled them to find original application techniques – including nail art techniques – as well as innovations in the formula (extra-fast dry, thermo-responsive, anti-aging, long-lasting, nail foundation, etc.). Market research confirmed that the domain was very dynamic, with sales in constant growth since 2006 and more than 10 million bottles sold each year. The group also conducted a survey on a sample of 23 women aged 10 to 74 years indicating that the first nail polish application occurs at 18 years old on an average (6 to 30 years old) and may continue throughout lifetime.

Target user tests were conducted with 5 women aged 18 to 68 years, 4 right-handed, 1 left-handed, expert to casual users of nail polish. Off-target user tests were conducted with 2 children and 3 men aged 4 to 56 years, all right-handed, non-users of nail polish. They were invited to paint their fingernails of the two hands and think aloud throughout the task. Afterwards they had to perform an auto-confrontation (Mollo & Falzon, 2004) and provide further comments on their nail polish experience while watching the video recording of their activity. They were finally interviewed about avenues and/or suggestions for improvement of nail polish products.

Most of needs reported by target users concerned the formula (viscosity, dry time, smell, easiness to remove). They also generally complained about the too-long time required to paint fingernails. They did not comment much on the devices, just mentioned that the brush used for the test was not flexible enough and too small. On the contrary, off-target users made a lot of comments on the devices: bottle plug difficult to screw and unscrew (in particular with fingernails freshly painted), brush difficult to handle (in particular with fingernails freshly painted), bottle difficult to hold, etc. They also mentioned the difficulty to paint their fingernails of the dominant hand (with their non-dominant hand) and to paint the thumb because its orientation is different from the other fingers. These needs are so obvious that target users did not mention them. We think that these are nonetheless actual needs, and may improve target users' experience if they were met. Indeed, target users interviewed in this study were still 60% to be dissatisfied and 80% to find nail polish application difficult (and 100% of off-target users).

Discussion

This study suggests that testing a product with off-target users could be a smart way of highlighting basic and unmet needs as the starting point of a Need-seeker innovation project. The other groups participating to this study obtained similar results with different products (two other cosmetic products, but also two types of food packaging and a hair straightener). Finding off-target users for cosmetic products and hair straightener was particularly easy since the students could involve men in their sample. For food packaging all human beings are potential target users, but in this case the students involved "extreme", or non-standard users: they conducted their tests with children and elderly users, with the same effectiveness in identifying unmet needs with comparison to middle-aged users. Other valuable extreme users could be found in people with perceptive, motor or cognitive impairments, but they may be more difficult to find in such short pedagogical projects.

The main advantage of involving off-target or extreme users was to highlight unmet although obvious needs. Make engineers (re-)discover them is likely to stimulate their creativity and result in new, original and hopefully more usable devices. We speculate that this could be the creative process that was followed in information technology to achieve the highly usable devices we have today: questioning and re-examining the fundamentals of interaction to create more usable interfaces. Famous companies like Apple have built their reputation on this kind of achievements despite sometimes lower technological capacities of their product with regard to their competitors.

Data collected by the groups in this study also suggested that off-target and extreme users showed less cognitive fixations on existing products and generated more divergent (uncensored, fanciful, ambitious) ideas to improve existing products. However, the timeframe of this pedagogical project did not enable the students to use the study outcomes and engage properly in a constructivist creative process. This could be the aim of a future experiment.

Anyhow, we consider that our goal was met to provide students with a simple method likely to support a Need-seeker innovation strategy, an approach that is currently insufficiently developed in French companies (Péladeau et al., 2013). Moreover, according to informal comments of the students, Off-target-user method enabled them to see the product through users' eyes instead of engineers' eyes, which is an achievement in itself.

General conclusion

In this chapter we reported on three pedagogical experiments related to teaching innovation to engineering students. The first study was an attempt to systematically analyze the relations between reasoning process, engineering tools and creativity. For this purpose we elaborated quite an artificial situation, with a single project addressed in parallel by 27 students, individual procedure and many traceability constraints (imposed number of sessions, self-reports, booklet to complete, etc.). That was the price to be paid for gaining more reliable insight and understanding how to design effective pedagogical programs.

The second study was partly designed on the basis of these insights and implemented more realistic situations, with real projects conducted in groups, during working hours – a situation analogous to what students might live in their (future) professional life. The methodological counterpart was that the 5 projects turned out to be impossible to compare in terms of creative performance. This study was nonetheless informative as to how the process and the methods were experienced by students, and evidenced further limitations about how they take advantage of user studies to innovate.

The third study enabled us to beta-test the Off-target-user method, which is usable by students and likely to help them catch what Need-seeking is like. The results were very encouraging and call for further experiment: the method now has to be integrated into a full-length innovation process in order to assess its impact on creativity and innovation.

The “best-of” pedagogical innovation process drawing on this set of results would have the following characteristics:

- A full-constructivist process iterating on all dimensions throughout the project (analysis, creativity, evaluation, business plan…) – sequential waterfall process may become relevant when students get experienced;
- An initial Need-seeker approach fed with Off-target / extreme users and/or Personas and/or Lead users;
- Field studies as mandatory steps;
- Not too much focus on constraints and function analysis – although important for routine design, they may be counterproductive in innovation;
- Mentorship, for example in the form of collegial sessions;
- Group work, and ideally *multidisciplinary* group work – this is a major limitation of the pedagogical experiments presented in this chapter to have entrusted innovation projects to too homogeneous groups in which engineers were among themselves.

In addition to promoting multidisciplinarity, we believe that two main directions should be investigated to further leverage engineers’ creativity: the first one consists in developing new creativity methods and tools (see e.g. Guegan et al., 2015; Afonso et al., 2014; Schmitt et al., 2012); the second one relies on orienting engineers’ creativity in relevant and original directions through prospective methods (e.g. Nelson et al., 2013, 2014; Barré et al., 2014a, 2014b), and particularly Need-seeker ones, as exemplified in this chapter. There is still tremendous scope for challenging experiments.

Acknowledgements
Study 1 was partly funded by ANR-CREAPRO project. We are very grateful to the experts who participated in study 1 and study 2 and of course to the 112 engineering students from 3 different schools who composed our sympathetic experimental population.

References

Afonso Jaco, A., Buisine, S., Barré, J., Aoussat, A., Vernier, F. (2014). Trains of thought on the tabletop: Visualizing association of ideas improves creativity. *Personal and Ubiquitous Computing*, vol. 18, pp. 1159-1167.

Altshuller, G.S. (1996). *And suddenly the inventor appeared*. Worcester, UK: Technical Innovation Center.

Aoussat, A., Christofol, H., Le Coq, M. (2000). The new product design – A transverse approach, *Journal of Engineering Design*, 11, 399-417.

Barré, J., Buisine, S., Aoussat, A. (2014). PLT (Persona Logical Thinking): A method to generate user requirements for multidisciplinary design teams. AHFE 2014 International Conference on Applied Human Factors and Ergonomics.

Barré, J., Buisine, S., Guegan, J., Aoussat, A. (2014). Le caractère ludique comme levier de performance pour l’anticipation des besoins des utilisateurs. ErgoIA 2014 Colloque francophone sur l'Ergonomie et l'Informatique Avancée.

Beck, K., Beedle, M., van Bennekum, A., Cockburn, A., Cunningham, W., Fowler, M., Grenning, J., Highsmith, J., Hunt, A., Jeffries, R., Kern, J., Marick, B., Martin, R.C., Mellor, S., Schwaber, K., Sutherland, J., & Thomas, D. (2001). *Manifesto for agile software development*: agilemanifesto.org.

Boehm, B.W. (1988). A spiral model of software development and enhancement. *IEEE Computer*, 21, 61-72.
Bouchard, C., Christophol, H., Roussel, B., Aoussat, A. (1999). Anticipation and integration of trends in design and engineering design. In Proc. of International Conference of Engineering Design (ICED).
Buisine, S., Plos, O., Aoussat, A. (2011). La conception universelle, inclusive (fiche pratique). *Déployer l'innovation*, Paris: Techniques de l'Ingénieur.
Buzan, T. (1991). *The Mind Map Book*. Penguin Books.
Cooper, R.G. (1990). Stage-gate systems: A new tool for managing new products. *Business Horizons*, 33, 44-54.
Cross, N. (2011). *Design Thinking: Understanding how designers think and work*. Berg/Bloomsbury.
DesMesnards, P.H. (2011). Mettre en œuvre la technique des rencontres inattendues: La bisociation. In *Déployer l'innovation*. Paris: Techniques de l'Ingénieur.
Diener, E., Smith, H., & Fujita, F. (1995). The personality structure of affect. *Journal of Personality and Social Psychology*, 69, 130-141.
Franke, N., Von Hippel, E., Schreier, M. (2006). Finding commercially attractive user innovations: A test of Lead-User theory. *Journal of Product Innovation Management*, 23, 301-315.
Guegan, J., Maranzana, N., Barré, J., Mantelet, F., Segonds, F., Buisine, S. (2015). Design and evaluation of inventive avatars for creativity and innovation. ICDC 2015 International Conference on Design Creativity.
ISO13407. (1999). *Human-centred design processes for interactive systems*. Genève: International Organization for Standardization.
ISO9241-210. (2010). *Ergonomie de l'interaction homme-système -- Partie 210: Conception centrée sur l'opérateur humain pour les systèmes interactifs*. Geneva: ISO International Organization for Standardization.
Jaruzelski, B., Staack, V., Goehle, B. (2014). Proven paths to innovation success. *Strategy+Business*, 77, 2-16.
Liem, A. (2014). Toward prospective reasoning in design: an essay on relationships among designers' reasoning, business strategies, and innovation. *Le Travail Humain*, 77, 91-102.
Mear, S., Moreau, S., Moussour, M., Pensé-Lhéritier, AM., Buisine, S. (2015). Application de méthodes d'innovation centrée utilisateurs au secteur cosmétique. Confere 2015 Colloque francophone sur les sciences de la conception et de l'innovation.
Mollo, V., Falzon, P. (2004). Auto- and allo-confrontation as tools for reflective activities. *Applied Ergonomics*, 35, 531-540.
Nelson, J., Buisine, S., Aoussat, A. (2013). Anticipating the use of future things: Towards a framework for prospective use analysis in innovation design projects. *Applied Ergonomics*, vol. 44, pp. 948-956.
Nelson, J., Buisine, S., Aoussat, A., Gazo, C. (2014). Generating prospective scenarios of use in innovation projects. *Le Travail Humain*, numéro spécial "Ergonomie prospective", vol. 77, pp. 21-38.
Nielsen, J. (1993). *Usability Engineering*: Academic Press.
OECD – Organisation for Economic Co-operation and Development. (2005). *Oslo Manual: Guidelines for collecting and interpreting innovation data*, 3rd Edition. OECD Publishing.
Osborn, A.F. (1963). *Applied Imagination* (3d ed.). New York: Scribner and Sons.
Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007). *Engineering design - A systematic approach*. 3rd ed. Berlin: Springer.
Péladeau, P., Romac, B., Rozen, A., Sevin, C. (2013). *L'innovation dans les entreprises en France*. Paris: Booz & Company Inc.
Picq, P. (2014). *Un paléoanthropologue dans l'entreprise*. Paris: Eyrolles.
Pruitt, J., & Adlin, T. (2006). *The Persona lifecycle: Keeping people in mind throughout product design*. San Francisco: Morgan Kaufmann Publishers.

Ries, E. (2011). *The Lean Startup: How today's entrepreneurs use continuous innovation to create radically successful businesses*. Crown Business.

Savransky, S.D. (2000). *Engineering of creativity: Introduction to TRIZ methodology of Inventive Problem Solving*. Boca Raton, FL: CRC Press.

Schmitt, L., Buisine, S., Chaboissier, J., Aoussat, A., Vernier, F. (2012). Dynamic tabletop interfaces for increasing creativity. Computers in Human Behavior, vol. 28, pp. 1892-1901

Simon, H.A. (1973). The structure of ill-structured problems. *Artificial Intelligence*, 4, 181-201.

Tomiyama, T., Gu, P., Jin, Y., Lutters, D., Kind, C., & Kimura, F. (2009). Design methodologies: Industrial and educational applications. *CIRP Annals - Manufacturing Technology*, 58, pp. 543-565.

Van Gundy, A.B. (2005). *101 activities for teaching creativity and problem solving*. San Francisco, CA: John Wiley & Sons.

Vanderheiden, G.C. (1997). Design for people with functional limitations resulting from disability, aging and circumstance. In: Salvendy, G. (Ed.), *Handbook of Human Factors and Ergonomics*. New York : Wiley, pp. 2010-2052.

Vanderheiden, G.C., Tobias, J. (2000). Universal Design of consumer products: current industry practice and perceptions. In: Proceedings of the XIVth Triennal Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, pp. 19-22.

Vansteelandt, K., Mechelen, I. V., & Nezlek, J. (2005). The co-occurrence of emotions in daily life: A multilevel approach. *Journal of Research in Personality*, 39, 325-335.

Visser, W. (2009). La conception : de la résolution de problèmes à la construction de représentations. *Le Travail Humain*, 72, 61-78.

Von Hippel, E. (2005). *Democratizing innovation*. Cambridge, MA: MIT Press.

Yoshikawa, H. (1985). Design Theory for CAD/CAM Integration. *Annals of CIRP*, 34, pp. 173-178.

Zelenski, J. M., & Larsen, R. (2000). The distribution of basic emotions in everyday life: A state and trait perspective from experience sampling data. *Journal of Research in Personality*, 34, 178-197.