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HETEROGENEOUS ENGINEERING: ESSENTIAL BRIDGE IMPLEMENTING CREATIVE DESIGN

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Abstract

This paper connects design creativity to engineering activities as means for smooth implementation of creative concepts. It applies C-K design theory and the IDER-innovation model as lenses to investigate three case studies. The results point to engineering activities as operators to transform the undecidable concepts in the C-space to objects with a logical status in the K-space. Engineering (E) knowledge as validated objects in the K-space supports the transformation process. If existing E-knowledge is sufficient, then this resembles single loop learning. If concepts in the C-space are too different from earlier concepts, then new E-knowledge needs to be developed which resembles double loop learning. The research for developing new E-knowledge unfolds in a similar fashion. Tentative theoretical insights in the C-space are 'engineered' by validated research methods from the K-space. Further research needs to address the complexity of real-life socio-interactive situations. The paper shows that the engineering act in a heterogeneous manner is at least of equal importance for innovation as the creative design act.

Keywords: Innovation, Creativity, Design methodology, Engineering, Implementation

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1 INTRODUCTION

There is no doubt that product innovation processes contain engineering processes and activities. Similarly, it goes unquestioned that product innovation can't do without design creativity. Since both are part of one and the same innovation process there must somehow be a connection. Question comes to mind: how are design and engineering as two indispensable activities related? The related scientific literature (e.g. design, innovation) pays some attention to the role of creativity, be it in in isolated forms, but seems to take the engineering activities for granted, let alone, discussing its relationship with creative processes. Therefore, connecting design creativity and engineering forms the subject this paper.

There is literature that focuses on the creative parts of the design and engineering process, however without providing rich descriptions of what the actual engineering activities contribute. For instance, design is believed to bring the romantic perspective whereas engineering brings the control perspective (Dong et al., 2014; Happold, 1986), but how are these two related in one particular process? Reich et al. (2012, p155) observe: "engineering does not value creativity per se and pure 'out of the box' solutions cannot be explored for themselves" and they propose a specific creativity strategy in the form of ASIT, Advanced Systematic Inventive Thinking, that might be of help to create expansions of our knowledge. Apart from this paper by Reich el al., engineering seems to be seen as a set of routinized and well-known activities based on existing knowledge that bridge the gap between the conceptual state of the product as created by design activities and its final state when it comes of the production line and/or is realized. Most engineering literature is dedicated to a certain class of objects (e.g. ships airplanes, dykes) and provides validated means, tooling and rules of dumb to engineer these objects. This raises questions in the case of creative concepts that require new sets of engineering knowledge; where does that fit in present theoretical descriptions of design, engineering and at aggregated levels the product innovation processes?

To answer this research question we made use of three studies/cases. One reports on the creative design and subsequent engineering processes of Formula One designer Gordon Murray (Cross and Clayburn Cross, 1995, 1996 and 1998). The second study focuses on the development of a new aerospace material Glare that is presently part of the fuselage of the A380 (Roebroeks, 1991; Smulders, 1988; Vlot, 2001). The last study reports on a study in two companies focused on the socio-interactive perspective on bridging the gap between design and volume production (Smulders, 2006).

The empirical data in the cases studied seem to point to a very distinct role of engineering activities in order to move from the creative concepting stage to the final realization stage. We will use two theoretical frameworks to analyze these cases and see if we are able to describe the relationship and roles of design creativity and engineering. C-K design theory as introduced by Hatchuel and Weil (2003) forms the first framework. The two spaces, concept (C) and knowledge (K) space, its relations and its operators to move within these spaces and move from one to the other provide the first set of footholds for our purpose. The second framework is formed by the IDER-model introduced by Smulders et al. (2014). This model provides an abstracted description of the full innovation process that starts with Initiating (I) the innovation endeavor followed by Designing (D) to create a concept that subsequently needs to be addressed by Engineering (E) activities to assure its validity for Realizing (R). The IDER-model as such makes explicit reference to design and engineering activities, but might be complimented with the logics of the C-K theory in order to arrive at the relationships searched for.

The remainder of the paper is structured as follows. First C-K theory will be introduced and discussed. This is followed by introducing the IDER-model and relating that conceptually to the C-K-theory. Based on this we will introduce briefly the three cases and analyze these through a lens related to engineering activities. The paper will end by showing the similarities and complementarities of the two theoretical descriptions.

2 CK THEORY

About a decade ago the C-K design theory was introduced as a new formal framework to support design reasoning. Two design spaces and four operators within and between these spaces form the building blocks of this interesting theory. Designing, according to this theory can be seen as a co-expansion or co-evolution process between the C-space and the K-space (e.g. Hatchuel and Weil, 2003; Agogué and Kazakçi, 2014). Concepts have no logical status in the K-space, whereas propositions have a 'true' or 'false' logic in the K-space. According to Hatchuel and Weil (2009) design faces a situation with an infinite list of ‘candidates’ as opposed to a chess game. The C-space allows for partially unknown objects that are ‘undecidable’ in the K-space. For instance, ‘all aero space materials that are fatigue resistant’ (see later) form a collection of undecidable propositions and are termed a C-set. It is the manipulation of collections of objects without stable definitions that forms the core of the design process. Manipulation in the C-space is preceded by a disjunctive operator (K->C) that proposes the concept and followed by either operators that ‘partition’ in the C-space, or conjunctive operators that initiate subsequent logical K->K reasoning activities in the K-space. Hatchuel and Weil (2009) point to the growth in the C-space as tree-structured whereas the expansion in the K-space resembles more an ‘archipelago by the adjunction of new objects’ (2009). The search for attributes either results in new tentative concepts, like ‘all aero space materials that are fatigue resistant’, or result in new propositions ready to be checked (true/false) in K-space, like ‘fiber reinforced materials are fatigue resistant in airplane structures’ (=true). Connecting this ‘island’ to another ‘island’ in the K-space, like aluminum sheets are sensitive to fatigue, could result in a undecidable proposition of ‘fiber reinforced aluminum laminates are fatigues resistant’ in the C-space and in fact forms a partitioning of the initial undecidable proposition ‘all aero space materials that are fatigue resistant’. The continuation of the design process, i.e. enacting its operators, results in “two different yet interdependent structures in the Space C and Space K.” (2009, p188) and where each of these spaces has its own logics. But, since the two spaces are interdependent, one could ask, what logics support the interplay between the two spaces? Lets look into another theoretical modeling of the innovation process that includes a design element.

3 THE IDER MODEL

This section describes the recently introduced IDER-model, first as a static representation of the product innovation process (Smulders et al., 2014) then followed by a deepening of the model by adding a temporal dimension as representative for dynamic situations (Smulders, 2014). The latter being illustrated by some vignettes from the data set.

3.1 The IDER-model as such

Innovating is about the realization of something new in an existing environment. The recent hype on design thinking caused us to examine what happens if design thinking is applied outside its conventional domain of new product development (NPD). Based on the generic steps as found in literature on product innovation processes (e.g. Roozenburg and Eekels, 1995; Ulrich and Eppinger, 2008) an abstracted model was developed that positions the design activity relative to its associated activities. This resulted in the IDER-model in which all four stages of innovating are sequentially dependent and each stage is characterized by a different set of dominant process characteristics (Smulders et al., 2014). The first element ‘I’ of initiating covers the front end of product development by, for instance, market research and/or ethnographic studies. The second element D of designing concerns the development of concepts of the new product/service. This includes the recent work by Dorst on framing and reframing as being the core of design thinking (Dorst, 2015). The third element E covers the engineering and embodiment of the artifact and the associated development of the necessary manufacturing processes and tools. Engineering aims to validate and consolidate what comes out of the D element and to prepare that content for implementation in the totality of the R element. The fourth realizing element R aims at inserting ‘life’ in the value chain, that is, ramping up all activities associated with, e.g., purchasing, logistics, production, sales and use of the new product. The R-element is to be seen as a new or adapted socio-technical reality in which actors perform on a routine basis activities that are part of the overall value chain, including the use of the new product or service. The R-element therefore stretches far beyond the product and includes all the operational processes necessary for realization of the new product or service. This operational situation marks the end of that particular innovation-cycle and possible the beginning of a new one. Smulders et al. showed that if design thinking is transferred beyond its original domain of product design, the qualities and properties of that new context matters, that is, will the new context be capable to ‘engineer’ or better, ‘robustinize’ the new concept resulting from this new ‘fremd körper’ of D-activities.

In a second paper, Smulders (2014) took the idea that the R-element containing all disciplinary objects belonging to operational processes one step further. He suggested that to develop all these necessary disciplinary and heterogeneous objects similar need to be subjected to IDER-cycles. Think of the department of legal affairs that details the contract with a new supplier, which is very similar to what engineers do when they detail components of the product and decide upon tolerances. And like product development, contract development first goes to a similar cycle of ‘initiating’ to look for suitable suppliers, ‘designing’ to discuss the conceptual contract in terms of what will be supplied in what quantity, quality and logistics before this concept ends up on the desks of legal that will ‘robustinize’ its content by applying their heuristics consisting of rules, regulations and former legal and contractual experiences.

In this holistic sense, each discipline (or innovating actor) that is affected by the innovation process moves through its own IDER-cycle to develop its disciplinary object and make it fit for use in the new or adapted socio-technical system, being the operational processes that produce the new products or services. These operational processes are to be seen as the summation and integration of a large array of interrelated operational activities that form the results of all separate sub-IDER-cycles. Therefore, the IDER-model must be seen as a system of nested and/or interrelated IDER-cycles that could run largely in parallel to each other causing all IDER activities may take place simultaneously, be it aimed at these different and heterogeneous disciplinary objects in a concurrent fashion. As Figure 1 aims to illustrate, the proportions of IDER-activities change over time from a sole focus on initiating activities at the start of the new product development process, to a mix of Initiating (I), Designing (D), Engineering (E) and Realizing (R) activities during the process, to almost full Realizing at the end. Over time and towards the end of the overall innovation cycle less and less objects need to be developed and need to go through IDER-cycles. At the same time, more and more content (i.e. developed objects) ends up as applicable knowledge ready to be applied in operational processes.

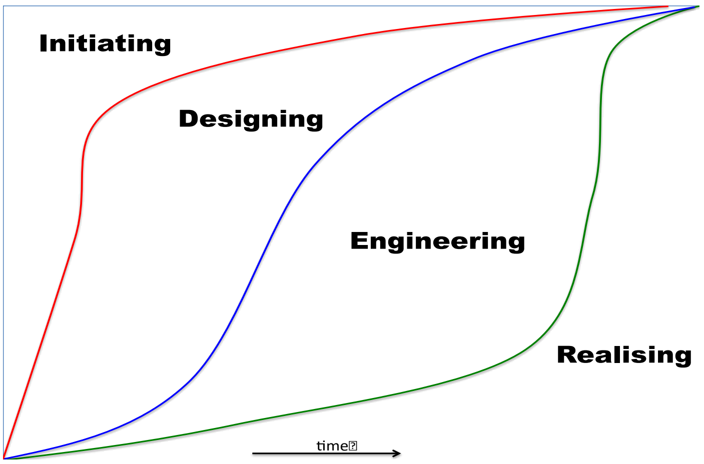

Figure 1. Schematic representation of the proportional changes of nested IDER-activities over the full innovation cycle (Smulders, 2014)

Figure 1 presents the ideal situation that has no or very little unforeseen iterations and most importantly no unexpected engineering design changes towards the end of the innovation cycle. It is to be noted that the IDER-activities are sequential dependent activities. One can’t realize any object, if there is no ‘engineering’ that aims to predict its robustness that again is part of a designed conceptual frame that at some point is initiated because of the need to have such an object for full-fledged realization (R). The duration of IDER-cycles and its sequential activities can range from seconds to months and years. Such depends on the level of aggregation.

From this point of view the IDER-model may be regarded as a basic innovation cycle that counts for every object that is affected by the development of the overall object, in this case, the new product or service (Smulders, 2014).

3.2 Engineering knowledge seen from dynamic perspective

Here we start from the observation that the IDER-model is cyclic and that every related disciplinary object affected by the overall innovation process needs to go through such a cycle, be it for small, medium or large cycles (in terms of duration). During the initiation of any sub-cycle the disciplinary actor needs to check if he/she will be able to arrive at realization, meaning, the actor needs to check if there is a suitable concept or framework to reason from and to base its ‘engineering’ or robustizing activities on in order to reach the R-situation.

Smulders (2014) used a large research base with over 30 projects to arrive at the insight that it is not only the emergence of new concepts from the D-element which are important to innovating (i.e. the new ideas), but the often related and necessary renewal of E-activities seems to form a much more challenging part for the actors involved. If actors are not able to solve any issue with existing E-knowledge, then new E-knowledge on how to ‘engineer’ this idea must be developed, at least for the new idea to reach operationalization.

Take for instance the changeover from monolithic aluminum airplanes to composites. While the composite engineering theories were still sought for, engineers simply applied the aluminum knowledge base to engineer and detail constructions. Since composites are much stronger and lighter, the sub-optimal composite solution still resulted in lighter constructions. Because of the applied aluminum engineering theories, heuristics and rules of thumb these planes were being referred to as ‘black aluminum’ planes (Tsai, 1993).

What is contended here is that a new concept or frame (Dorst, 2015) from the D-element might require new or adapted theories, heuristics and rules of thumb to ‘engineer’ the idea as to prepare it for use in the R-element. In essence a new or adapted E-practice needs to come into place. An E-practice consisting of new ‘knowing how’ being the capacity to act effectively in the E-element (e.g. Ryle, 1949; Orlikowski, 2002). Smulders (2014) suggests that developing new E-knowledge for new D-concepts resembles double loop learning whereas, new concepts using existing E-knowledge resembles single loop learning as described Argyris and Schön (1978).

Typical E-knowledge consists of formulas, heuristics, procedures, rules of thumb, earlier experiences and insights, etcetera. In short, E-knowledge is to be seen as knowledge that has proven its reliable application in the past, like the contract experiences of the legal department. These proven engineering activities (i.e. sciences of the artificial, Simon, 1980, 1996) support all the separate disciplinary engineering processes in such a way that whatever comes out of these E-activities is fit for use in the R-element, that is, fit for use in targeted disciplinary operational process. A further analysis of the projects showed that the D-E and the subsequent E-R transitions are crucial for realization (R) and form the core of the innovating activities.

4 CONNECTING C-K THEORY TO THE IDER-MODEL

At first glance one could see the C-K theory as representative for the design activity, being the D-element in the IDER-model. However, as we have discussed, in the IDER-model, the D-E and E-R transitions are crucial. Actors are not able to ‘engineer’ or ‘robustinize’ the object if they lack the knowledge for doing so. In terms of C-K, they lack the availability of true propositions that supports the conjunction of a conceptual object to the K-space, suggesting here that the conjunction operator in fact is made up by engineering and robustinizing activities, that in their turn are based on true propositions from the K-space.

If one applies/connects, for instance, aluminum E-knowledge (true in K-space) to undecidable carbon composite proposition in the C-space, then this conjunction might result in true proposition in the K-space, be it sub-optimal since it doesn’t take the particularities and properties of composites fully into account. Seen from this perspective, (proven or validated) E-knowledge as such is part of the K-space and the conjunction with undecidable propositions in the C-space (concepts) supports the testing of these propositions to become true or false in the K-space. The existing aluminum based E-knowledge is adapted by classic types of reasoning to testable propositions for the composite structures. Such adaptations seem to represent single loop learning for the actors involved, that is, a new concept is engineered with existing or slightly adapted E-knowledge. Seen through the lens introduced by Reich et al. (2012) the black-aluminum planes might be the result of advanced systematic inventive thinking (ASIT) that creates K-expansions in the existing knowledge box. On the other hand, the 30 years of developing suitable E-knowledge for composite structures that takes the specifics of composites into account might be regarded as a process of double-loop learning in which new governing variables and rules are developed.

Apart from these observations, we assumed that all disciplinary objects that are affected by the innovation process end up in the K-space. Be it products, production processes, contracts, logistics, sales processes, product use activities, etcetera. It is hypothized here that all these developed objects can be described using IDER-cycles as well as the conjunctions between C and K spaces by engineering and robustinizing activities.

Lets return to the focus of the paper and its research base to see if we find any support for this.

5 RESEARCH BASE

This paper is based on three cases. The first case considers the design and subsequent engineering process of Formula One designer Gordon Murray as he developed world champion cars (Cross and Clayburn Cross, 1995, 1996 and 1998). The second case concerns a study focused on the transition from design and engineering to ramp up of the manufacturing process (Smulders, 2006). The third case focuses on the 30 year long research and development of a new aerospace material Glare that is presently part of the fuselage of the A380 (Roebroeks, 1991; Smulders, 1988; Vlot, 2001).

5.1 Gordon Murray: from ideas to F1 world championship

This section draws heavily on the analysis of the work by Nigel Cross and Anita Clayburn-Cross (1995, 1996 and 1998). The Formula One world is highly competitive and dominated by innovative behavior of the designers, engineers and drivers. The regulations leave very little design space to ensure all cars are somehow comparable and therefore only successfully applied creativity can make the difference. Winning four championships (1981, 1983, 1989, 1990) makes Gordon Murray to an exceptional design engineer. During a season, when pressure is at the highest levels, the design and engineering efforts are dominantly focused on doing the right modifications and improvements without making the jump to a whole new car design. For any new season such dramatic changes are possible, however, most competitors developed a new version of the previous season’s car by a new chassis, new engine, new aerodynamics and new suspensions, to name a few. For Gordon this opportunity was mostly met by creating a new concept. This was not just creating new ideas, but carry these through with the same speed and quality of actions until full realization. As Murray says; 'You have the idea, but you have to do it, and that's what cuts the bullshit out.' (op cit, Cross and Cross, 1996, p94). Meaning, he needed to go through a full IDER-cycle and by doing so expansion of the K-space happened.

The regulations for the 1981 season required a 6 cm clearance between car and road surface. However, Gordon knew that 1 cm clearance provides much better down force and high corner speeds. He wondered how the hell he could develop something (not man operated) that brings the gap back to 1 cm while driving at high speeds whereas brings the gap to the (required) 6 cm in stand still. He entered the C-space by proposing: ‘there exists a physical thing […] that drives the car down on its own’ (op cit, Cross and Cross, 1996, p94). This is a typical undecidable proposition facilitating disjunction from the K-space. Gordon aimed to develop a hydro-pneumatic suspension that allowed the car to go as deep as 1 cm above the road surface during high speeds. However, the issue he needed to address before he would be able to engineer his suspension was a slow transport of the fluid because he wanted the car to stay low during the whole race, so also while driving relatively slow in corners. So he was in need of a filter that would release the fluid very slowly, yet fast enough to increase the clearance back to the required 6 cm during the final slowing down lap and before the car would be checked by the FIA-authorities.

After the identification of a micro-filter (in K-space) they needed to build a very tiny little throttle valve. By experimenting they found out what size holes were enough slow in releasing the fluid during the race and fats enough while slowing down after the checkered flag. The latter activity could be considered a pure engineering activity that caused the hydro-pneumatic suspension as an undecidable proposition in the C-space to become a true proposition in the K-space. The first race was a success and the Brabham team “just blew everybody into the weeds, just totally; and everybody went bananas!” (op cit. Cross and Cross, 1996, p95). From the team’s perspective new knowledge on hydro-pneumatic suspensions in the K-space was created, whereas this was not the case for the competing teams that had no idea what Gordon and his team had created, since they didn’t knew Gordon successfully went through the C-space to identify a new underlying frame/concept of slow fluid transport by carefully engineered micro-filters. This clearly illustrates the relationship between design creativity in the C-space and the engineering activity to bring the concept into the K-space.

5.2 Glare: the development of a new aerospace material

GLARE (Glass Laminate Aluminium Reinforced Epoxy) is a relatively new aerospace material that was developed at Delft University of Technology (DUT) and belongs to the class of Fiber Metal Laminates (FML). FML’s are specifically developed to increase fatigue resistance of sheet materials in airplanes. Although, the development of this new material was initiated by the work done by Fokker and DUT on bonding aluminum structures during the post war period, we start here at the moment the first FML was invented in the early 80’s. This material, Aramid Reinforced Aluminum Laminate (ARALL) was very promising during the first years of its development and testing (Marissen, 1988). Tests of specimens showed excellent fatigue behavior. The subsequent testing of wing panels in the Fokker F27 needed to provide the proof of the ARALL-proposition in the K-space (Van Burg et al., 2008). These and other ARALL parts were developed at DUT as is illustrated by the following quote: “It was remarkable, certainly at that time, that Delft had designed the wing panels and had even made the production drawings according to Fokker specifications, so that Fokker could easily produce the panels. Delft also designed all kinds of detailed test specimens and tested them. So, Fokker could test the larger size panels including the full-scale panel” (Van Burg et al 2008, p150). DUT applied existing aluminum based engineering knowledge for the detailed design and production drawings. In fact, the conjunction of the ARALL-concept and existing engineering knowledge is not just a click-and-go action, but a real engineering activity leading to a testable proposition in the K-space. Also along the lines of the IDER-model, the E-element secured the bridge from the D-element to the R-element. The very positive results of testing the wing panels brought the ARALL-concept to proven proposition in the K-space. Looking through the lens of the IDER-model, one could say that the development and testing of these full-scale panels, was to validate the concept of ARALL at this stage of the development. This not only illustrates the role of engineering to transform an undecidable concept in the C-space to a testable proposition, but evenly shows that prototypes and test panels are also objects that need to go through IDER-cycles as part of the overall development process. All these activities took place in the mid 80’s and its positive results made Alcoa decide to continue the market introduction of ARALL (Alcoa Aerospace Technical Factsheet, 1986; Vlot, 2001).

However, almost at the same time, in 1986 it was discovered that similar test panels of ARALL had disappointing results for the cyclic loading conditions of the fuselage, at that time a potential target application for larger volumes of ARALL panels. Aramid fibers that were believed to bridge the cracks in aluminum broke under these cyclic loading conditions resulting in poor behavior of the laminate as a whole. From this, ARALL as a material consisted at the same time of two propositions, one true (wing application) and one false (fuselage), both in the K-space. Grounded research (Glaser and Strauss, 1967) to uncover and describe the fiber failure mechanism resulted in testable hypotheses to falsify this new theory (Smulders, 1988), and by that bringing these theoretical insights on the actual fiber-adhesive behavior into the K-space. Here the research methods formed the E-knowledge to test tentative theoretical insights. These true propositions initiated a new disjunction from the K-space to the C-space with an undecidable proposition of a laminate containing glass fibers instead of aramid fibers, the second frame/concept. A decade long co-evolutionary process followed iterating between C- and K-spaces aimed at the creation of additional and new validated E-knowledge for engineering and robustinizing this aluminum glass concept; et voila, there was GLARE and its application in the A380, all in the K-space (Vlot, 2001). From an IDER perspective the new E-knowledge made it possible to bridge between the C-space concept of glass fiber laminates to a GLARE application in the fuselage of the A380 (Roebroeks, 1989; Vlot, 2001).

We have seen in this case is that developments around the original frame/concept (ARALL) as a result of the first creative D-activities in the early 80’s applied existing E-knowledge to prove its value which resulted in a false proposition. However, new theoretical insights on fiber-adhesive interactions formed the base for developing additional and new E-knowledge that turned the second frame/concept into the true proposition of GLARE within the A380, hence a double loop learning process. Let’s have a look at the third case to see how this continues in the social dimension.

5.3 Ramping up production: Engineering in the socio-technical domain

The third case concerns a research project that focused on describing and understanding the transition from the design of a new product via ramp-up to volume production (Smulders, 2006). A socio-dynamic lens was used to investigate this transition in a grounded fashion ((e.g. Glaser and Strauss, 1967; Glaser, 2002; Locke, 2001). The core of the research was performed within two companies (audio equipment, Audiocom and festival lighting, Lightcom) and concentrated on two cases in each of the companies.

One of the observations in Audiocom of relevance here was the development and implementation of a new automatic and refined method of testing the sound quality of televisions. During ramp-up on the assembly line, however, this new object brought to the surface sound problems that were never detected before in any of the previous products of Audiocom. At first glance there were two paths to resolution.

One, to adapt the procedure of handling these sound problems at the assembly line and another one to redevelop the internal sound absorption system of the set aimed to eliminate these sounds. The first was not acceptable for the assembly workers, since there was too much noise in the assembly area. In IDER-vocabulary, the assembly workers would not be able to robustinize this new procedure. The second path, new theories and heuristics on sound were needed to engineer the TV-set properly. Such double loop learning process would result in unacceptable delays in time to market. Finally, a third solution was chosen: it was decided to abandon the new test method altogether. Since no consumer ever complained about these sounds in the past, the unwished sounds were believed to be largely outside the human hearing spectrum.

This vignette illustrates that the new testing method couldn't be realized due to insufficient 'engineering' activities to prepare the new object for the R-element in assembly. Interesting to see that the route traveled by the object from undecidable proposition in the C-space at the development department, to a 'false' proposition in the K-space could be considered from the perspective of the C-K-theory a success, i.e. new knowledge (false propositions) was developed by design and engineering. However, the same object seen through the lens of the IDER-model that considers a full innovation cycle was unsuccessful, since the sound box never arrived at the R-element and was abandoned before volume production (R) was reached. Finally, we observe here the limiting human dimension of the assembly workers to properly 'engineer' their own behavior around the sound box.

Finally, the last vignette will show that at an aggregated level the whole development project including all its many disciplinary socio-technical objects needs to become a true and integrated proposition in the K-space. The situation once volume production is reached is to be considered as an integrated socio-technical reality that at some point was initiated as disjunction from the K-space and becoming an undecidable proposition in the C-space. For instance: 'there exists a TV-set with excellent user experiences 'x' that can be produced by us'. To arrive at volume production, i.e. number of products per unit of time, the people at the production and assembly line need to be able to arrive at a certain level of routine.

> **"…we still have a few things that our mechanical designers are working on. Another solution of … we have a glass frame… they are developing another way to do it, because it is to tricky to do it in the present way, to assemble it in the factory. Now they are assembling it in the ugly way, that will say, it is difficult for them, it takes time. It is OK for the costumer, the costumer cannot see anything, it is only it takes too much time, to difficult, …[the assembly people] have to check it too much and so on …they have to be careful about quality. So they [NPD] are working for the moment on another way to do it and it is…. in a week or two we have the solution we think, and the tools are finished, so we can get the parts for it…" (Audiocom.NPD.5.599).**

The quote describes a design iteration in which the engineers have to re-conceptualize (D-activity) and engineer (E-activity) a particular part of the new product in order to ease the assembly process for the people at the production line. A false proposition is OK for C-K theory that concentrates on the design process as such, but not for the IDER-model that concentrates on knowledge in action (R-activities) at the end of every individual IDER-cycle. This quote also illustrates that in parallel to the already started production and assembly (R-) activities there are still some IDER-activities going on that are necessary for completing the transition to manufacturing and to make it possible to realize the required level of volume production. In other words, IDER-activities are still part of the final stages of the innovation process and design and engineering activities (C-K) are nested within that.

In this third case the C-K conjunction consists of two sets of different actors (NPD and Assembly) that have a sequentially dependent relationship. The technical object from NPD was found a true proposition, however, as a socio-technical object and brought into the assembly area the proposition was found partly untrue. Therefore, this case suggests that also at the level of the receiving actors 'engineering' activities are needed to bridge from C- to K-spaces, that is, if there are two sets of actors involved. The first set of actors has their true proposition that is seen by the second set of actors partly undecidable. Finally, we see here that the assembly workers have their own IDER-cycles as well as their personal (and inter-personal) C-K activities.

6 CONCLUDING

In this paper we looked at the connection between design creativity and engineering that both are believed to be an indispensible part of product innovation processes. By the use of two theoretical models, C-K theory describing design and the IDER model describing innovation, and three case studies we aimed to describe the relationship between design creativity and engineering. Based on the IDER-model we stated that the design creativity aims to create a new frame, a new concept that subsequently needs to be subjected to an engineering activity aimed at robustinizing the concept in such a way that its final realization is predicted to be successful. C-K theory complemented our reasoning in the sense that it could clearly demarcate the transition from undecidable propositions in the C-space to true or untrue propositions in the K-space. In C-K theory, untrue and true propositions are both considered knowledge. Within the IDER-model, untrue propositions are to be seen as unfinished or inadequate design and engineering activities and therefore require design and/or engineering iterations.

In all three cases, we found that engineering and robustinizing activities indeed form the bridge between concepts resulting from creative design in the C-space to true (or false) propositions in the K-space. Existing E-knowledge, that is, true propositions in the K-space, seems to support the transformation of undecidable propositions in the C-space to testable propositions in the K-space (true/false). At an aggregated level, the full innovation cycle, this relationship seems to be more complicated. In the first case of F1 we saw that existing E-knowledge indeed resulted in a true proposition in the practice of F1 championship, hence single loop learning. In the ARALL/GLARE case, the existing E-knowledge (based on monolithic aluminum) resulted in a true proposition for ARALL wing panels. However, the same E-knowledge resulted in false proposition for the application of ARALL as material for the skin of an airplane fuselage. Based on research cycles equally moving from C-to K-space in which the E-knowledge base was formed by rigorous research methods new (true) propositions on fiber-adhesive behavior were developed which in their turn initiated in the C-space a new aluminum laminate concept with glass fibers. Many research projects that meandered between C-and K-spaces resulted in the required large set of additional and new E-knowledge to bring the glass fiber laminate into the K-space of the A380. The development of new and additional E-knowledge (know-how) as conjunction operators to facilitate and support the transformation of undecidable concepts to true/untrue objects in the K-space resembles a double loop learning process for the case of GLARE. Here we clearly see the Russian Doll effect of nested IDER-cycles and CK-transitions. Rigorous research and test methods to validate tentative theoretical insights are as much E-knowledge for the scientific researcher as are engineering heuristics and formulas for the design engineer. The third case brought creative design and engineering into the socio-technical dimension. The sound box as technical object was considered a true proposition from the side of NPD-actors and ready to be realized in production. However, once in the social context of the assembly line, the assembly workers were not capable with their existing E-knowledge to turn the sound box into a true proposition. Also, the assembly of the glass frame proved to be beyond their E-capabilities and required a different design and engineering by NPD. The observation that the same proposition can be true or untrue depending on the perspective taken opens an interesting discussion on criteria that demarcate true/untrue propositions while moving from C-space to K-space while innovating. A discussion about handing over the resulting knowledge (true propositions) from one set of actors to the next actors downstream the development path. Are these to be seen as undecidable objects for the receiving actors? Must these be treated as concepts? Are these elaborated results of creative design still in the C-space? If so, then existing E-knowledge belonging to the receiving actors must be capable to transform the undecidable proposition into a true proposition ready for handing over to the next set of actors until the final actors, often the users, are reached. It would be interesting to further investigate the situation with sequential dependency among the innovating actors through a lens as developed here. For instance, what caused the delay and double development costs of Boeing’s 787 Dreamliner? Was the undecidable proposition to outsource 70% of the design, engineering and manufacturing not too much treated as a single loop activity by applying Boeing’s existing E-knowledge to robustinize the Dreamliner project? The 40-months delay certainly seem to point to unexpected untrue propositions in the midst of the Dreamliner project. Were the 40 months necessary to develop new heterogeneous E-knowledge to transform the undecidable proposition into a true proposition? Most likely double loop learning and maybe even triple loop or deutero-learning?! Watch future publications on this Dreamliner project.

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