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INVERSE TECHNOLOGY C-K IN ENVIRONMENT C-K TO OVERCOME DESIGN FIXATION

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Abstract

Formal theories of design have described design as a quest for the fit between two spaces such as form-context, solution-problem, structure-function and presently Technology-Environment (T-E). On the contrary, existing methods tempt to focus on E; most engineering disciplines serve T; designers are consequently left barehanded to apply formal principles. More specifically a design method should help to overcome design fixations and enable to steer T-E double exploration. First we extend Concept-Knowledge formalism by defining the inverse C-K of a considered C-K, i.e. the knowledge base is put into question to formulate a new initial concept and the initial concept has an assumed logical status to become the new knowledge base concept. In this configuration, one C-K can benefit from expansions of the other. Second a method is deduced by applying this principle to the T-E framework: designers should steer their exploration by drawing simultaneously T C-K and E C-K. Four empirical cases are analysed. The results suggest that the method enables to identify a maximum of fits before converging on one when used from the start or can provide defixating knowledge expansions when not.

Keywords: Design theory, C-K theory, fixation effect, Technology, Environment

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1 INTRODUCTION

Alexander (1964) observed that houses in indigenous civilisations fitted well to their environment despite they seem rudimentary to our eyes, whereas sophisticated modern houses tend to be disappointing regarding their fit. Designing artefacts deals with designing their fit to their environment and even if the idea seems simple, it has induced lots of work from the point of view of formal theories –section 2.1– as well as methods –2.2. Technology intensive firms such as an aerospace tier-one supplier –3.2– are not at rest with these difficulties which interact with organisational issues. This paper describes a dual technology-environment exploration method –3.1– and analyses the results of its experimentation –4– in order to contribute to formal theories as well as their methodical implementation –5. In following sections T stands for Technology, E for Environment.

2 LITTERATURE REVIEW AND RESEARCH QUESTION

2.1 Technology-Environment Fit in formal theories

2.1.1 Starting design from knowledge on the Environment (E) the product should fit with

In Systematic Design (Pahl et al. 2007), the customer and the need to be addressed are defined in the specifications which are the input for Conceptual design. This fixates knowledge on the environment the product should fit with in order to focus on technological efforts until the end of product design. Design For X (DFX) techniques, where X stands for a particular life-phase or a virtue that the product should possess, enable to broaden the knowledge on the environment of the object being designed in order to make the best technological choices, notably they may consider environments in and out firm boundaries (Holt and Barnes 2010). Is that possible to reverse the process by defining the technology before the market is identified, even before a product is envisaged?

2.1.2 Starting design from knowledge on the Technology (T) which will compound the product

Reverse Inventing has been proposed as a method to regenerate opportunities in technology-intensive firms by identifying new markets in which their core technologies are potentially valuable (Glaser and Miecznik 2009). In the same stream, D4 method enables in the case of exploratory partnerships to prospect new customers, to give value to a technology and to outline new perspectives of development (Gillier and Piat 2008). Where the first utilizes TRIZ contradictions and inventive principles, the second utilizes technology properties and generic functions to reformulate T knowledge to steer E exploration. If design may start equally from T or E knowledge, what is the formal explanation for such a contingent factor for designers?

2.1.3 Technology and Environment designed simultaneously in formal theories

Alexander (1964), described design as an *"effort to achieve fitness between two entities: the form in question and its context"*. In his vision, designers should not focus only on the form but on the ensemble form-context. This framework has then be reformulated as problem-solution fit (Simon 1977) or geometry-functions fit (Shapiro and Voelcker 1989) –and we shall add T-E. Yoshikawa's General Design Theory (GDT) expresses Fitness by a mathematical mapping from the artefact description to function –i.e. from T to E- (Reich 1995). In Axiomatic Design (Suh 1990), Customer Attributes (CAs) –i.e. E- are translated in Functional Requirements (FRs) and Constraints (Cs) -i.e. reformulated E- which should be addressed by Design Parameters (DPs) –i.e. T. FRs differ from Cs which dependence is not affected by designers' choice –FRs are more malleable E knowledge than Cs. Hence, Fitness occurs between the range of a FR and the range addressed by DPs. If the Independence Axiom is respected –the E knowledge is well structured- each FR is addressed by a DP and the maximal FR range can be addressed rather than a compromise between two or more FRs –the T-E Fit is better. Moreover DPs must be chosen so that there is no conflict with the Cs which might be either Input constraints or System constraints (Suh 1998). System constraints are typical of the E knowledge modern industries are facing and Axiomatic Design gives few explanations on how to deal with them whereas Input constraints are addressed when translated in FRs boundaries. Couple Design Process (CDP) puts emphasis on the dual evolution of specifications and design solutions through an iterative process (Braha and Reich 2003). In the "basic model", Fitness occurs between the Functional Descriptions *fi* and the Structural Descriptions *di* in Closures. More specifically, the good fit between a closure of functional descriptions *Uf(fi)* and a closure of structural descriptions *Ud(di)* depends on the availability, richness, and coherence of knowledge. In CDP, i.e. the real design model, iterations concern a couple of functional and structural descriptions *<fi,di>*. Hence the basic model concerns particular cases where decoupling can be done. Therefore section 2.1.1 describes decoupled examples where E establishes the specifications for T, section 2.1.2 describes decoupled examples where T features steer E exploration. Presently we see that coupled cases have been addressed in formal theories to the point that recent Concept-Knowledge formal language would not even distinguish T from E (Hatchuel and Weil 2009), unless, as it is the purpose of this paper, we distinguish T knowledge *Kt* from E knowledge *Ke*. This gives our theoretical framework as illustrated Figure 1. At this point we are not sure that both *Kt* and *Ke* expansions are possible in a single process. What method could guarantee this? From an organisational standpoint, difficulties include Kt and Ke keepers are often spread within the firm (engineering and research for T ; marketing, intelligence, sales for E) or between firms (firm A is a supplier of firm B, firm A possesses Kt, firm B possesses Ke).

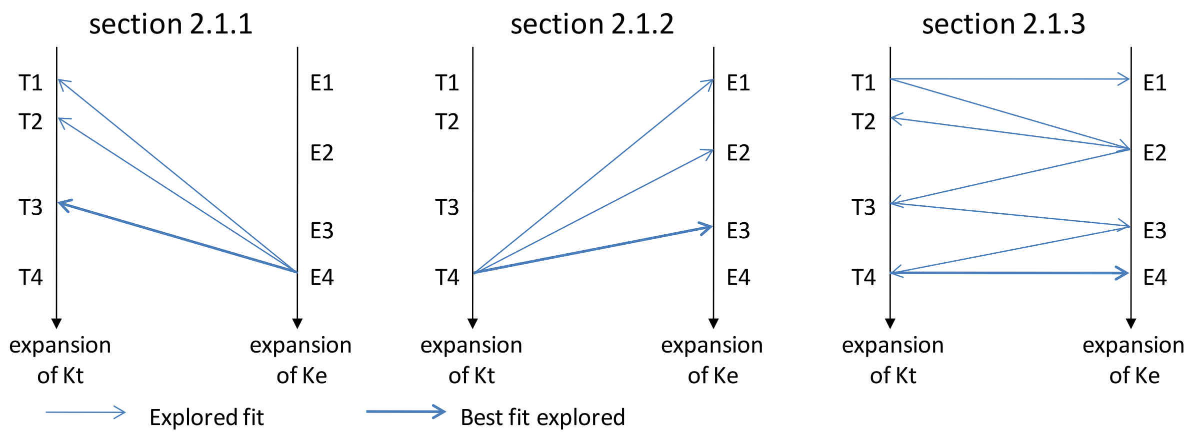

Figure 1: theoretical framework of Technology-Environment Fit

2.2 Methods to steer Technology-Environment dual expansion

2.2.1 Reaching Technology-Environment Fit

Because of the latter considerations, System Engineering has focused on both formalisms (definition of system, system of system) and organisational implementations (system life cycle processes and activities) (De Weck et al. 2011, Haskins et al. 2006). One famous System Engineering tool namely Technology Readiness Levels (TRLs) was invented at National Aeronautics and Space Administration (NASA) to formalise how new scientific knowledge (TRL 1) found applications (TRL 2) and then the technology is demonstrated in prototypes with growing fidelity to the intended real environment (TRL 3 to 9) (Mankins 1995, Mankins 2009). In a first assumption illustrated in blue in Figure 2, once the target environment has been fixated, efforts are put on making work the technology in this environment by testing more of its features at each TRL (Högman and Johannesson 2013). However TRL assessment methodologies (ASD(R&E) 2011) clarify that technology developer and integrator should collaborate at least to understand the critical features of the environment for the new technology, at best to design jointly technology and environment as illustrated in green in Figure 2 (see Comanche helicopter versus other cases in (GAO 1999)). Parameter Analysis methodology has been translated in C-K theory of design operators and characterised as "steepest first" approach (Kroll et al. 2014). In other words, it ensures convergence to one T-E Fit but it does not prevent designers from design fixation (the cognitive bias has been broadly studied as reviewed in (Linsey et al. 2010)). Methods to broaden the exploration and overcome certain specific fixations are reviewed hereafter.

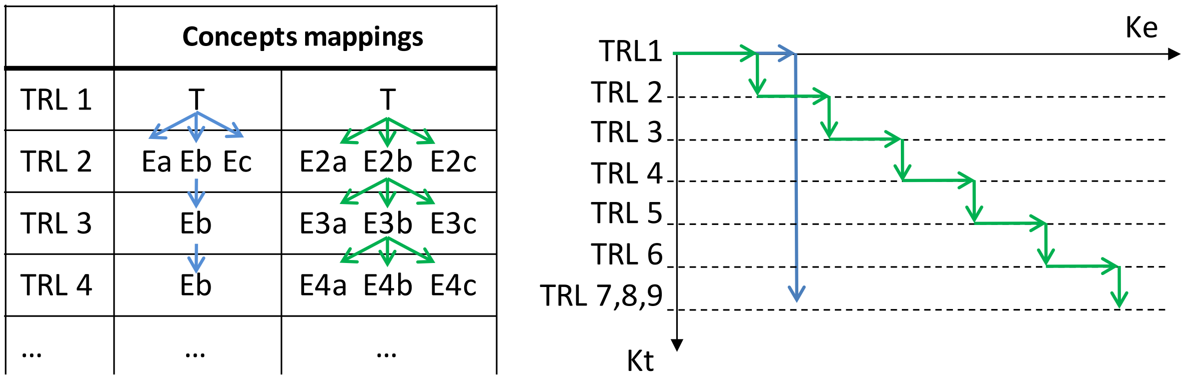

Figure 2: Concept and knowledge expansion for each interpretation of TRLs

2.2.2 Fixation on Technology at the expense of Environment

Management literature has broadly encouraged to design technology in a separate process than products, notably by adopting a stage-gate approach (Cooper 2006) which could be adapted from TRLs (Högman and Johannesson 2013). Freed from market constraints, technologists seem more able to explore. However such approaches can easily fall in the trap of low 'value creation / research spending' ratio and are hardly sustainable. Edison's labs were highly criticised as such.

2.2.3 Fixation on Environment at the expense of Technology

It has been recommended to focus on business model to augment competitiveness by avoiding long technology development cycles (Lee and Hong 2011). For instance Customer Value Chain Analysis may help to focus on value proposition (Donaldson et al. 2006). However such DFX methods have been said to lack a holistic approach because applied separately they fail at helping the designer finding compromise between divergent constraints (Meerkamm 1994). In other words, moving from a fixation on one environment to another is not a design rationale to reach a satisfying fit. User Centered Design (UCD) has been proposed to refocus design on human-machine interactions as advances in technology lead to poorly usable products (Carroll 2000). As UCD fixates on usability whereas affective aspects are as important, Product Ecosystem for User eXperience has been proposed to ensure that a still broader environment is explored beside T (Zhou et al. 2011). We see then that methods to stir E explorations are still debated whereas formal theories claim it is not enough in all cases as designers need to explore T as well.

2.2.4 Methods to lead dual expansions

Product/Service-System (PSS) design is a recent attempt at avoiding design fixation on *either* business *or* engineering (Sakao and McAloone 2011), notably by moving the value proposition from physical products to functions (Wallin et al. 2013). PSS puts the emphasis on the necessity to design coupled products and services in an integrated way (Cavalieri and Pezzotta 2012). These methods tempt to compensate a lack of tools for practitioners without providing a formal understanding and may not help at most early stages. Design rationales have been described in the case of generic technologies development, i.e. technologies which address disjoint markets by realising their common functions (Kokshagina et al. 2013). They differ in the way the T knowledge domain for the generic concept is acquired. These strategies to define a generic concept are one approach to perform T-E double exploration, can we define others? Can we reach a more general theory for T-E double exploration? *How should designers steer the double Technology-Environment exploration to prevent fixation on Technology, Environment or one poorly valuable Technology-Environment Fit?*

3 METHOD

3.1 Method experimented: Segregating Technology (T) and Environment (E)

To avoid fixation on either T or E by dissociating their explorations, the method considers two C-Ks:

1. The T C-K admits the explored value of the technology in various environments as its Initial Knowledge Base. By formulating the Initial Concept "Demonstration of the technology", this knowledge base should be expanded only with knowledge inherent to the technology.
2. The E C-K is obtained by *inversing*[1] the T C-K as illustrated Figure 3: demonstrated features of the technology constitute its Initial Knowledge Base which should be expanded by formulating the Initial Concept "Value of the technology" with various environments explorations.

We have described the core of the method; Figure 4 further illustrates it by providing typical questions and concepts appearing in such C-Ks.

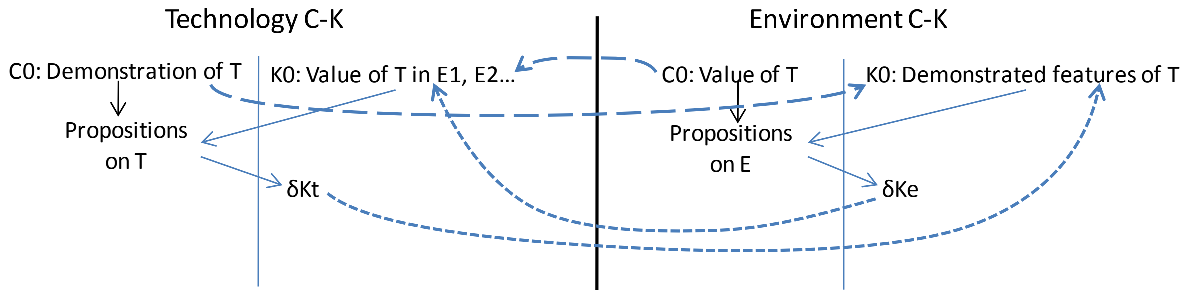

Figure 3: Basic method of dissociated Technology and Environment C-Ks

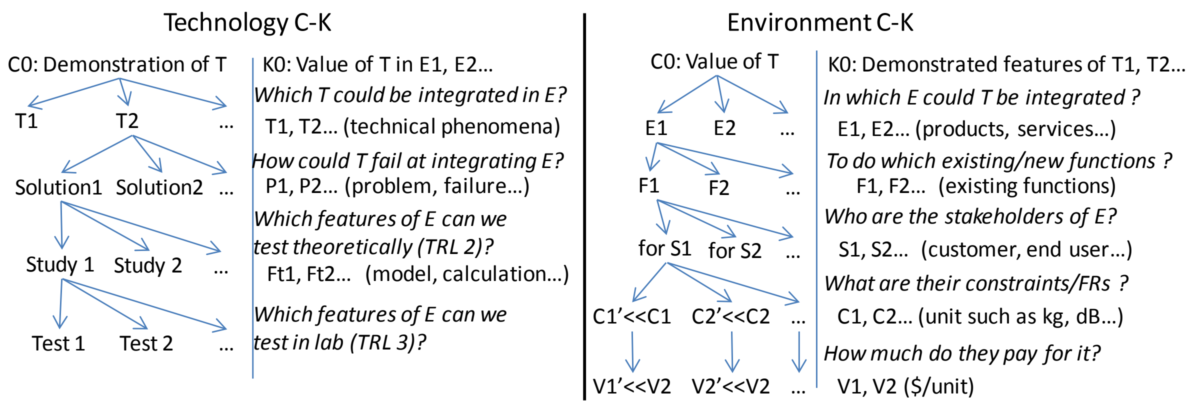

Figure 4: Typical dissociated Technology and Environment C-Ks

3.2 Four cases grounded at SAFRAN

SAFRAN is a conglomerate of tier one suppliers in space, aeronautics, defence and security. The companies within SAFRAN are technology intensive, they utilise extensively System Engineering and TRLs. The first case is the exploration of energy-non-dissipative concepts without a specific method. The second case is the exploration of an energy conversion technology which led to the descriptive model hereupon. In the third case, the model is employed prescriptively to make two separate explorations benefit from one another. The fourth case is an exploration steered from the beginning with the model, hence consolidating the method.

3.3 Data

3.3.1 Data collection

In accordance with intervention-research methodology (David and Hatchuel 2007), one searcher was fully employed among practitioners in the empirical cases in order to gather all possible data and process epistemic loops. In short, every loop entails providing theoretical scaffold by researchers to model SAFRAN reality, refining those models collaboratively with SAFRAN, and experimenting

[1] The inverse operator of a C-K has not been formally described in literature. In his thesis, Mathias Szpirglas depicts how a piece of knowledge in one C-K can be interpreted as a concept in another C-K. To the best of our knowledge, interpreting a concept from one C-K as knowledge in another C-K has not been studied.

those models. The searcher joined the Innovation Head Office team with the mission to coordinate some explorations and eventually steer them towards structured projects. Data collection summarised in Table 1 was then possible at very early phases of design in real industrial situations.

Table 1: Data Collection Summary

	Case 1: NDEC	Case 2: NECT	Case 3: DTIC	Case 4: NETT
Method	None	In progress model	Prescriptive model	Consolidated Method
Duration	4 months	15 mths	15 mths	5 mths

3.3.2 Data analysis

Our goal is to test the proposition that the dissociating T-E method presented in 3.1 *prevents fixation on either T or E (P1) and prevents fixation on one T-E Fit (P2)*. (P1) implies that knowledge on both T and E is explored, (P2) that various {T,E} couples are explored. Consequently our metrics are knowledge incremental expansions in both domains (δKt and δKe) (P1) and T-E Fits explored (F1, F2...) (P2). We do not count concepts of T-E Fits identified but left unexplored.

4 RESULTS

4.1 Cases analysis

4.1.1 None Dissipative Energy Converter (NDEC) – when a single idea is explored and killed

Background - initial knowledge base. Related to the global energy crisis (Ke0), explorations were lead on energy efficiency and the concept “NDEC” was identified as applicable to Company E (CE) products. A first energy conversion (EC1) was identified to replace current dissipative energy conversion (EC0) (Kt0). This draft fit was summarised to the Innovation Head Office (IHO) (F0).

Single C-K intervention. An expert on such energy conversion technologies is consulted; the power to convert is estimated (+1δKe). The replacement would highly deteriorate weight (+1δKt). The proposition “...hybrid EC0-EC1” is added to the Initial Concept and explored (F1). As energy is dissipated through different channels (Ci) (+1δKe), the proposition “...in C1” is added as only one is suitable (F1'). The energy saved is estimated (+1δKt). Cost avoided for airlines is deduced from technology efficiency (+1δKt), current energy supply cost and average consumption (+2δKe). Finally a formal meeting oblige to deep the overall energy at stakes (+1δKe) and to compare with an alternate patent (+1δKt). During the meeting two alternate energy conversion types are identified as long-term perspectives (+2δKt). No good fit has been found and the exploration is ended.

4.1.2 New Energy Conversion Technology (NECT) - when fixation on technology is overcome by taking pitched objectives by a supplier as true propositions

Background - initial knowledge base. A New Energy Conversion Technology (NECT) had been identified by Company A (CA) to harvest wasted energy. After few explorations of the basic principles (Kt0), CA collaborated with Company B (CB) to identify three locations where wasted energy could be harvested thank to this technology. CB identified one concept to use the harvested energy but its lacking availability in time was considered as a show stopper (Ke0, F0).

First steps with single C-K. CA presents the exploration to the IHO who asks for more applications to be explored among other companies. The Initial Concept is formulated "Energy harvesting with NECT" and adds "...in E1" as a separate project at CB could provide E for NECT. The project manager is interviewed and adds the proposition "...to make my product under development energetically autonomous" and shares knowledge about its product energy grid (F1,+1δKe). But the exploration stops as integrating NECT would delay the project. CA turns to Company C (CC) who explains two new locations for harvesting energy (+1δKe) and proposes many energy usages. The latter raise the question of NECT thermal behaviour, weight and power.

The birth of our method. A three-step seminar is organised, step E is a discussion with 4 additional product experts, step T is Supplier S (S) presentation of preliminary studies on NECT and step D is a debriefing without S. In step E, experts reveal one major issue justifying a first energy usage (F2, +1δKe), and proposes a new energy usage without details. In step T, S answers the question of NECT thermal behaviour (F2, +1δKt), range of weight (+1δKt), present possible configurations

(+1δKt), and gives its objectives of power. Next move is a workshop on the concept "Value of NECT for customer" which interprets S power objectives as true in K-base and reviews all the propositions of energy usages. Two generic criteria to choose energy usages are added as well as a client valuing criterion (+3δKe). We should notice that this was tried before but fixation on certain features of NECT prevented it. Then a group of experts is consulted on a specific proposition and establishes its certification conditions (F3,+1δKe). A manager is interviewed and shares its constraints from clients and power required on another proposition (F4, +2δKe). Finally CC provides the power required and TRL in current configurations and future configurations for a former proposition (+2δKe, F5).

Agile usage of our method. The next move is various interviews discussing first "value of NECT" and then "Demonstration of NECT". A product manager in another company confirms a significant weight loss as well as three other benefits if NECT was integrated and gives a critical demonstration required (F0, +1δKt, +3δKe). Similarly an expert at CB shares a value criterion for clients and one required demonstration step (+1δKt, +1δKe). Finally the workgroup presents the exploration to top managers and a specific budget is granted.

4.1.3 Disruptive Technology for an Identified Customer (DTIC) - when value model gap prevents validation at the gate because of Technology fixation

Background - initial knowledge base. Very disruptive and holistic explorations were led within CB (Kt0, Ke0). A summary is supplied to IHO who observes that the exploration is too broad (the concepts overwhelmed SAFRAN competences and markets) and too fuzzy (confusion between concepts and technical solutions) to launch a project. Still high potential is perceived.

Intervention with single C-K. The fuzzy summary and related investigations are translated in a C-K diagram. The C-K formalism enabled to represent both E and T continuously. Questions to fill knowledge gaps were added. The diagram is presented to CB management in order to enhance the reasoning and jointly prioritise concepts. CB R&T manager actively engages in the reasoning as expected and shares knowledge on estimation of fuel burn property (F1, +1δKt), related previous explorations (F2, +1δKt), one operability property, (F3, +1δKt), noise-induced constraints (F4, +1δKe), fluid tightness property (F5, +2δKt), current technology velocity, existing technological alternatives, predictive maintenance properties, one client value criterion (F6, +4δKt, +1δKe), one significant failure-mode, current security properties, one technological alternative (F7, +3δKt), energy required, one technological alternative, client usage (F8, +2δKt, +1δKe), flying procedures, certification constraints (+2δKe). The C-K is then reshaped to integrate this new knowledge. In the meantime, CC starts the development of a DTIC closely related but IHO refuses to fund because of a neglected value model - i.e. there is a big Ke gap to close. The C-K is then modified and presented to a CB pre-project manager so as to close this gap. The manager shares two other operability properties, velocity problem, maintenance property, user practices (F6, +4δKt, +1δKe), one structural failure mode, non-valuable environment, integrating system evolution (F7, +1δKt, +2δKe).

Intervention with our method. As the latter failed at completing CC value model, an E C-K with the Initial Concept "Value of DTIC" is started. The first proposition added to the concept are "...to reduce field length" and "...to increase the number of operable Airports". These properties lead to simple calculations and sharing an airport data base (F6, +2δKe). At this point that data fails at providing a business case. More useful information is a Target Airport (TA) for the Identified Customer (IC) (F6, +1δKe). So a T C-K is started with the Initial Concept "DTIC"+"...to ensure TA operability". Three technologies (Ti) previously integrated by IC are found (F6, +3δKt). Back to the E C-K, this new knowledge enables to add the propositions "...by Ti" which obliges to decompose phenomena in E to explain their value (F6, +2δKe). Later a list of significant airports (Ai) for IC is obtained (F6, +1δKe) which enables to change the proposition "...to increase the number of operable Airports" into "...to ensure Ai operability", ensuring a viable value model to start the project.

4.1.4 New Energy Transport Technologies (NETT) - when technology and environments knowledge keepers break the rules together methodically

Background - initial knowledge base. A technology allowing to transport energy usually not transportable was explored (Kt0) as well as five energy sources and six functions requiring such type of energy distant in a plane (Ke0). Then the concept of "NETT smart-grid" was defined (F0) and CC submitted a summary to IHO which regretted that technologies needed were too immature.

Intervention with our method. The T C-K is started by the Initial Concept "Demonstrated NETT" which leads to discover previous explorations on another disruptive energy transport technology led at Company D (CD) (F1, +1δKt). As previously acquired knowledge on energy nodes was too shallow, the E C-K is initiated by formulating the concept "Value of NETT". Four products at CB and Company E (CE) are identified as potential environments (F1, +4δKe). In a meeting involving the four companies CC and CD present the technology opportunity -setting Kt0-, then CB and CE confirm their interest and add a product, explain two major issues at stake, two power ranges, each product expected time-to-market and client and three new energy sources (F1, 18δKe). Then a workshop compound of T step, E step and one Idea Generation step is organised. In T step, CD presents its efforts on two commercialised technologies (+2δKt) and the disruptive energy transport technology main features (F1, +1δKt). In E step, CE presents the main features of its products: their common architecture, their differentiating design parameters and value criteria for clients (+3δKe). We learn from CB presentation the energy transport details on one known architecture and a new architecture based on energy transport (+2δKe). In Idea Generation step, five main concepts are identified and explored in the workshop (F2, F3, F4, F5, F6, detailed data analysis not performed at the time of writing). Besides, four complementary technologies are evoked (+4δKt).

4.2 Summary of results

Table 2: Summary of results

	Case 1	Case 2			Case 3		Case 4
	no method	no method	birth of the method	T and E interviews	single C-K	T and E C-K	built with our method
T-E Fits explored	2	1	4	1	8	1	7
E and T C-K switches	0	0	2	3	0	2	4
δKt	6	0	3	2	19	4	8 counted
δKe	5	2	9	4	8	6	27 counted

Design theories insist that both T and E should be explored; we find that it is the case with or without our method. However the method ensures that more different Es are explored and provides a better control to face fixation. Some methods such as Parameter Analysis focus on converging on one fit without addressing the risk of missing better T-E Fits because of early fixation. Case 1 is typically in this situation. At the opposite when our method is employed, four different T-E Fits in Case 2 and seven in Case 4 are explored before starting convergence on a specific fit. Other methods fixate on either T or E. In Case 3 fixation on T when value for E was low (19 δKt, 0 switch) was overcome with the E C-K and then switching C-Ks enabled to explore even more Es. E is explored with more relevant focus regarding the fit being explored. Ts are described with physical phenomena instead of functions because generally functions are T-E Fits. This enabled new T-E Fits to be explored in all cases.

5 CONCLUSION AND DISCUSSION OF THE CONTRIBUTION

Main findings are that our structured Technology-Environment (T-E) approach increases innovative design quality on both T, E and the coupling between T and E: more variety and originality on T and E concepts, more knowledge on T and E and more T-E Couples explored. More specifically, many Es are explored rather than fixating on one like most methods. Designers are not obliged to focus on pairs {single T, single E} but can envisage generic technologies. Knowledge structure is also improved as Ts are described in a more abstract and generic way and Es are deeper understood.

The method enables new forms of collaboration. Usual processes tend to restrict marketing actors to E exploration and engineering designers to T exploration. With T-E processes all actors can participate to both explorations if they obey the design rules (either T knowledge or E knowledge as invariant). This ensures that they adopt a relevant focus to contribute to the exploration. Similarly supplier and buyer find a model for collaboration... this paves the way to creative collaboration.

We believe this represents a significant extension of C-K Theory of design by determining how two C-Ks can interact and share benefits of their expansions. Previous attempts would allow interactions only with an intermediary space (Kazakci et al. 2008) or focus on generating a common concept (Gillier et al. 2012). Our formal proposition of *inverse* C-Ks -section 3.1- seems to allow two C-K to defixate one another and facilitate learning. This should not be restricted to the T-E framework in further research. Other design theories proposing models for collaborations (Product Social Institutional framework, computational models etc.) may also benefit from this work. In fact this work may provide a base for bridges between design theories and other disciplines such as project management, marketing or organisational studies.

REFERENCES

Alexander, C. (1964) *Notes on the Synthesis of Form,* Harvard University Press.

Arden, W., Brillouët, M., Cogez, P., Graef, M., Huizing, B. and Mahnkopf, R. (2010) '"More-than-Moore" White Paper', *International Technical Roadmap for Semiconductors*.

ASD(R&E) (2011) *Technology readiness assessment (TRA) Guidance*, Washington DC:

Braha, D. and Reich, Y. (2003) 'Topological structures for modeling engineering design processes', *Research in engineering design,* 14(4), 185-199.

Carroll, J. M. (2000) *Making use: scenario-based design of human-computer interactions,* MIT press.

Cavalieri, S. and Pezzotta, G. (2012) 'Product–Service Systems Engineering: State of the art and research challenges', *Computers in Industry,* 63(4), 278-288.

Cooper, R. G. (2006) 'Managing technology development projects', *Research-Technology Management,* 49(6), 23-31.

David, A. and Hatchuel, A. (2007) 'From actionable knowledge to universal theory in management research', *Handbook of collaborative management research*, 33-47.

De Weck, O. L., Roos, D. and Magee, C. L. (2011) *Engineering systems: meeting human needs in a complex technological world,* MIT Press.

Donaldson, K. M., Ishii, K. and Sheppard, S. D. (2006) 'Customer value chain analysis', *Research in engineering design,* 16(4), 174-183.

GAO (1999) *Better Management of Technology Development Can Improve Weapon System Outcomes*,

Gillier, T., Osman Kazakci, A. and Piat, G. (2012) 'The generation of common purpose in innovation partnerships', *European Journal of Innovation Management,* 15(3), 372-392.

Gillier, T. and Piat, G. (2008) *Co-designing broad scope of technology-based applications in an exploratory partnership,* translated by.

Glaser, M. and Miecznik, B. (2009) 'TRIZ for reverse inventing in market research: a case study from WITTENSTEIN AG, identifying new areas of application of a core technology', *Creativity and Innovation Management,* 18(2), 90-100.

Haskins, C., Forsberg, K., Krueger, M., Walden, D. and Hamelin, D. (2006) *Systems engineering handbook,* translated by.

Hatchuel, A. and Weil, B. (2009) 'CK design theory: an advanced formulation', *Research in engineering design,* 19(4), 181-192.

Högman, U. and Johannesson, H. (2013) 'Applying stage-gate processes to technology development—Experience from six hardware-oriented companies', *Journal of engineering and technology management,* 30(3), 264-287.

Holt, R. and Barnes, C. (2010) 'Towards an integrated approach to "Design for X": an agenda for decision-based DFX research', *Research in engineering design,* 21(2), 123-136.

Kazakci, A., Hatchuel, A. and Weil, B. (2008) *A model of CK design theory based on term logic: a formal CK background for a class of design assistants,* translated by.

Kokshagina, O., Le Masson, P., Weil, B. and Cogez, P. (2013) *How design theories enable the design of generic technologies: Notion of generic concept and genericity improvement,* translated by.

Kroll, E., Le Masson, P. and Weil, B. (2014) 'Steepest-first exploration with learning-based path evaluation: uncovering the design strategy of parameter analysis with C–K theory', *Research in engineering design,* 25(4), 351-373.

Lee, J. H. and Hong, Y. S. (2011) *A MORPHOLOGICAL APPROACH TO BUSINESS MODEL CREATION USING CASE-BASED REASONING,* translated by.

Linsey, J., Tseng, I., Fu, K., Cagan, J., Wood, K. and Schunn, C. (2010) 'A study of design fixation, its mitigation and perception in engineering design faculty', *Journal of Mechanical Design,* 132(4), 041003.

Mankins, J. C. (1995) 'Technology readiness levels', *White Paper, April,* 6.

Mankins, J. C. (2009) 'Technology readiness assessments: A retrospective', *Acta Astronautica,* 65(9–10), 1216-1223.

Meerkamm, H. (1994) 'Design for X-A core area of design methodology', *Journal of Engineering Design,* 5(2), 145.

Pahl, G., Beitz, W., Feldhusen, J. and Grote, K.-H. (2007) *Engineering design: a systematic approach,* Springer.

Reich, Y. (1995) 'A critical review of general design theory', *Research in engineering design,* 7(1), 1-18.

Sakao, T. and McAloone, T. C. (2011) *Product with service, technology with business model: Expanding engineering design,* translated by.

Shapiro, V. and Voelcker, H. (1989) 'On the role of geometry in mechanical design', *Research in engineering design,* 1(1), 69-73.

Simon, H. A. (1977) 'The structure of ill-structured problems' in *Models of discovery*, Springer, 304-325.

Suh, N. P. (1990) *The principles of design,* Oxford University Press New York.

Suh, N. P. (1998) 'Axiomatic Design Theory for Systems', *Research in engineering design,* 10(4), 189-209.

Wallin, J., Chirumalla, K. and Thompson, A. (2013) 'Developing PSS concepts from traditional product sales situation: the use of business model canvas' in *Product-Service Integration for Sustainable Solutions*, Springer, 263-274.

Zhou, F., Xu, Q. and Jiao, R. (2011) 'Fundamentals of product ecosystem design for user experience', *Research in engineering design,* 22(1), 43-61.