Complexity in Design-Driven Innovation: A case study of knowledge transfer flow in subsea seismic sensor technology and design education

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Abstract
To the extent previously claimed, concept exploration is not the key to product innovation. However, companies that are design-focused are twice as innovative as those that are not. To study design-driven innovation and its occurrence in design education, two case studies are conducted. The first is an example of design practice which includes observation and cooperation process maps in an offshore project. The second is an example of product design education which includes observations of teamwork, team member interviews and archival studies. While the first case study demonstrates how a company innovates through a design-driven process with complex knowledge transference and systematic planning and improvisation, the second case study shows students managing their design processes through concept generation in a less complex trial and error process. Knowledge exploration as a part of design activity was analyzed through the criteria of network paradoxes. A pedagogic concept has been synthesized and validated internally based on the case study, and externally based on other design practices and design research. The pedagogic concept synthesized was Knowledge Transfer Flow [KTF]. The KTF concept can help to orient design students within the information-saturated design processes integrated within complex innovation systems.

Key words
knowledge transfer flow; design thinking; network paradoxes; professional practice in design education

The skill of generating ideas in a variety of ways relates to design practice, but this skill is transferrable to other fields of product development that can result in design-driven innovation. This is why general competence in design thinking has gradually influenced several professional fields (Stamm, 2008, Brown, 2009). According to Stamm, this could happen because design activity includes processes of expertise, which do not necessarily include any particular technological or system knowledge. These processes can be used for encounters with professional practices across technological and social traditions. This can be done by generating, manipulating or combining product and system design features through the generative process of concept exploration. Design-focused companies in Norway are twice as innovative as those that are not, according to Skule Storheil, speaking at the "Inspiration-Innovation" seminar at the Norwegian Design Council in Oslo on April 17th, 2013. If companies already have the necessary knowledge but lack the ability to explore concepts, which is the key to design-driven innovation, then this should reflect on design education as well. However, researchers aim for the skill of "connecting the right dots" (Nussbaum, 2013, p. 58).rather than exploring concepts in multiple directions (Nussbaum, 2013). Therefore, the following question should be critically explored: How does concept exploration lead to increased innovation? The following elements seem relevant in this process:

Problem setting is one of the core values of the creative design process (Schön, 1983). This value emerges from discussing and interpreting a design problem. In educational and professional practice problem setting and concept development have been intensively adopted and methods have been developed (Micheli et al., 2012), while overlooking other methods of gathering and choosing design aspects that have been similarly effective in innovative processes (Gillier et al., 2010). According to Concept-Knowledge theory innovative and creative work happens in a concept space (Hatchuel et al., 2011). Once concepts are affirmed, they pass on to knowledge space; thus, they describe how knowledge is systematized and used again as an essential design factor in creative methods that can lead to new concept generations. Concept space is where many creative methods take place, from combining design aspects to formulating design problems (Lawson, 2006). Thus, in design practices, both associative and cognitive creative methods operate while exploring possibilities within a specific design field (Stamm, 2008). This approach seems too fixated on generating new solutions from existing knowledge, so some researchers propose that these approaches could be developed further from a creative perspective by including a greater exploration of possibilities, which happens by actively using phases of divergent and convergent thinking (Baregheh et al., 2009). This idea that possibilities can emerge from complexity is

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Figure 1. Sensor system deployment preparation

connected to system-oriented design theories, and this is what some design educators frequently aim to achieve in practical design projects (Sevaldson, 2011). However, this is not obtainable without the richness of data to combine and the opportunity to explore the topic in a complex environment. Such a complex environment can be identified in product design practice today, a profession that has evolved from product branding in the 1980s to being part of New Product Development (Perks et al., 2005).

With a lot of suppliers and collaborators in this complex innovation environment there is a need for the skill of choosing what is most relevant in each situation, and what can contribute to innovation. It has been demonstrated that a design team has to be able to explore knowledge space and to generate concepts at the same time (Valtonen, 2007). Another factor for successfully implementing concept generation methods in NPD practice is the ability to handle the increased complexity of knowledge space content and its interconnections to relevant fields (Visser et al., 2007). Despite these studies in design-driven innovation and industrial technology, there still seems to be a knowledge gap concerning the complexity of design-driven innovation in product design education. There is a need to expand knowledge about this design practice, reflected in a pedagogic model that includes practice in complex design work. The research question therefore is: how can network paradoxes in practice contribute to education for design-driven innovation? This question will be discussed in relation to what extent the product designer can be situated in the creative process through a methodical choice of relevant knowledge. The aim is to find a pedagogic tool for design education.

Method

According to Concept-Knowledge theory creative work happens in a concept space through the combination and manipulation of existing knowledge (Hatchuel, Le Masson, & Weil, 2011). This process is termed disjunction, or knowledge transfer. Once concepts are affirmed, they pass on to knowledge space. This process is termed conjunction, or concept transfer. Knowledge is then systematized and reused as an essential concept-generating factor in a new disjunction cycle. Concept-knowledge theory has been useful from a theoretical perspective that allowed for framing research. By tracing conjunctions and disjunctions in different design processes it might be possible to understand how concept exploration and knowledge transfer can induce design-driven innovation. Concept mapping was chosen to record the findings because it presents processes in a visual way, which allows for the comparison of concept and knowledge exploration (Maxwell, 2005).

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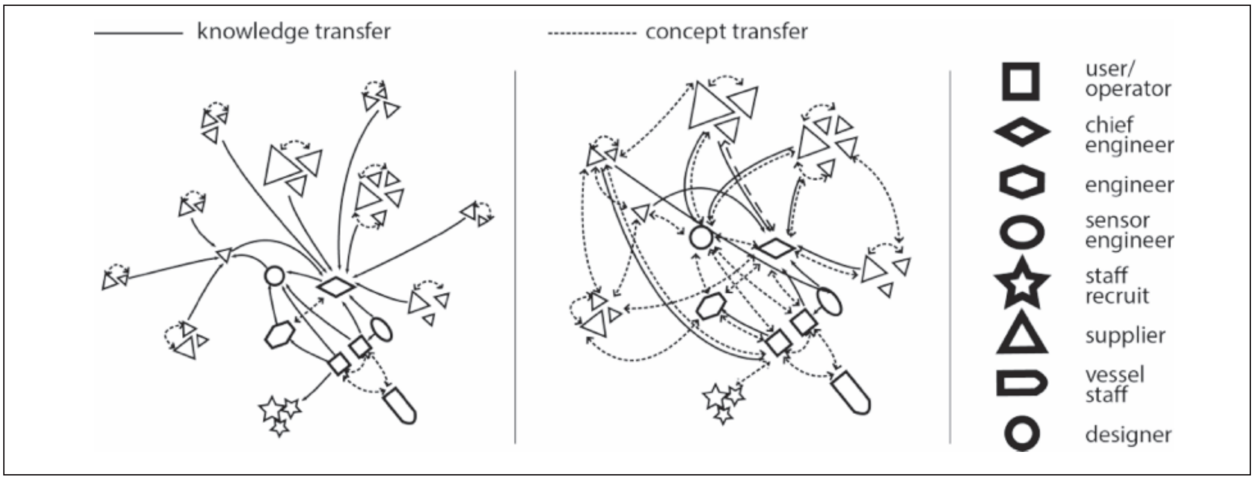

Figure 2a *Figure 2b*

A case study was chosen because there was a need to exemplify theory in the field–such as, in this study, network paradoxes–in relation to practice (Yin, 2009). In order to understand how complex design problems and innovations are managed in practice, problems such as network paradoxes (Håkansson and Ford, 2001), a relevant design project from the offshore industry was chosen for the case study. A participatory design approach (Asaro, 2000) was used to gather the documentation from offshore field work in order to examine the organizational structure and dynamics of cooperation between participants in the process. The aim was to collect material about learning outcomes that enhance understanding, skills, and general competence related to complexity in design-driven innovation. The case study contains observations of two student groups doing their projects to gain direct information about their everyday practices and perspectives concerning the design process (Powell and Steele, 1996). Archival studies of their project reports were used to analyze their reflections on the accomplished projects. As both innovation and knowledge transfer flow occur in certain environments defined by relationships and networks, both case studies are described and questioned by mapping these relationships between participants (called "nodes"). The results have been analyzed and selected through the identification of network paradoxes in organizations to understand how design students become more conscious of how to integrate knowledge space and how to handle complexity in practice (Håkansson and Ford, 2001).

Results from Practice and Design Education

A case study of complexity in design-driven innovation in subsea technology

The case study for illustrating a new practice in product design is from the offshore exploration industry. The design task was to commercialize seismic sensor technology (Figure. 1) and explore the possibility of big scale data production. Technology gave far richer 4D data (Derfoul et al., 2013) that enabled easy oil and gas detection. By compressing the seismic sensor unit size and optimizing the handling system, the amount of sensor units per vessel was doubled and the operating time of the planting of a sensor unit was reduced to one minute.

The organizational context of the case study was the offshore company Seabed, now Seabird. The company, the owner of the technology, and a seismic vessel recruited possible suppliers through a series of pilot projects (Figure. 2a). These pilot projects were time-consuming processes that the administrative leadership frequently opposed. On the other hand, the practitioners in the engineering team gained from them.

The onboard handling system, including trolleys and elevators for automatic transport of the seismic sensor units, was designed by a company that specializes in airport baggage belts for passenger self-service; thus, the system was based on engineering skills and knowledge of logistics. The subsea sensor unit handling (Figure 1) was executed by a company that specializes in remotely operated vehicle [ROV] navigation. This company provided the whole subsea navigation service and was a source of knowledge that enabled the core team to define design demands for the seismic sensor unit and the ROV tool. The sensor unit deployment system and ROV tool that handled subsea loads and placement of the sensor units was fully outsourced to the engineering company that handled high-quality mechatronics to sustain active deep-water use. The construction of the sensor unit components was also outsourced to these companies. A metal frame and some metal vessels were outsourced to

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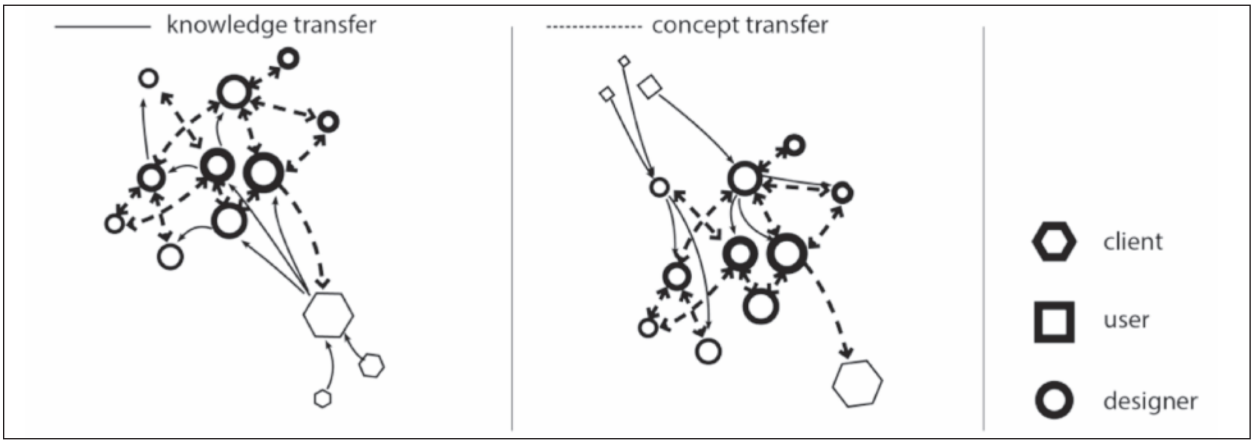

Figure 3a. *Figure 3b.*

a company specializing in metal processes, and this knowledge transfer influenced the frame design and handling procedures. The sensor unit shell production was executed by a company specializing in rotational molding that allowed for the design of numerous multipurpose sensor unit features for both onboard and subsea handling, maintenance, and human interfacing. Logistics and design were outsourced to a company that suggested including a product designer as a permanent member of the team. Software and electronics were designed in a separate division of the home company that housed the core of the new technology. The team leader stated that: "The crucial factor for innovation success was early, initial involvement of suppliers through pilot projects. This allowed the team members not only to pick and choose partners but to learn new practices they were not familiar with." J.F Næs (personal communication, February 21, 2009), (Figure 2a).

The Seabed team featured two chief operators who worked on development in the laboratory and offshore operating seismic procedures on the vessel. Other team members included an engineer, a chief developer, and a product designer who was outsourced from another company. The designer's role was to design systems and product features, and to facilitate discussions through knowing how to visualize animations and to rapidly generate solutions by exploring suppliers' competencies (Figure 2b). The product designer worked daily with chief operators on human aspects through participatory design. Daily decisions were made through discussions and operation simulations. This understanding enabled the designer to facilitate assembly and operating systems through manuals and user interfaces. The product designer worked intensively with an engineering team but also communicated on a daily basis with suppliers about solutions and relevant discussion topics.

A lot of testing of the sensor unit handling system was required. The tests demonstrated that the results were not only merely good but also that the system needed improvement. When the practical operation had started, improvements were still made in the process. When an average sensor unit planting operation took only one minute, the commercial goal was achieved. At that point, it was not just technology but also a relevant service. The process was generative and the participants were expanding their knowledge as well as making solutions. In this approach, people adjusted to the system and the system adjusted to the people.

The design project won an Honors Award for Design Excellence at the annual evaluation of the Norwegian Design Council. It was also nominated for Best Design in British Design of the Year 2010. The concept was characterized as innovative, and its benefits were identified to contribute to functionality in terms of logistics, timing, and branding. It changed the perceptions of the clients of the data sales service.

A case study of complexity in design-driven innovation in design education

Experiences in a subsea technology context and approaches from this practice were used in an analysis of the practical approaches of product design students. The documentation from this student project included direct observation, archival studies, and interviews that would demonstrate students' reflections during design education. The reflections were related to function, performance, originality, and product appeal. Two groups of ten and twelve students each were observed and interviewed during a six-week period in November and December 2012. They were told that observations and interviews were conducted as part of the module evaluation. The goal of the second case study was to exemplify a student

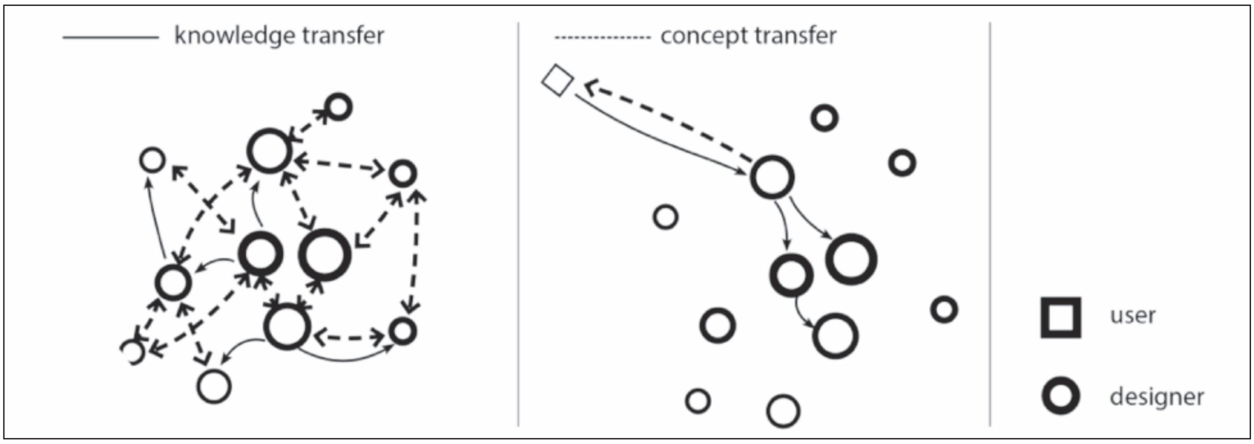

Figure 4a. *Figure 4b.*

project in the context of an educational setting similar to a start-up company where students are set up to form and use network connections to develop a commercially viable design concept. Prior to this subject module, students were trained for two weeks in different skills: third-year students in dynamic project leadership; second-year students in branding, presentation, and communication; and first-year students in mock-up building and workshop equipment. The design students were then merged with several groups of up to twelve students across the three years of the bachelor's program. They were instructed to form and self-manage a design team using the knowledge they had gained in the previous two weeks. The first chosen group for this case study was involved in a realistic project with Akershus Energy, a local hydroelectric plant providing home heating. In order to stay competitive, the plant has to implement new technologies and widen harvesting capacities to be able to reduce prices. Therefore, the plant was seeking the opportunity to expose itself to the local community, raise awareness of its benefits to the environment, and create goodwill and increase satisfaction among its customers. The second group responded to a furniture design competition for Bolia, an interior design chain and producer. The company was seeking a new set of products that would fit in with their portfolio: a specific aesthetic expression with the topic 'nature in the city.' The first interview with members of both groups was conducted at the end of design research and the problem formulation phase, and the second interview was conducted at the end of the six-week period.

The results for the problem definition period showed that the first group hadn't considered any other design aspects than those that were discussed with the client, that the client had pointed out, or that they had discovered themselves through concept generation (Figure 3a). Students had a weekly review with the client in addition to email communication. The leader stated: "We have tight cooperation with the client and they are providing us with relevant information that we need to know." I. Ryland Hasle (personal communication, November 23, 2012) The group had spent a great portion of their project on finding and defining a concept that would promote company values.

The second group didn't establish any contact outside the group and defined their design problem through the interpretation of competition propositions (Figure 4a). When asked how they decided on the most important design aspects to address in their project and how they collected relevant information, the students claimed that they focused on the ideation process. "Since we don't have direct communication with the client, we are focusing on gathering ideas and then deciding how they could fare in the competition"; "We have the specifications from the competition entry, but we have mostly discussed on our own how these ideas could be commercialized." M.C Torgrimsen (personal communication, November 20, 2012). After the first round, students were encouraged to observe or interview users. The first group conducted interviews with several users within their target group and adopted their insights as a valid design aspect when generating final solutions (Figure 3b). The second group focused on finishing a functional prototype without previously interviewing or observing any users. The final prototype was presented to a user and an interview was conducted where the user reflected on the prototype design (Figure 4b). These insights were then delivered in the group report.

Discussion on Network Paradoxes

Network connections have been defined by the opportunities and restrictions they give to participants; these network connections have been called "nodes" (Håkansson and Ford, 2001). This research describes three paradoxes in the nature of node relationships. The first paradox explains that "The stronger the threads are—the more content there is within them—the more important they will be in giving life to the node, but the more they will also restrict the freedom of the node to change." The second paradox describes how the nodes and the threads are interdependent, meaning that companies build relationships that are in their own interest, after which relationships start defining companies. The third paradox describes how relationships influence a company by putting companies under the influence of their partners. Controlling these relationships is crucial for a company, but at the same time the dynamics of the relationships bring change and new ideas which tend to happen due to a lack of control (Håkansson and Ford, 2001).

As shown in the offshore case study, similar opportunities and threats could be applied to knowledge transfer flow within a network relationship. The study showed how pilot projects were used in establishing new relationships as effective managerial moves in order to minimize restrictions, stimulate opportunities, and gain knowledge transfer while establishing connections with component suppliers who saw a relevant professional challenge for themselves. Pilot projects were a form of establishing cooperation and also an establishment of a policy and company culture that made the company less inert and more innovative. In the case study, a pilot project was a good method to diminish paradoxes to a certain extent. In the case of the first paradox, healthy threads were established through trial and error. In the case of the second paradox, healthy threads were created by defining the scope of action. Finally, the third paradox was partly diminished by focusing on the goal rather than on a way to achieve it.

In the case study of the first student group, the project was strongly affected by the first paradox as they had only one connection established over a longer period of time, analyzed and visualized through concept mapping (Figure 3a) (Maxwell, 2005). As soon as they had established the link with the third node–the user–the knowledge transfer flow gained new meaning for them and the first node, and this enabled the second paradox (Figure 3b). The knowledge they gained by interviewing users influenced the client's knowledge space as well. In contrast, the second group of students minimized the amount of knowledge in their concept space by not developing any network outside their own group task sharing. This reduced the opportunity for commercial refinement and further detailing of their concept. In this case study, the initial knowledge transfer (Figure 2a) seemed to enable the most effective innovation process.

A pedagogical concept in network paradoxes

The results shown indicate that it is difficult and unlikely for design-driven innovation to occur in educational settings. Design can play an important role in innovation, but, for this to happen, design has to be present in the commercialization process, not just in concept generation (Stamm, 2008). This is not yet common practice in randomly chosen design education problem-based learning settings. Studies also show significant knowledge transfer activity in the innovative offshore project, which is absent in studies of student projects, indicating that education is not preparing designers for using design as a tool for innovation. The study of design in a subsea technology context showed that extensive collaboration created the opportunity for the knowledge transfer flow to emerge. This was analyzed, visualized, and categorized by concept mapping (Maxwell, 2005) into a pedagogical concept: Knowledge Transfer Flow (KTF) (Figure 2b). Furthermore, the case study demonstrated an example of how complexity can be demanded in professional practice and how certain design competencies are essential in order to manage and organize problem complexity. However, it also revealed that complexity cannot be obtained without a thorough examination of knowledge space in practice. This complexity consists of many highly advanced professions within a dynamic interplay, and these premises are crucial for design-driven innovation.

The complexity demonstrated in the subsea technology context was not reflected in the design education. Although the problem-based learning process demonstrated how design students were motivated to choose their own problem perspectives, how they discovered it, and how many aspects of the problem were considered before or during the design activity, the implication of the study was that design education should be viewed from a wider perspective than only as a concept-focused process method (Aagaard Nielsen and Svensson, 2006).

The study exemplify in practice how knowledge space can be explored in network paradoxes. The case studies showed that in real-world projects the design process relies intensely on knowledge space exploration and knowledge transfer than design subjects conducted in cooperation with external factors. The case study of the design education, contrary to the design process, relied on massive concept generation that was later analyzed and from which conclusions were drawn. The second group of students used most of their time to build a propositional model that needed validation in reality. They learned how to explore concepts but seemed to fail in directing their knowledge into a broader implementation and commercialization context, and they did not implement their work into a complex network setting. Such an implementation is crucial for innovation (Figure 3a). Therefore, it can be useful in design education to expand student activity into more complex contexts. Design education should teach students to design and innovate in specific real-world settings (Figure 2a).

The knowledge transfer flow that might happen in network paradoxes was exemplified. It was shown how it was necessary to experience problems in practice in order to understand them from the design studio. In one anthropological study an architect bureau was observed (Rudningen and Hagen, 2009). According to this study, the professional design practitioners working in the group had the tendency to be confined by their materials, and extended their work in their studios. This is quite opposite to openness to new experiences and communication which was stimulating for creative processes, (McCrae, 1987). It was essential to learn and try to design elements outside the knowledge field. The more unknown, the richer the solution, so ambiguity was crucial in the design process even though it could break the experience of the flow (Csikszentmihalyi, 2008). Complexity and generative processes were inevitable for creative solutions. It has been argued (Buur and Jakobsen, 1991) that design is a process method and that designers need to master design as a process tool. This is a valid view, but it is also crucial to acquire the ability to immerse oneself in a problem and to obtain any necessary knowledge in one's chosen field (Csikszentmihalyi, 2008). The second case study demonstrated that, while students were able to generate valid concepts, they were not aware of the necessity of immersing themselves in relevant knowledge space, possibly because they had not learned to do so. If designers are to master and handle design process, they would gain from knowing how to facilitate the knowledge transfer flow as a substantial source of creative provocation. It would be a good preparation for professional practice if design teachers made students experience how to enable knowledge transfer flow in an academic and practical way. Design education can contribute to this by enabling interdisciplinary environments for problem-based learning.

Implication for Design Education and Design-Driven Innovation

The result from the two case studies documented that concept exploration can be enhanced through knowledge transfer flow, especially in the incubation of the creativity phase. The design approaches have been developed through a case study of subsea seismic technology to enhance commercially-based innovation in design education. The educational goal has been to prepare students to tackle complex design processes and elements in their future jobs. The theory of flow could help explain the psychological mechanics of dealing with complexity. According to that theory, a problem-solver's experience of a problem-solving process depends on the relation between problem complexity and the problem-solver's skills (Csikszentmihalyi, 2008). Flow is defined as the opposite state of apathy where the problem-solver experiences enough difficulty to be stimulated and enough mastery to be able to handle working on the problem. Csikszentmihalyi's subjects have reported that they tend to lose track of time and experience a sense of satisfaction by working on a problem. These subjects had long-time experience working with these problems, which means that they have mastered problem aspects of knowledge space. Reflecting on this, it would be reasonable to consider that, by limiting the amount of design aspects, students are making it easier for themselves to achieve the flow. This might make it easier for students to adopt concept exploration mechanics, but they would miss the complex settings in which innovation tends to happen. From a pedagogical perspective it might be equally important to teach students to generate creative ideas as it is to allow and manage complexity. It should therefore be carefully considered how to provide students with intuitive methods for accessing and assessing knowledge space to create network settings that simulate the complex environments in which innovation occurs. Pilot projects seem to be a good method for establishing relationships in business settings, but further research is needed about their implications in educational settings.

It is in human nature to solve puzzles, which gives a sense of purpose and, once solved, a sense of achievement (Lawson, 2006). He warns that designers need to delay this sense of achievement as part of the design, unlike puzzle games, which almost always lead to multiple solutions. Choosing the acceptable solution is then part of the convergent creativity phase. In newer creative personality theories, one of the properties of a creative personality is tolerance of ambiguity (Stamm, 2008). It is argued that designers have to be flexible enough to keep the problem open while at the same time having enough

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confidence to choose paths in convergent phases of creative processes. Some researchers would see the tolerance of ambiguity as essential for the innovative results that emerge from complexity (Sevaldson, 2011).

Product development activity should, according to the requirements from the Bologna process, reflect a more holistic and complex view similar to business practice. The discussion is about how complex methods have to be modified to integrate large amounts of data throughout the whole commercialization process, not only in concept development, which demands that designers learn even more rapidly. The new pedagogical concept of knowledge transfer flow based on complexity in design-driven innovation (Figure 2b) can enhance this design practice. In the aim of solving complex problems it is not valuable to convert design education to a total integration of designers into the company workflow as there is a danger that valuable perspectives can be lost. Instead, most design education has intrinsic qualities that can be enhanced through the extension of design activity rather than changing the designer's role. Further research should be executed on how design practitioners allow and manage complexity in engineering and in complex institutions such as hospitals and other contexts. Designers must often search for relevant design aspects from knowledge space in a very short period of time. It would contribute to the culture of innovation if designers worked with knowledge sharing to a larger extent in complex situations. The effort should be put into researching how successful designers manage their knowledge space exploration process. Students who experience more complex situations in their design education thus could become more independent in organizing design processes. Learning to experience and tolerate ambiguity in practice could contribute to strengthening designers' identities and the creative qualities needed for knowledge-based innovation.

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