Titre: Title:	The Cognitive, Social and Organizational Factors Contributing to Creativity in Eco-Design Ideation: Two Case Studies in The Electrical and Chemical Industries
Auteur: Author:	Andrea Gideon
Date:	2019
Type:	Mémoire ou thèse / Dissertation or Thesis
Référence: Citation:	Gideon, A. (2019). The Cognitive, Social and Organizational Factors Contributing to Creativity in Eco-Design Ideation: Two Case Studies in The Electrical and Chemical Industries [Mémoire de maîtrise, Polytechnique Montréal]. PolyPublie. https://publications.polymtl.ca/3863/

URL de PolyPublie: PolyPublie URL:	https://publications.polymtl.ca/3863/
Directeurs de recherche: Advisors:	Manuele Margni, & Christophe Abrassart
Programme: Program:	Maîtrise recherche en génie industriel

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

The cognitive, social and organizational factors contributing to creativity in eco-design ideation: two case studies in the electrical and chemical industries

ANDREA GIDEON

Département de mathématiques et de génie industriel

Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

Génie industriel

Février 2019

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Ce mémoire intitulé :

The cognitive, social and organizational factors contributing to creativity in eco-design ideation: two case studies in the electrical and chemical industries

présenté par **Andrea GIDEON**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

a été dûment accepté par le jury d'examen constitué de :

Fabiano ARMELLINI, président

Manuele MARGNI, membre et directeur de recherche

Christophe ABRASSART, membre et codirecteur de recherche

Marine AGOGUÉ, membre

DEDICATION

"Be wild; that is how to clear the river. The river does not flow in polluted, we manage that. The river does not dry up, we block it. If we want to allow it its freedom, we have to allow our ideational lives to be let loose, to stream, letting anything come, initially censoring nothing. That is creative life. It is made up of divine paradox. To create one must be willing to be stone stupid, to sit upon a throne on top of a jackass and spill rubies from one's mouth. Then the river will flow, then we can stand in the stream of it raining down."

~ Clarissa Pinkola Estes, Women Who Run With the Wolves

ACKNOWLEDGEMENTS

Manuele took me in as his student when I was cluelessly entering research from the corporate world. At the time, I had no idea what I was getting in to, but I felt this was where I needed to go. My intuition brought me here. This project nourished my soul and truly transformed me. It taught me to revive my dormant creativity by studying the subject so closely. It taught me to accept that positivism might not resonate with me, despite it being so deeply rooted in my training as an engineer. I was able de-fix and connect with a style of research that reflects my true self and what is meaningful to me. It taught me to accept that the corporate life is not for me, and that it's possible to work in a place that shares my values. Research is a place I feel nourished. I feel like I am fulfilling a larger purpose by being true to myself: through creative exploration in research.

Thank you Manuele for giving me the freedom to build a project that fit so well with my personality and my values. Thank you for grounding me in your engineering expertise of LCA, in which I felt so comfortable, and for supporting me in breaking free from it to explore something new and unknown to us both. Thank you Christophe, for opening me up to the world of design, for showing me new worldviews, for lifting up my work to a new level with your (possibly limitless?) expertise. You both complement each other so well, and gave me joint guidance that balanced the worlds of engineering and design. My thesis brought us exciting discussions of sustainability and creativity in Montreal, on Skype, and even on a terrasse in Montmartre, and for that I am truly grateful.

Thank you to the CIRAIG, my academic family. You are truly a passionate and supportive community with such intellectual rigour. Your willingness to welcome my critique of your field amazes me and I love how you challenge me back, bringing that rigour and robustness to my work. Thank you for welcoming me in a space that feels like home. I am left with so many wonderful memories of ukulele karaoke, totems and friendships I will always cherish.

Thank you to my industrial partners who gave me a space to create my fieldwork in Montreal and in France. To my colleagues at Solvay, I am grateful for the warm welcome in your offices in Lyon, especially Guy-Noel who believed in my project with conviction and made it a reality against all odds.

Writing this thesis would not have been possible without hundreds of pomodoros at Espace Thèsez-vous, at home and at the CIRAIG, daily boosts of motivation from Hassana, and many, many poke bowls, and *kardemummabullar* with Gabrielle. Thank you to Marie-Luc, for your mentorship on my embrace of constructivism from the worldview of an engineer. Thank you to Carolyn who taught me how to “laser focus”. Sophie, your endless support is so greatly appreciated; you inspire me every day as a powerful and graceful leader. This thesis was built on hours of practicing yoga and teachings from Marie-Pier, whose elegance, creativity and connectedness taught me so much about overcoming fear. Thank you to my partner Nico, for your love, your patience, your encouragement and for believing in me. To my beloved Vôvô, spending your final days with you in the hospital gave me the force to persevere, and reminded me of the divine guidance and eternal love from my grandparents (who are always with me in spirit), and from my parents, my family and my friends.

RÉSUMÉ

À la lumière des défis mondiaux en matière de développement durable, l'innovation systémique et transformative est sans doute nécessaire pour réduire radicalement les impacts anthropiques sur l'environnement. La pensée cycle de vie est souvent citée comme un puissant cadre pour atteindre cet objectif. En utilisant un produit existant comme point de départ de l'exploration, la pensée cycle de vie empêche la créativité en cadrant de manière trop restrictive le problème d'éco-conception. Bien qu'elle soit appropriée pour les approches d'éco-conception incrémentales et réglées, la pensée cycle de vie peut être un facteur de fixation dans des contextes de conception innovante.

Ce mémoire vise à comprendre l'effet de fixation dans l'éco-conception et comment il se manifeste dans des environnements d'entreprise réels. L'effet de fixation est un élément distinctif entre deux régimes de conception: réglée et innovante. La conception réglée fonctionne selon des principes de fonctionnement et des cadres connus, où la fixation sur le *dominant design* est nécessaire pour converger vers une solution. Toutefois la conceptions innovante la fixation est déliberément surmontée en recadrant le problème pour imaginer de nouveaux produits avec de nouvelles identités, en utilisant de nouveaux principes de fonctionnement. Notre premier objectif était donc de mettre en contraste une approche d'éco-conception réglée, fondée sur la notion de cycle de vie, et une approche d'éco-conception innovante, fondée sur des méthodes créatives. Cela nous a permis d'appréhender comment la pensée du cycle de vie pourrait limiter une exploration de l'entièreté de l'espace de conception. La nature interdisciplinaire et complexe de la créativité implique qu'elle peut être affectée à trois niveaux: individuellement, soit le style cognitif et les réactions aux déclencheurs créatifs, socialement, soit la dynamique du pouvoir entre les participants à l'exercice d'idéation, et au niveau de l'organisation, soit comment les structures et les styles de gestion peuvent affecter la motivation intrinsèque. Nos deuxième, troisième et quatrième objectifs étaient respectivement de décortiquer les facteurs cognitifs, sociaux et organisationnels qui contribuent également à la (dé)fixation pendant l'idéation en éco-conception.

Avec la recherche intervention, des méthodes qualitatives et une approche d'études de cas multiples, deux firmes mondiales d'ingénierie ont chacune vécu une série de deux ateliers soigneusement conçus: l'un axé sur l'ACV et l'autre sur les méthodes créatives. À l'aide d'entretiens, d'observations et d'enregistrements des expériences des ateliers, les études de cas ont été analysées à l'aide de la théorie de la conception et d'un cadre conceptuel de créativité cognitive, sociale et organisationnelle répondant à nos objectifs.

Les résultats démontrent que la pensée cycle de vie seule peut entraver la créativité, mais lorsqu'elle est associée à des conditions cognitives de créativité, à des interactions sociales favorables et à des contextes organisationnels spécifiques, la fixation en éco-conception peut être surmontée. La pensée cycle de vie aurait provoqué la fixation lorsqu'elle ait été utilisé dans son contexte organisationnel habituel en tant qu'outil d'éco-conception réglée bien connu et accepté. Lorsque la pensée cycle de vie était nouveau et que les participants étaient plus détachés de l'outil, la pensée cycle de vie était moins politisé et constituait un élément déclencheur expansif pour des idées créatives. Dans ce contexte, la pensée cycle de vie a effectivement permis aux participants de reformuler le problème. L'utilisation de la conception participative (co-création) était également favorable à l'exploration de l'éco-conception, en particulier lorsque les intérêts de toutes les phases du cycle de vie sont pris en compte au cours du processus de conception, l'entreprise est moins susceptible de rester concentrée sur son *dominant design*. L'effet de cadrage d'une méthodologie d'écoconception est donc dépendant de son contexte organisationnel.

Cela a de profondes implications pour la communauté de l'innovation durable, qui dépend souvent uniquement des cadres inhérents aux approches du cycle de vie pour rechercher l'innovation radicale en faveur de la durabilité. Le simple fait d'évaluer une innovation avec la pensée cycle de vie à différentes étapes de son développement ne permet pas aux questions de développement durable d'être au cœur d'une enquête de conception innovante. Les professionnels du développement durable doivent maîtriser les notions de la créativité et de la conception innovante s'ils souhaitent positionner la pensée cycle de vie dans le processus d'idéation afin d'imaginer des produits durables du futur qui défient radicalement le statu quo.

ABSTRACT

In light of global sustainability challenges today, systemic and transformative innovation is arguably needed for radically reducing anthropogenic environmental impacts. Life cycle thinking is often cited as a powerful framework to achieve this goal. By using existing products as a starting point exploration, life cycle thinking inhibits creativity by too restrictively framing the eco-design problem. Although appropriate for incremental and rule-based eco-design approaches, life cycle thinking can be a factor of design fixation in innovative design contexts.

This thesis aimed to understand the fixation effect in eco-design and how it manifests in real-world corporate settings. The fixation effect is a distinguishing element between two regimes of design: rule-based and innovative. Rule-based design operates within known working principles and frames, where fixation on the dominant design is necessary to converge towards a solution. In innovative design, however, fixation is purposely overcome by reframing the problem to imagine new products with new identities, using new working principles. Our first objective was thus to contrast a rule-based eco-design approach, driven by life cycle thinking, and an innovative eco-design approach, driven by creative methods. This allowed us to apprehend how life cycle thinking might limit a full exploration of the design space. The interdisciplinary and complex nature of creativity implies that it can be affected on three different levels: individually, through the cognitive style and reaction to creative triggers, socially, through the power dynamics between participants in the ideation exercise, and at the organization level, how structures and management styles can affect intrinsic motivation. Our second, third and fourth objectives were respectively to unravel the cognitive, social and organizational factors that also contribute to (de)fixation during eco-design ideation.

With research intervention, qualitative methods and a multiple case study approach, two global engineering firms each experienced a series of two carefully designed workshops: one life-cycle-driven, and the other creative-methods-driven. With interviews, observations and recordings of the workshop experiences, the case studies were analyzed with design theory and a framework of cognitive, social and organizational creativity to address our objectives.

The results show that life cycle thinking alone may hinder creativity, but when paired with cognitive conditions for creativity, favourable social interactions and specific organizational contexts, eco-design fixation can be overcome. Life cycle thinking caused fixation when it was

used in its routine organizational context as a well-known and accepted rule-based eco-design tool. When life cycle thinking was new and the participants were more detached from the tool, life cycle thinking subsequently had little political value, and was an expansive trigger for creative ideas. In this context, life cycle thinking effectively allowed the participants to reframe the problem. The use of participatory design was also favourable for eco-design exploration, especially when the interests of all life cycle phases are given agency during the design process, the firm is less likely to remain fixated on its dominant design. The framing effect of an eco-design methodology therefore does not exist independently of its organizational context.

This has profound implications for the sustainable innovation community who is often reliant purely on the frames inherent in life cycle approaches to strive for radical innovation for sustainability. Simply evaluating an innovation with life cycle thinking at different stages of its development does not empower sustainability issues to be at the heart of an innovative design inquiry. The sustainability professional needs to become fluent in creativity and innovative design issues if they are to position life cycle thinking as part of the ideation process to imagine sustainable products of the future that radically challenge the status quo.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

3E	Environmental Economic Evaluations (team at Solvay)
AIS	Air insulated substation
BU	Business Unit
C	Concept
CFC	Chloro-fluoro carbons
C-K	Concept-Knowledge
COP21	Conference of Parties ’21
CSA	Canadian Standardization Association
Eco-QFD	Ecological Quality-Function-Deployment matrix
EMS	Environmental Management System
EPD	Environmental Product Declaration
FU	Functional Unit
GBU	Global Business Unit
GI	Growth Initiative
GIS	Gas-insulated substation
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Standardization Organization
K	Knowledge
KCP	Knowledge, Concepts, Propositions
LCA	Life cycle assessment
LCT	Life cycle thinking
PAC	Product-Application Combination
POEMS	Product-oriented Environmental Management System

REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
R&D	Research & Development
R&I	Research & Innovation
R-I-D	Research-Innovation-Development
SETAC	Society of Environmental Toxicology and Chemistry
SPM	Sustainable Portfolio Management
SbyD	Sustainability-by-Design
UNEP	United Nations Environment Programme
V2OR	Value, Variety, Originality, Robustness

LIST OF APPENDICES

CHAPTER 1 INTRODUCTION

In response to global sustainability challenges such as energy transition, decarbonisation, circular economy, and related pressure from governments and citizens to reduce anthropogenic environmental damage, more firms are inclined to put sustainability at the heart of their innovation processes. The most robust and well-established sustainability strategy taken by firms since the 1990s is to manage the environmental impacts of their activities all along their value chain, with a life cycle approach (Guinée et al., 2011). At the same time, firms are increasing their creative capacity to spark innovations that distinguish them on the market, leveraging contemporary innovation with design thinking. In an attempt to align these two objectives, firms are opting to combine their sustainability and innovation strategies to achieve *sustainable innovation*, or more specifically, *life cycle innovation*, when life cycle thinking is used. This combination of intentions is ideal, but are life-cycle-driven sustainability and contemporary innovation approaches compatible in practice?

Many authors have shown that we need to radically shift our impacts through highly innovative designs of products, services and systems, rather than incrementally improving technologies through efficiency (Ceschin, 2014; Ceschin & Gaziulusoy, 2016; McAloone & Pigosso, 2017; Nill & Kemp, 2009; Tukker, 2008; Tukker & Butter, 2007). We could therefore argue that *innovative eco-design*, which aims to define new product identities, is necessary for firms to complement their usual practices of *rule-based eco-design*, which aims for increased efficiency, product improvement and optimization (Abrassart, 2011).

The predominant framework for managing sustainability in the corporate world is rooted in a life cycle thinking (LCT) philosophy (CIRAIG, 2015; Life Cycle Initiative, 2018), the consideration of the impacts of a product, service or system over its entire life cycle from raw materials extraction to production to distribution to use to end of life and potential future lives. Since the 1990s a strong network of competencies, tools, methodologies and standards have emerged around the life cycle thinking framework such as life cycle management (LCM) (Sonnemann & Margni, 2015) and life cycle assessment (LCA) (ISO, 2006a, 2006b; Jolliet, Saadé-Sbeih, Shaked, Jolliet, & Crettaz, 2016). Even the most recent update to widely used quality assurance certifications[1] for managing environmental footprints of firms now mentions the need to include life cycle aspects.

The logical step for firms wishing to undertake the task of putting sustainability at the heart of the innovation process, is to take the sustainability tools at their disposal, such as life cycle assessment, and merge them with radical innovation processes. Recently, we've seen the emergence of the term "Life cycle innovation", such as at the LCIC Conference in Berlin (FSLCI, 2018). Yet the process of life cycle thinking emerged from a rule-based design paradigm, while radical innovation processes emerged from an innovative design paradigm (Abrassart, 2011; Le Masson, Weil, & Hatchuel, 2010).

What lies behind the difficulty of merging the innovation process of a firm with the sustainability processes to encourage life cycle innovation?

First, we invoke design literature to build on existing arguments that the life-cycle driven design process is rooted in a rule-based design paradigm with a strong tendency towards technical rationality, path dependency, rooted in a strong dominant design (Abrassart, 2011; Cucuzzella, 2011, 2016). The life cycle of a product, service or system frames the design problem in a limited way by keeping the *dominant design* (Abernathy & Utterback, 1978; Utterback & Abernathy, 1975) stagnant. For example, one of the first steps in the LCA process is to define a quantified function (functional unit), which serves as a basis for comparison of alternative products over their life cycles (Jolliet et al., 2016). This functional unit is an abstraction of the dominant design (Abrassart, 2011). On the other hand, an innovative design process requires reframing the design problem, using *design thinking* (Dorst, 2011) to encourage reflexivity, define new functions and product identities, therefore breaking the dominant design intentionally. The principles of innovative design, grounded in creativity and design theory, are seemingly incompatible with the life-cycle-driven eco-design approaches grounded in life cycle thinking. Innovative eco-design encourages reframing the problem while rule-based eco-design is built on a foundation of a life cycle frame that might discourage creativity.

---

[1] The EMS certification is a continuous improvement methodology inspired by quality assurance standard ISO 9001, which traditionally encouraged end-of-pipe solutions and risk management approaches for local environmental impacts.

To illustrate this clash between these two design regimes in an eco-design setting, consider the example of using LCT to eco-design the conventional vehicle. We might choose a functional unit of "conveniently transporting a person 15 km to work", where the hotspot on the life cycle of the conventional vehicle is "fuel consumption during the use phase" (CIRAIG, 2016). Rule-based eco-design reasoning would lead us to address the hotspot by developing the clean-powered electric car. Whereas with innovative eco-design we might question the implicit notion of "convenience" as "wasted time in transit", and instead design an experience where mobility provides an enriched experience (i.e. for health, social interaction, mindfulness, aesthetic impressions) and therefore enables a "convenient slow mobility" system to reduce emissions. We might even go as far as questioning the purpose of "transporting", if for example we abstract the function as "communicating for work", we can then imagine re-designing the conventional vehicle as a video-conferencing device in smart cities.

We are therefore faced with a paradox that LCT frames the problem in a way that might limit creativity, yet it is the most reliable and well-renowned tool for sustainable design. If we want to innovate by using innovative design, we must reframe the problem in such a way that we question the functional unit, and the LCA results of the original product may no longer be helpful. The "life cycle thinking" paradox led us to the research question that motivated our research project:

> ***How is creativity affected during life-cycle-driven eco-design ideation in practice?***

Our initial hypothesis was therefore:

> ***Life cycle thinking is a frame that contributes to design fixation and inhibits creative reasoning by reinforcing the dominant design and therefore works counter to the innovative design processes which aim to break these same frames.***

Though life cycle thinking can be thought of as a frame (Dorst, 2011; Schön, 1983) that creates cognitive fixation during design or other creative tasks (Agogué, Kazakci, Weil, & Cassotti, 2011; Cassotti & Agogué, 2016; Jansson & Smith, 1991), there are also systemic factors in an organization that position life cycle thinking as a form of path dependency (Dosi, 1982). Organizational structures and forms of management have a strong effect on the creativity of their employees (Amabile, 1988, 1996), as well as social interactions with colleagues, especially political tensions or synergies during creative tasks (Le Masson, Weil, & Hatchuel, 2014; Paulus, 2000; Paulus & Brown, 2007) that might affect fixation during eco-design.

This project aimed to understand the "eco-design fixation effect" that can limit creativity on cognitive, social and organizational levels during eco-design ideation, and how it surfaces in tandem with the frame of life cycle thinking. Creativity management is a relatively new and emergent field of research, which offers many different perspectives on the factors affecting creativity. Notably, this literature offers a framework of three different levels: **individual creativity**, and the cognitive processes that can limit our creative ability (Finke, Ward, & Smith, 1996; Mumford & Gustafson, 1988; Smith, Ward, & Schumacher, 1993), **team-level creativity**, and the social interactions that can affect the emergence of creative ideas during team-work (Paulus & Brown, 2007; Stroebe & Diehl, 1994), and finally **organizational creativity**, or the management styles and organizational structures in place that discourage or encourage intrinsic motivation of employees (Amabile, 1988, 1996).

For this project we wanted to explore real professional environments and how eco-design tools such as LCA, LCM and LCT enable employees to use creative reasoning in different contexts. We therefore had four main objectives:

1. ***Contrast a rule-based (LCA-driven) eco-design regime with an innovative (creativity-driven) eco-design approach to understand their effects on creativity***
2. ***On an individual level, investigate the cognitive factors that also contribute to fixation during eco-design***
3. ***On a team level, when working on eco-design ideation in groups, investigate the team dynamic that affects creativity***
4. ***On an organizational level, investigate the institutional factors that contribute to fixation during eco-design***

In this study, I critique the seemingly contradictory use of life cycle approaches for innovation by colliding life cycle thinking, sustainability, design theory, cognitive and social psychology of creativity and creativity management literatures to address these objectives in real-world corporate settings. The chosen methodology addresses these four objectives with research intervention in two case studies in two global engineering firms.

.

CHAPTER 2 LITERATURE REVIEW

This literature review begins with a survey of eco-design practices and justifies the need for an innovative approach for sustainable development, especially within the context of firms. A review of relevant design literature also critiques the eco-design community for taking an innovative approach with life-cycle tools. The innovation context is then deconstructed to into different components of creativity that contribute to a firm's innovative capacity, and links how life cycle driven approaches and sustainability considerations tie in to these issues. Following Woodman, Sawyer, and Griffin (1993)'s theory of organizational creativity, the review on creativity literature extends from individual-level creativity and cognitive fixation, social nature of creativity and organizational contextual factors that contribute to overall organization-wide creativity.

2.1 The origins of eco-design: a paradigm of life-cycle-driven eco-efficiency

2.1.1 Life cycle approach

Taking a life cycle approach for sustainability implies going beyond the production facility and immediate operations of the firm, to include environmental and social impacts all long the life cycle: from raw materials extraction, to production, to distribution, to use, and end of life. The arrival of the life cycle approach was indeed an innovation in the 1990s (Hunt & Franklin, 1996) and represented a paradigm shift in the understanding of the environmental impacts of products. Previously, firms were fixated on optimizing their internal operations, putting them at risk for the potential displacement of environmental impacts along the value chain. LCT gave firms a new way to frame their environmental issues that brings light to the issue of displacement of impacts by considering the entire value chain of a product, encouraging a holistic perspective of the product's entire footprint. For example, LCT can bring an increased awareness of the displacement of impacts from one life cycle phase to another (ie. reduced impacts in production phase might lead to higher impacts in distribution), from one impact category to another (ie. lowering carbon emissions might lead to higher impacts in ecosystem quality), from one region to another, etc.

In the 1990s, many global organizations emerged for building a community of practice around life cycle thinking, such as the UNEP-SETAC Life Cycle Initiative (Guinée et al., 2011; Life Cycle Initiative, 2018).

Where LCT can be thought of as a philosophy, there exist many tools, methodologies and standards that emerged under this umbrella term. Notably, life cycle assessment (LCA) is a robust quantitative tool for calculating environmental impacts all along a product's life cycle, over multiple environmental impact categories (not just climate change). The environmental profile is calculated for a given functional unit (FU), defined as the quantified expression of the function of that product. The LCA methodology is governed by ISO 14040 & ISO 14044 standards. Carbon footprint, water footprint, are examples of life cycle assessments in one impact category only.

While the development of LCA and LCT were growing in the late 1980s and 1990s, the paradigm of eco-design was anchored in this philosophy (Abrassart, 2011). It became accepted that in order to properly "eco-design" a product, it was necessary to look at all of the impacts of the product along its value chain, and optimize those hotspots while avoiding compromises through the displacement of impacts on other parts of the life cycle.

2.1.2 The dominant eco-design paradigm : eco-efficiency

The motivation for eco-design of products emerged from life cycle thinking: products should be designed with their entire life cycle in mind for them to be considered environmentally-friendly. This approach to eco-design adds a lot of value to the environmental relevance of the product beign designed. Life cycle thinking, and especially the use of a LCA-inspired tool, gives a starting point to the design process to prioritize the areas along the value chain where reduction of environmental impacts is most needed. This is called identifying "hotspots". A typical eco-design process uses these hotspots as a springboard for re-designing or optimizing the existing product.

This life-cycle-based approach to eco-design became standardized by the International Standardization Organization (ISO) as well with the ISO 14006 & 14062 guidelines. These guidelines define eco-design as the "integration of environmental considerations into product design & development", where product development is defined as "a set of processes that transform requirements into specific characteristics or the specification of a product, process or system." Luttropp & Lagerstedt (2006), lead authors in eco-design in the early 2000s also use this definition.

The ISO 14062 guidelines on eco-design propose that environmental impacts be verified with a life cycle tool all along the product development process. This fits in quite nicely with a stage-gate product development process, which emerged from the foundational texts of engineering product design and development (Pahl & Beitz, 1996; Ulrich & Eppinger, 2011b).

Not only did the development of eco-design remain anchored in life cycle thinking, it also anchored itself in the traditional form of engineering design, characterized by balancing trade-offs of quality, cost, and time, but by adding a fourth constraint of "environmental concern". This approach maintained that the specification for a product's function and technical qualities would be given. This represents what we will refer to as "rule-based design" (Hatchuel & Weil, 2008) or "rule-based eco-design" (Abrassart, 2011).

These methods are also known as "eco-efficiency" methods of designing a product with environmental considerations. Eco-efficiency is defined as increasing value while decreasing a product's environmental footprint.

Rule-based eco-design processes inspired by eco-efficiency in theory are a series of optimizations of different constraints on a classic engineering design problem. In practice, rule-based eco-design practioners are faced with management challenges such as the design paradox between data availability and freedom, and choosing the benchmark product to which a product is compared. In early design stages when few decisions have been made, there is little data available and many degrees of freedom. At this stage, a full LCA is difficult to carry out due to the lack of data, but more qualitative, simplified assessment methods inspired by LCA are recommended. This is also the moment in the design process where the LCA could paradoxically most influence the final design of the product. Later in the design process when most decisions have been made, there is sufficient data available to carry out a full and detailed LCA to identify the product's hotspots, yet there are fewer degrees of freedom to have an impact on the design of the product. The eco-designer is therefore faced with this classic design paradox (Midler, 2004).

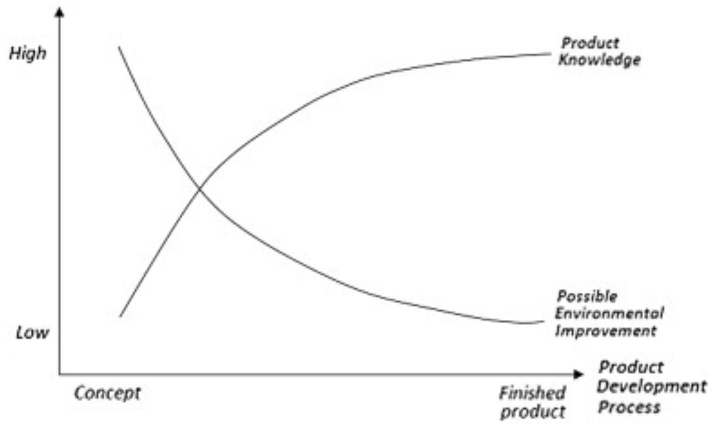

Figure 2.1– Rule-based eco-design paradox (Bhander, Hauschild, & McAloone, 2003; Poudelet, Chayer, Margni, Pellerin, & Samson, 2012)

A common practice in using life cycle-based eco-design for product development is the comparison of the product to a "reference" product, already existing on the market, which can be used as a benchmark for the development of the existing product. The LCA results of this product are therefore used as a basis of comparison when designing and ideating for the eco-designed product in question. Both of the compared products have the same function and the same FU is used in the life cycle assessment to ease the comparison.

Some early stage eco-design methods are lists of guidelines and rules, such as the Golden Rules of Eco-design (Luttropp & Lagerstedt, 2006), and Design-for-X approaches such as Design-for-Environment , Design-for-Recycling, Design-for-Sustainability.

Luttrop & Lagerstedt's Golden Rules, for instance, offer a list of recommendations for eco-designing products that frame the eco-design problem around optimizing physical aspects of the product that will generally lead to lower environmental impacts. The rules are as follows:

> *"ONE Do not use toxic substances and utilize closed loops for necessary but toxic ones.*
>
> *TWO Minimize energy and resource consumption in the production phase and transport through improved housekeeping.*
>
> *THREE Use structural features and high quality materials to minimize weight … in products … if such choices do not interfere with necessary flexibility, impact strength or other functional priorities.*

FOUR Minimize energy and resource consumption in the usage phase, especially for products with the most significant aspects in the usage phase.

FIVE Promote repair and upgrading, especially for system-dependent products. (e.g. cell phones, computers and CD players).

SIX Promote long life, especially for products with significant environmental aspects outside of the usage phase.

SEVEN Invest in better materials, surface treatments or structural arrangements to protect products from dirt, corrosion and wear, thereby ensuring reduced maintenance and longer product life.

EIGHT Prearrange upgrading, repair and recycling through access ability, labelling, modules, breaking points and manuals.

NINE Promote upgrading, repair and recycling by using few, simple, recycled, not blended materials and no alloys.

TEN Use as few joining elements as possible and use screws, adhesives, welding, snap fits, geometric locking, etc. according to the life cycle scenario." (Luttropp & Lagerstedt, 2006)

This method is a clear example of rule-based eco-design by offering "rules" for the designer to follow. While these rules may spark new ideas for additional environmental considerations for designers who are mainly focused on technical feasibility and common design constraints (ie. quality, cost, delay), I will argue later in this thesis that rules such as these may actually have a counter-productive effect to creativity in a larger sense.

Later stage eco-design methods are designed to balance the trade-off of environmental hotspots with existing technical design criteria such as environmental adaptations of Quality-Function-Deployment matrices (Eco-QFD), and product-oriented environmental management systems (POEMS) (Bellini & Janin, 2011; Rossi, Germani, & Zamagni, 2016). These methods are used to converge towards a design that will meet traditional quality, costs and delay constraints that characterize a traditional engineering product design process.

It is precisely the characteristic of **convergence** in existing and well-known eco-design methods that present a challenge for creativity when the intent of the design process is to be innovative.

There seems to be a paradox between the status quo of eco-design tools, rooted in a rule-based eco-design paradigm, and the widespread intention of the industry to go further than optimization of products to achieve innovative eco-design.

2.1.3 Does eco-efficiency address the transformational sustainability issues we are facing today?

Many have argued that we need radical innovation, rather than incremental product improvement to address the sustainability challenges of today (Ceschin, 2014; Ceschin & Gaziulusoy, 2016; Cucuzzella, 2016; Nill & Kemp, 2009; Tukker, 2008; Tukker & Butter, 2007).

Globally, we are starting to feel the effects of climate change, there has been a global decline of 60% of species population sizes between 1970 and 2018 (WWF, 2018), North America is being forced to deal with the massive amounts of waste they are creating since exports of waste to China are being refused (Brooks, Wang, & Jambeck, 2018). There is a global cry to reduce our reliance on fossil fuels, energy transitions towards clean energy with renewables and storage are advancing (IEA, 2018).

From the establishment of the definition of "sustainable development" in 1987 with the Brundtland report, to the present day, the policy climate around sustainability has drastically changed in 40 years. Sustainability discourse in liberal policy circles has evolved from « preventing » climate change to « attenuating » or « adapting to » climate change. Conservative policy discourse is also evolving from environmental protection (for example Nixon's creation of the EPA and George Bush seeing climate change as an economic opportunity for innovation with the development of hydrogen-powered vehicles), to a neo-liberal view of the demonization of environmental regulation as destructive to economic development (for example Trump's executive order to eliminate Obama's Clean Power Plan). Even the Canadian government has not lived up to its emissions reduction goals established at the COP21 meeting and is supporting the development of new pipeline development which is expected to increase the nation's emissions.

Though the policy sphere in North America seems bleak today, European sustainability policy is much more advanced. The EU has established an "eco-design directive" which establishes a status quo for the eco-efficiency of categories of products that firms must respect. They have also implemented the REACH program, limiting certain toxic substances from being used in products imported to and developed in the EU. We have also seen successful policy on a global level (for example, Montreal protocol for the Ozone layer, which forced the refrigerator industry to stop using chloro-fluoro-carbons (CFCs) in their design and effectively regulated the problem).

The EU is more advanced than North America in sustainability policy, but still regulates firms by imposing eco-efficiency guidelines, regulations and rules to follow. By taking a technocratic[2] approach to sustainable product development, they do not encourage sustainable innovation that would radically change the impacts of firms through transformational design.

Finally, the eco-efficiency approach for product improvement through eco-design is also limited in its inevitable cause of rebound effects of increased overall consumption (Alcott, 2005; Polimani, Mayumi, Giampietro, & Alcott, 2008). Also known as the Jevons Paradox, energy efficiency can lead to more energy use, not less, due to decreased operational costs (Polimani et al., 2008).

Another common term in sustainability discourse is the "decoupling" of economic growth from environmental impact, relying on the increased efficiency of products to maintain capitalism's socio-economic benefits while reducing its downsides of negative externalities (UNEP, 2011).

With a political context that sees environmental regulation as a threat in North America, or one that relies exclusively on efficiency measures in Europe, we are not going far enough to radically and drastically reduce impacts on the environment. If "decoupling" is really where we are intending to go, we need to evolve our approach from incremental improvement of products towards transformative, innovative eco-design (Stamm, Dantas, Fischer, Ganguly, & Rennkamp, 2009). COP21 commitments require radical and systemic changes in our systems (H. de Coninck, 2018).

---

[2] Take for example the IPAT equation (Ehrlich & Holdren, 1971), where Impacts (emissions) = Population (people) x Affluence ($-spent/person) x Technology (emissions / $-spent). By making more eco-efficient technology, we are only working on the "T" part of the equation, which can be drastically outweighed by the exponential increase in population and inflation of affluence by the increased middle class worldwide.)

2.1.4 Responding to the environmental crisis with function and system innovation in eco-design

In his foundational book, *Ecodesign: A Promising Approach to Sustainable Production and Consumption*, Han Brezet et al. (1997) encourages taking “leaps” for sustainability that go further than just life cycle product improvement. Eco-design occurs in four stages of innovative potential, represented by S-curves, from product improvement, to product re-design, to function innovation, to system innovation (see Figure 2.2). Radical innovation is needed to pass from one stage to another.

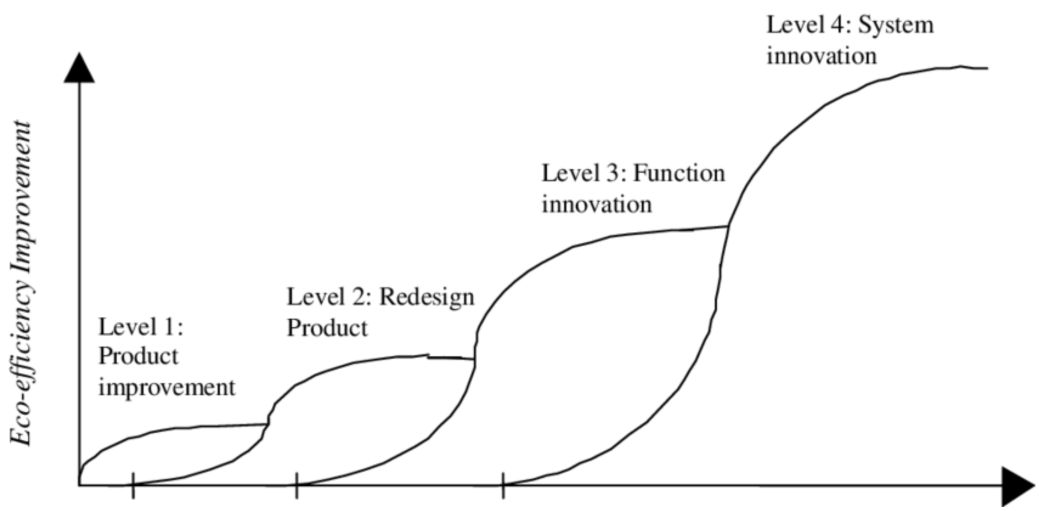

Figure 2.2 – Levels of innovation in eco-design (Brezet & van Hemel, 1997)

Contemporary eco-design is conscious of the limitations of merely improving products for sustainability and borrow notions from contemporary innovation to reach for the type 3 and 4 eco-designs according to Brezet and van Hemel (1997). It is also aware of the difficulties to achieve radical innovation and offers an explanation as to why the dominant eco-design paradigm rests in the product-improvement sphere. Ceschin and Gaziulusoy (2016) also offers a model of the transformational potential of eco-design (see Figure 2.3). The insular nature of product-design and eco-efficiency does not lend itself well to the systemic sustainability issues, which require a systemic approach to deisgn. He also critiques the technology-focused approach to eco-design which doesn’t take into account the human and societal aspects of the design that will lead to transformational change. He characterizes eco-design by an evolution from the product level, to the product-service-system level, to a spatio-social level to a socio-technical system level (Ceschin & Gaziulusoy, 2016).

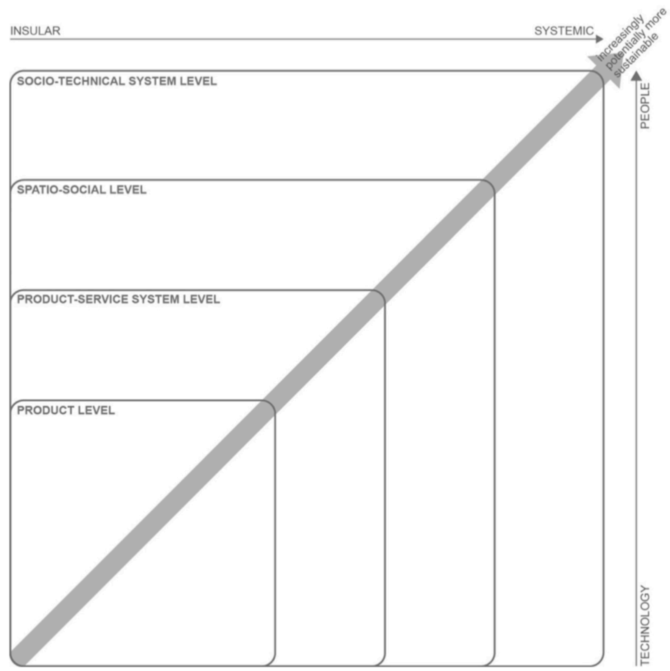

Figure 2.3 – The evolution of design for sustainability (Ceschin & Gaziulusoy, 2016)

Simply using a life-cycle approach by appending an LCA assessment at different stages of the product development process is evidently not enough to re-imagine products in the ways Brezet and Ceschin suggest. Yet many firms are still using a life cycle approach despite trying to achieve radical innovation for sustainability. LCA is a wonderful tool for product improvement but is not designed for inspiring radical innovation. Firms are embedded in a system of standards, networks, established tools and methodologies of life cycle thinking and turn naturally towards these tools, but are they appropriate for radical innovation? There seems to be a mismatch of intentions, tools and methods for two different regimes of design, rule-based and innovative.

2.2 Contemporary eco-design: two professions with different epistemologies

Though the dominant life-cycle-driven eco-design paradigm brought an exciting way to integrate environmental concerns into the design of products in the 1990s, it is limited in dealing with the innovation issues we are facing today, 30 years later. The life cycle approach is optimized for product improvement and has adapted itself to the well-established, convergent product development process known to engineers, what we will refer to as “rule-based eco-design” or the “engineer’s approach to eco-design” (Abrassart, 2011).

With modern innovation characterized by the creation of new product identities by radically challenging the existing functions of products (Le Masson et al., 2010, 2014), new terms have emerged in eco-design discourse that seek to embody this evolution of eco-design such as “eco-innovation”, “life cycle innovation” and “sustainable innovation”. I will refer to these approaches as “innovative eco-design” or the “designer’s approach to eco-design” (Abrassart, 2011).

When we look closely at the LCA community’s definition of *product design*, they consider “design” to be a process of balancing design constraints and converging towards a solution. This definition corresponds to an engineering product design definition made popular by Pahl and Beitz (1996) and Ulrich and Eppinger (2011b), in which a product development process is quite linear and convergent, stemming from a set of specifications and well-known design principles and rules.

We could contrast this definition of design with that of an industrial designer, "a creative activity whose aim is to establish the multi-faceted qualities of objects, processes, services and their systems in whole life-cycles” (Manzini, 2006). Manzini (2006) says, “the openness of the field of possibilities where designers are operating is one of the factors that characterizes their actions. When there is no room for choice, because the solution is dictated by strong social conventions and/or technological constraints, there is no design.”[3] Manzini seems to encourage an openness and divergence of the eco-design problem, where technological constraints are not important right away, whereas the LCT community’s definition stems from an engineering approach to product development that is reliant on strict technological constraints and convergence of the problem from the beginning.

Along these lines we can distinguish two regimes of eco-design: the engineer’s approach and the designer’s approach (Abrassart, 2011). The engineer’s approach is rule-based, incremental,

[3] Though for many practitioners the term “eco-design” is synonymous with eco-efficiency and rule-based eco-design (see for ex. EU Eco-design directive), I wish to re-appropriate the term “eco-design” in this thesis to embody the transformational nature of design that Manzini evokes in his definition.

deductive and uses technical rationality, while the designer's approach is exploratory, transformative and uses reflexivity (Abrassart, 2011; Cucuzzella, 2011, 2016).

C-K Theory

Concept-Knowledge (C-K) Theory is a model of innovative design reasoning, or the creative process, by the co-expansion of two spaces: the Knowledge space (K) and the Concept space (C).

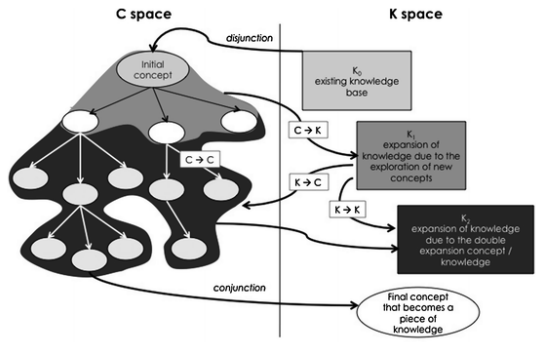

Figure 2.4 – C-K method (From (Agogué & Kazakçi, 2014)

The C-space is a tree representing the imaginary but rational exploration of concepts that do not have a logical status, whereas the K-space is a network of knowledge, that can be affirmed as true or false, activated for the generation of new concepts.

C-K theory can demonstrate the fixation effect by a limitation in the expansion of C and K spaces (Agogué et al., 2011). C-expansions can therefore either be expansive or restrictive. Knowledge can either be classified as known, accessible or missing.

We evaluate the quality of an innovative design experience with a V2OR analysis where we evaluate the Value, Variety, Originality and Robustness.

In the concept space, we evaluate the Variety (number of different branches explored) and Originality (number of expansive partitions that challenge the dominant design).

In the knowledge space, we evaluate the potential contribution of the new concepts to a future rule-based design: Value (new value spaces that bring together actors that did not previously work together) and Robustness (the validity of the propositions when the context changes).

For more information see (Agogué, Hooge, Arnoux, & Brown, 2014; Hatchuel & Weil, 2008; Le Masson et al., 2010)

Abrassart (2011) offers an interpretation of the two regimes of eco-design, grounded in Hatchuel and Weil (2008) ''s C-K Design Theory. These authors distinguish two regimes of design: *rule-based design*, where the product identities remain stable within a working dominant design, and *innovative design*, where product identities are questioned, and the dominant designs and rule-based designs of tomorrow are re-invented (Hatchuel & Weil, 2008; Le Masson et al., 2010). When the life cycle of an existing product is used as the starting point for a design process (by for example, using the LCA results of a product as a basis for ideation), we are reasoning in a rule-based eco-design paradigm. If instead, the life cycle of a product is the result of a design process, then we are reasoning in an innovative eco-design paradigm (Abrassart, Margni, Beaulieu, & Imbeault-Tétreault, 2016).

Cucuzzella however, positions what Abrassart refers to as rule-based design using LCA, as a simplistic, positivist and technologically deterministic approach, grounded in the prevention principle that only leads to optimization of existing systems. She suggests we need a paradigm shift (Kuhn, 1970) in eco-design, to transition towards what she calls "transformative eco-design" that encompasses complexity in a constructivist epistemology with the precautionary principle. The engineer is therefore bound to his technical rationality when reasoning with LCA for eco-design, whereas the designer is free to use his reflexivity to imagine new systems in which the products he designs could bring transformational value.

There are many similar critiques from the eco-design community that the life cycle approach may be limiting to creativity (Cluzel, Yannou, Leroy, & Millet, 2012; Millet, Bistagnino, Lanzavecchia, Camous, & Poldma, 2007; Tyl, Legardeur, Millet, & Vallet, 2014). Millet et al. (2007) question the pertinence of using life cycle approaches for design, and conclude that LCA's "utility in the design process is limited to an analysis of existing products or well-defined products at the final stages of the design process" and "may generate confusion within the design team while restricting the capacity for innovation within the company."

Cucuzzella (2016) eloquently summarizes the problem of using LCA as a quantitative methodology for reducing risk as having a profound effect on creativity of the designer:

> *"The attraction of quantitative methods [...] is that they have predictive powers where judgment based on computable data are simpler to rationalize. [...] Can creativity exist in a prescriptive and quantitative environmental methodology? Is the instrumentality of*

environmental requirements in design projects as a means towards environmental efficiency redirecting the designer's energy of fantasy or imaginary?" (Cucuzzella, 2016)

From this point of view, my argument would benefit from a deeper analysis into the intricacies of design theory and creativity. The design literature offers a useful point of view in understanding the engineer's tendency to gravitate towards life cycle approaches when they are in a position to integrate sustainability for innovation. When it comes to innovation, the engineer is often trained to use systematic design (Pahl & Beitz, 1996), which comes easier to them than embracing complexity the way a designer is trained (Cucuzzella, 2011).

2.3 LCT as a frame in design thinking

Designers have established professional practices to naturally deal with complex problems: creating frames (Dorst, 2011). For a designer, problem framing is a common heuristic used in abductive reasoning to define the *design space* of an unknown object, product or service (an unknown WHAT) which will respond through a "working principle" (a HOW) to a *design brief* (the aspired VALUE he wishes to achieve). For instance, an inspector imagines scenarios (possible WHAT) to give coherence to a clue (a RESULT noticed) by relying on laws (HOWs). For an engineer, deductive reasoning on known objects and functions (a defined WHAT) with the help of conceptual models and catalogues of rules (which embody possible HOWs) are more familiar (Dorst, 2011).

WHAT (thing) **+ HOW** (working principle) leads to **VALUE** (aspired)

Figure 2.5 - The base logical equation for design, from which different settings of knowns & unknowns show different reasoning methods to design (Dorst, 2011)

??? + HOW leads to **VALUE**

Figure 2.6 - "Closed reasoning" requiring Abduction-1, also known as basic problem solving (Dorst, 2011)

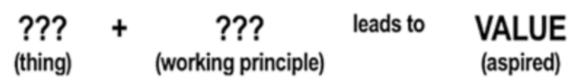

Figure 2.7 - “Open reasoning” requiring Abduction-2 (Dorst, 2011)

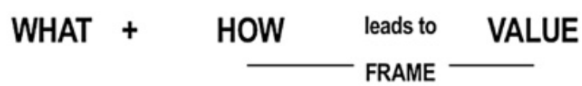

Figure 2.8 - Design reasoning as imposing a frame to use Abduction-2 (Dorst, 2011)

The designer therefore alternates between frames to test and explore different solutions, whereas the engineer remains confined to a single frame, taking the working principle for granted, as a given to solve the problem.

Life cycle thinking can be understood as a way to frame the eco-design problem. The aspired VALUE of the eco-design process is known, we want to maintain the existing product’s function, but with reduced externalities. The HOW or the working principle, is to reduce the impacts along the life cycle of the existing product, where the FRAME is life cycle thinking.

For the designer, life cycle thinking is only one among many possible ways to frame the problem. They have a much larger design space (WHAT) to work with, where the function is brought into question, whereas the engineer is limited to the design space offered by the life cycle thinking frame, keeping the function constant (i.e. by addressing hotspots along the product’s value chain).

We can also use this heuristic to understand the innovation that life cycle thinking brought in the 1990s. Previously, the eco-design problems was framed by an environmental management system or reducing waste and emissions from within the walls of the factory. The arrival of LCT represented an institutional reframing of the eco-design problem from one life cycle phase to the entire product’s life cycle.

Schön’s framework is also frequently used by design scholars to describe “design thinking” (Cross, 2001, 2010; Cucuzzella, 2011), where a designer’s skill is mastered reflexivity, and an engineer is often bound to their technical rationality. Schön was the first to use the term “framing” to refer to "the creation of a (novel) standpoint from which a problematic situation can be tackled" (Dorst, 2011). We could therefore also say that the use of Abduction-2 is a reflexive activity, whereas Abduction-1 is calling on technical rationality (Dorst, 2011).

As shown in Figure 2.9, the engineer's rule-based framing is centered on the life cycle phases of the product but does not consider the functional unit. The designer's innovative framing can open up a new innovation field on any of the life cycle phases *including* on the functional unit.

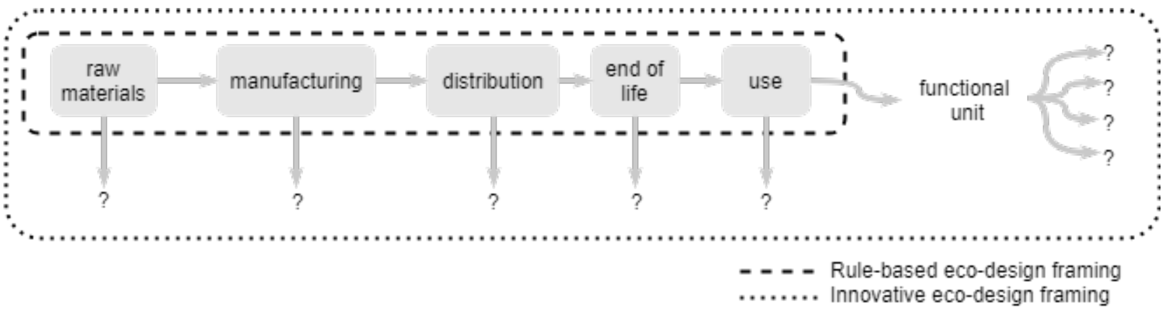

Figure 2.9 - Framing the problem in different schools of eco-design

2.4 LCT as reinforcing the dominant design

The life cycle frame as discussed in the previous section requires that the *functional unit (FU)* maintains the notion of a dominant design. In the act of designating a quantified function as a basis of comparison of the desired product with a benchmark or "reference" product, as recommended by the ISO 14062 guidelines (Lewandowska & Kurczewski, 2010), we are deliberately laying the ground for a rule-based eco-design process.

The dominant design is a stagnant product identity where its key features have become a de facto standard (Abernathy & Utterback, 1978; Utterback & Abernathy, 1975). For example, the conventional vehicle's key features are that it has four tires, four passengers, a single human driver who owns and operates the vehicle, with ample storage space in the back, powered by a combustion engine, and many more.[4] A dominant design is not a bad thing, it is necessary for different actors to organize themselves around the optimized production of an existing product. For instance, in the conventional vehicle industry, maintenance is simple and any mechanic can repair any vehicle because they all have a similar structure and similar components. Standardization associations, such as ISO, CSA, IEEE standards are examples of established dominant designs for common products to maintain consistency in large systems with many providers of the same products (for example, electrical equipment on the electrical distribution network must operate at a common voltage and peak current rating so that maintenance staff can easily do repairs regardless of the producer of that product).

If it is so effective for maintaining large systems, why do we need to challenge the dominant design? Why do we need to create new product identities? For one, companies who never reinvent themselves and their products are subject to the innovator's dilemma: the threat of incumbents with lower quality versions of the same product, making their expertise a commodity (Christensen, 1997). Second, if we need radical innovation to address the global sustainability challenges and ecological crisis we are facing, questioning the product identity and reinventing the functions of the future go hand in hand with radical innovation of systems. These systems often have high *technological momentum* (Hughes, 1987), or encourage *path dependency* (Dosi, 1982), making them extremely difficult to welcome innovation, and maintaining archaic technologies that have only been subject to incremental improvements in their efficiency, and optimized over the course of their life time. This is precisely the paradox we are facing in eco-design today: we need innovative design to radically reduce the emissions of these systems, but they are so embedded in a rule-based design paradigm that life cycle approaches for incremental improvement and optimization speak best to them.

---

[4] Some contemporary innovations that challenged the dominant design of the car are car-sharing services (where the driver and owner are not the same person), electric vehicles (where the combustion engine no longer exists, and a 'frunk' provides more storage space in the front of the vehicle) and smart cars (where there is less trunk space and only 2 passengers), for instance.

Systemically, LCT lends itself well to rule-based design processes in markets with high technological momentum who wish to pursue eco-design. Even when they wish to use innovative eco-design, often the only tools at their disposal are life-cycle-based.

Now that I have argued *why* we need to question the dominant design to achieve innovative eco-design's radical reduction of impacts I argued for earlier in this chapter, now I would like to argue *how* to question the dominant design, and why it is more difficult than it seems.

2.5 Individual creativity and cognitive fixation

From the macro-level of market pressures that may make an innovative eco-design approach difficult for some firms, this section zeroes in towards the micro-level of the cognitive processes of individuals that make challenging the dominant design difficult. By calling on literature in cognitive psychology of creativity, this section delves into the cognitive blocks and barriers to creativity that are often at play during eco-design.

To begin, I would like to make the distinction between creativity and innovation. The most common and agreed upon definition of a *creative idea* is something that is both novel and useful, whereas an innovation is the implementation of that creative idea (Amabile, 1996; Mumford & Gustafson, 1988).

2.5.1 Design fixation

Research on the cognitive blocks to creativity in design originated in the early 90s with Jansson and Smith (1991)'s publication on *design fixation*. These authors define design fixation as a "blind adherence to a set of ideas or concepts limiting the output of conceptual design". Jansson and Smith presented a design brief to two groups, one with an example design and one without, and found elements of the example in the final design presented by the groups with the example. This demonstrated fixation on an example shown immediately before design. This was the first work to link cognitive psychology to engineering design and opened up more questions about the nature of creativity and what unconscious processes might be limiting our creative capacity during the design activity.

When the existing object or example design is presented, the designers are prone to using the "path of least resistance", creating a fixation in the concept-space of their potential design (Le Masson et al., 2014).

2.5.2 The dual system of thought

Daniel Kahneman (2011)'s contribution on the dual system of thought (*Thinking Fast and Slow)*, similarly shows a link between cognitive psychology and decision-making, clarified through a series of rigorous scientific experiments which founded the field of behavioural economics. Kahneman explains that we have a fast thinking system, that is automatic and intuitive, useful for every day decisions, but prone to biases. Our slow thinking system on the other hand, is analytical, conscious and reflexive, requiring effort to overcome the biases encountered by system 1. System 2 is useful for complex decisions. Cognitive fixation happens because the mind is "lazy" and follows the "path of least resistance", using its fast thinking in settings where it might be inappropriate (Cassotti & Agogué, 2016; Cassotti, Camarda, Poirel, Houdé, & Agogué, 2016).

Kahneman uses thought experiments to demonstrate our System 1's adherence to anchors that bias our capacity for logical decision making in System 2. Take for example an American man named Steve, a very shy bookworm who didn't go out much and like to spend his Sundays cuddled up with his cat and a cup of tea. Is Steve more likely to be a librarian or a farmer? Our intuitive response is that Steve is a librarian! This is because we are anchored in the context presented before the question, adhering to occupational stereotypes rather than referring to statistics. "Did it occur to you that there are more than 20 male farmers for each male librarian in the United States? Because there are so many more farmers, it is almost certain that more 'meek and tidy' souls will be found on tractors than at library information desks" (Kahneman, 2011).

Clinging to recently activated, readily available knowledge therefore creates fixation in the exploration of new knowledge spaces (Le Masson et al., 2014). In presenting a piece of knowledge on social stereotypes, the intuitive mind reasoned with this piece of information instead of accessing a more robust and logical piece of statistical knowledge about the ratio of farmers to librarians in America.

These cognitive blocks and fixations occur when our System 1 is activated in situations where it should not be. For example, in a professional environment, an engineer with 20 years' experience works with rules of thumb, professional routines, relying on past experience and existing knowledge that no longer require calculation or referring to reference manuals. In situations where he needs to be creative, his System 1 intuitively activates these short-cuts when he searches for "creative" solutions, but he is bound to his technical rationality. It takes a creative trigger to activate reflexivity in these situations, as Schön proposes. Reflexivity requires accessing new knowledge, and using heuristics to explore what is unknown to his technical rationality (Schön, 1983).

Kahneman takes however an unwavering stance on the dual nature of the mind. He states that System 2 is and always will be the slave of System 1 (Houdé, 2014; Kahneman, 2011). System 2 is intrinsically lazy and system 1 is inevitably going to take the lead in decision-making, and there is nothing we can do about it. In response to this, Houdé (2014) counters this point in suggesting we also have a System 3: one which can inhibit System 1 in order to activate System 2 when making decisions.

2.5.3 Creative cognition

Creative cognition, or the connection of cognitive psychology with creativity (Finke et al., 1996), is a line of research that builds precisely on Houdé (2014)'s "system 3". "Creative reasoning" is defined as using inhibitory control to purposefully activate system 2 during a creative exercise like design (Cassotti & Agogué, 2016). With a scientific approach and controlled psychological experiments, many studies have repeatedly demonstrated how our system 1 affects our ability to be creative in ideation exercises (Agogué et al., 2011; Agogué, Poirel, Pineau, Houdé, & Cassotti, 2014; Cassotti et al., 2016). In one particular experiment, the power of examples presented before ideation was investigated. Much like the Jansson and Smith (1991) experiment, teams were presented with either expansive, restrictive or no examples. The results found that the teams with the expansive example were more creative than the ones with restrictive or no examples. Schon also talks about the creative triggers that create a surprising element in the design process to initiate reflexivity.

2.5.4 Creative cognition in eco-design

In relation to eco-design, this means we need expansive, not restrictive, triggers to activate our slow thinking system before ideating in order to be creative. When we thus expose ourselves to LCA results before ideation, we are showing a restrictive example that is not enough to trigger creative reasoning.

A particular experiment published in design literature demonstrated the fixation effect during eco-design with an experimental approach in a controlled environment (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010, 2011). The experiment consisted of giving different groups of students environmental information with varying levels of detail before ideation: either a full LCA, an LCA of a similar product, a simplified LCA or a journal article with qualitative environmental information. The group with the most generic, qualitative starting point (i.e. the journal article) proposed the most creative ideas compared to those who were given detailed LCA results as inspiration (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010, 2011). This study confirms that life cycle environmental information can frame the possible set of solutions and cause cognitive fixation during eco-design ideation. However, this study is limited in terms of real-world application; a controlled environment is insulated from the organizational pressures and routines that professionals experience when doing eco-design.

Cucuzzella (2016) also studied creativity in eco-design with design students who had used different eco-design tools in a series of workshops. She measured their creative output and found that when the tools were too restrictive (ie. detailed LCA results suggesting specific hotspots to work on), the students were less creative. However, when they were given too little information, their creativity was also low.

Many other authors explored the use of LCA as limiting to the creative process during eco-design ideation (Millet et al., 2007; Tyl et al., 2014; Vallet et al., 2013). This existing work shows that more time may be spent on environmental evaluation than ideation (Vallet et al., 2013), and that there isn't yet a suitable eco-design tool geared towards "eco-ideation" (Tyl et al., 2014). Some authors even go as far to say that LCA isn't appropriate for the design process (Millet et al., 2007)! This literature is focused on the "missing tools" of eco-design, proposing additions to existing tools and the conception of new tools altogether. There is however a gap in creating a process for eco-design that is specific to the design team needs, rather than creating a generic tool that would work for the average case scenario.

In sum, cognitive fixation and the lack of awareness and skill to use creative reasoning or inhibitory control are precisely what make it so difficult to think beyond the dominant design and reframe the design problem (Dorst, 2011). The cognitive barriers to creativity limit the generation of new concepts by taking the path of least resistance and fixating on the existing object's dominant design, and limit access to new knowledge by clinging to recently activated, immediately available knowledge (Le Masson et al., 2014).

2.6 Collective creativity: social factors

Research in the field of creativity not only focuses on the individual's creative processes but also the social nature of creativity (Fischer, 2004). Though ideation in and of itself is a cognitive process, the social dynamics of a group setting inevitably influence that process (Paulus, 2000; Paulus & Brown, 2007).

2.6.1 The origins of social creativity: *Applied Imagination*

The social nature of creativity lies in the interactions and collaborations during a design process or an ideation exercise. Osborn (1953) was the first to recognize that ideation activities in groups cause social pressures on individuals that affect the creative process and limit the quality and quantity of ideas resulting from ideation. Individuals are apprehensive about sharing their ideas for fear of the judgement of others. Osborn therefore established the well-known four rules for brainstorming: suspend judgement, quantity over quality, welcome crazy ideas, and build on the ideas of others (Osborn, 1953).

Though this particular brainstorming method is revered as the standard for reducing social inhibitions in group creativity exercises, it has been shown to be *unproductive*, in that the same number individuals brainstorming alone generate more ideas than they would in a group (Diehl & Stroebe, 1987). It is clear that participants in a brainstorming group need to feel "psychologically safe" in order to fully express their creativity. Osborn's rules do not acknowledge that the social, cognitive and motivational factors of the group are intrinsically linked together. Like we saw in the previous section, cognitive fixation occurs on the individual level, but *collective fixation* also exists in generating new concepts for a number of reasons (Le Masson et al., 2014).

2.6.2 Collective fixation in the concept-space

Collective fixation occurs in both the exploration of the group in the concept-space and in the knowledge-space (Le Masson et al., 2014).

Fear of judgement for putting forth "crazy concepts", or what Diehl and Stroebe (1987) call "evaluation apprehension", and the tendency to privilege convergence and development of a single concept through compromising an idea that all agree on can limit exploration of new concepts.

The advantage of diversity is in the increased range of possibilities with the combined knowledge of the participants from different backgrounds, the constructive conflicts that can arise in the group discussion (Badke-Schaub, Goldschmidt, & Meijer, 2010; Shalley & Gilson, 2004), stimulating production of "less accessible" ideas. If there is too big of a range in knowledge between the participants, they may not have enough conceptual overlap to ideate together.

2.6.3 Collective fixation in the knowledge-space

Access to new knowledge is often limited by the reluctance to mobilize knowledge that is not available to all participants, especially in interdisciplinary groups. The group conversation will gravitate towards common knowledge rather than on the sum of all available knowledge (Stewart & Stasser, 1995). There is also a reluctance in a group to question the established rules and knowledge of the "expert", or to propose new rules or ways of reasoning (Le Masson et al., 2014).

While some studies show that cognitive diversity of groups has a positive effect on creativity (Diehl & Stroebe, 1987; McLeod & Lobel, 1992; Mumford, Feldman, Hein, & Nagao, 2001; Shalley & Gilson, 2004; Stroebe & Diehl, 1994), other show that it can in fact be detrimental if there is too much distance between the knowledge bases and skills of the participants (Paulus & Brown, 2007; Shalley & Gilson, 2004). There needs to be enough overlap in knowledge for the group to effectively work together.

Homogeneous groups can exhibit diversity on differing levels of expertise within a domain (Fischer, 2004). The expert might be too fixated on his ways of knowing and the novice might bring new insight from his naïve point of view. The reverse may also be true, the novice might not have enough domain-relevant skills (Amabile, 1996) which limits him in his creative abilities compared to the expert (Fischer, 2004). Homogeneous teams are hence weakened by groupthink, whereas they are strengthened by a common understanding of the subject matter. Heterogeneous groups, an interdisciplinary group of stakeholders with a common interest (Fischer, 2004) are characterized by their strength in conceptual diversity across many domains, which can lead to more creative ideas, but are weakened by their lack of shared understanding (Fischer, 2004).

With the transition to the open innovation paradigm (Chesbrough, 2003), where the inputs and outputs of innovation are no longer consolidated within the firm but seep out to a larger ecosystem, firms have become interested in new methods of design that include stakeholders in the process. Participatory design (Schuler & Namioka, 1993) is one such method, also known as co-design and co-creation (Sanders, 2008; Sanders & Stappers, 2008).

Co-creation brings an interdisciplinary group of stakeholders together, all from different backgrounds with different knowledge and skills, leveraging their diversity for co-creation. The resulting collectives can bring tremendous value to the firm (Dubois, Le Masson, Weil, & Cohendet, 2014). A participatory design method where low cohesiveness between the stakeholders from different organizations can create a different dynamic than an internal design team of colleagues with high cohesiveness.

2.6.4 Productivity loss in brainstorming

The cognitive load caused by the delicate balance between *listening* to the others' ideas and generating one's own ideas can cause **production blocks** in idea generation. The value of brainstorming is obviously in listening to others' ideas to stimulate new associations in memory and consequently access ideas they wouldn't be able to access on their own. However, if the participants focus *too much* on listening to others, they won't have cognitive space to generate any ideas, whereas if they remain strictly in their own minds, they won't benefit from exposure to new ideas from the diverse group. Brainstorming can be thought of as a "divided attention task", where cognitive capacity needs to be divided (Paulus, 2000; Paulus & Brown, 2007).

Social loafing, or the reduced accountability for one's individual performance, and strong power dynamics can also have a great impact on the motivation of the participants to share and develop new ideas (Diehl & Stroebe, 1987). Participants' motivation to participate in the group is just as important as their individual task-related motivation. Some authors have shown that participants compare themselves to others in the group and tend to converge towards the low performers in these cases. However, when there is a sense of competition, they tend to converge upwards towards the higher performers.

Some authors propose that there is an "illusion of effectivity" in group brainstorming, that no matter the conditions to counter these negative effects, the same number of individuals brainstorming alone can come up with more ideas than as a group (Diehl & Stroebe, 1987) (Stroebe & Diehl). This concession can be misleading because only looking at the number of ideas generated is a limited measure of creativity, we are missing the quality of ideas and the new value they bring, as well as the originality of those ideas (Le Masson et al., 2014). Kazakçı, Gillier, Piat, and Hatchuel (2014) show that brainstorming can actually be more successful with few original concepts that demonstrate high potential value creation rather than a high quantity of unoriginal propositions.

There are however recommendations for overcoming these which have proven to be successful, such as using brainwriting (Paulus & Brown, 2003), using anonymity (Jessup, Connolly, & Galegher, 1990), relating to knowledge (Kazakçı et al., 2014), and structuring the interactions with the presence of a facilitator (Paulus, 2000).

2.7 Organizational creativity: leadership styles and organizational culture

Woodman et al. (1993) propose a theory of organizational creativity, that links together individual, group and organizational features that overall contribute to organizational creativity. Their theory has many links with Amabile (1996)'s work on intrinsic motivation in creativity management for firms.

According to Amabile, there are three dimensions of individual creativity: domain-relevant skills (technical knowledge), creativity skills (cognitive style and skills in taking new perspectives on problems and in generating ideas) and motivation (Amabile, 1996, 1998). She highlights that extrinsic motivation (for ex. innovation bonuses, carrot-or-the-stick, forcing them to do the job) works counter to creativity, but intrinsic motivation (a passionate, genuine interest in the problem) does. Amabile says that managers have the most influence on motivation, and that working on building the intrinsic motivation of employees will have the most immediate results in their creativity. She suggests seven aspects of motivation on which managers can work: resources, challenge, freedom, workgroup features, supervisory encouragement, and organizational support.

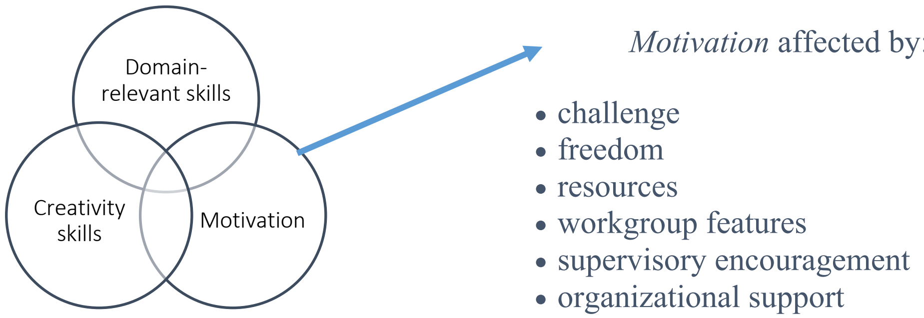

Figure 2.10 - Three components of creativity and factors of intrinsic motivation. Adapted from (Amabile, 1998)

An individual's creative capacity can contribute to the organization's overall level of creativity. For example, a longitudinal study showed that creativity training to increase creativity skills, led to increased intrinsic motivation of employees, leading to an overall increase in organizational creative capacity (Rampa, Abrassart, & Agogué, 2017).

However, the organizational context can also be detrimental to an individual's ability to express their creativity and affect their intrinsic motivation. Organizational culture (Nyström, 1990; Woodman et al., 1993), systems of evaluation, reporting tools, and organizational structure often highly influence individual routines, with a range of possible effects, from normalisation of conducts to stimulation of learning (Franck Aggeri & Julie Labatut, 2010). Creative personalities can therefore only express themselves in organizational contexts that allow for it (Cummings & Oldham, 1997).

There is also evidence that authoritarian organizations with formal reporting relationships are less likely to be innovative, when compared to organizations with transformational leadership styles (Shalley & Gilson, 2004).

2.7.1 Organizing for innovative design: the R-I-D structure

Le Masson, Hatchuel and Weil (Hatchuel, Le Masson, & Weil, 2001a, 2001b; Le Masson et al., 2010) investigated innovative, design-oriented firms and found that there is a need to move from a simple R&D model towards an R-I-D model, where Innovation is no longer considered a quality of a product but a management process in itself that should be distinct from Research and Development. They propose that the quality of the innovation management process cannot be managed like a project nor a strategic portfolio, two management trends that lend themselves well to Research & Development, as per their definitions. Research should aim to produce new knowledge, Development should aim to activate existing knowledge and competencies with classic project management, whereas Innovation aims to define new values and identify new competencies. While the outcome of Research is knowledge, and the outcome of Development is a product, the outcomes of Innovation are multiple, and characterized by an "innovation field". This field could consist of new questions, new product ideas, new competencies or new knowledge. It cannot be managed on a strict horizon, but on a contingent horizon that changes as the project evolves. It needs to be an organized exploration of divergence, exploring many pathways in parallel. It cannot be managed as a project because its goals are multiple and ever changing. It cannot be managed as a strategic portfolio of projects because it needs to "go further than general market orientations" to define criteria for selection of research projects and innovation issues. The project and portfolio of projects are managed in an intentional dominant design, whereas the innovation activity aims to define the dominant design of the future, the new design criteria for the development of products of tomorrow.

2.8 Conclusion

This literature review began with a brief overview of the history of eco-design, showing how it is anchored in a life cycle thinking philosophy. I then outlined how the existing framework of eco-design might be limiting when faced with the sustainability challenges of our time; traditional life-cycle-based eco-design may not be going far enough to challenge the status quo. The status quo can only be challenged with creativity and innovation; which led to a review of literature in design theory, individual, social and organizational creativity. By merging these two fields of research together, I showed that there seems to be a lack of taking into account the state-of-the-art in creativity when using these traditional methods for eco-design, notably when using and relying heavily on life cycle assessment results during the eco-design process.

CHAPTER 3 METHODOLOGY

3.1 General methodological approach

Existing studies on fixation in eco-design have used experimental approaches in classroom environments (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010). The goal of this study is to use an applied, on-the-field approach in an organizational environment, where the use of experiments might be inappropriate. For this reason, action research was chosen as the overarching methodology, using a multiple case-study design to reinforce complementary findings from two different engineering organizations (ACME and Solvay).

In order to investigate these questions in a real-world corporate setting, we decided to use a case study approach (Yin, 2009), with two engineering firms in different sectors. Each firm would select a specific project, and associated team of interdisciplinary participants to experience two eco-design workshops: one LCA-driven, and one creativity-driven.

Since we could not perform a controlled experiment in an organizational setting, we opted for a constructivist approach instead. The nature of the data we were collecting was socially constructed in tandem by the researcher and the participants in the workshops, whose perceived experience in the workshops might override an "objective" external assessment. The participants were therefore interviewed before and after the workshops. This data was analyzed with discourse analysis (Charmaz, 2014; Creswell, 2013; Patton, 2002).

Creativity depends on cognition (Cassotti & Agogué, 2016), on intrinsic motivation, creativity skills and domain-relevant skills (Amabile, 1996). The observation of these aspects is complex, and would therefore benefit from a constructivist, qualitative approach inspired by grounded theory (Charmaz, 2014). However, in contrast to grounded theory, the results did not emerge from the data, rather the sought-out themes were searched for in the data. The perception and behaviour of each individual in the workshop was assessed through qualitative data from interviews and observations.

With research intervention, we were able to immerse ourselves in the field to understand the corporate setting of each case. The idea behind research intervention is begin by observing the organization's initial state with a diagnostic, followed by implementing a change in the organization, and observing the outcomes of that change. According to David (2000), this corresponds to an alternation between testing theory in practice and enriching existing theory from what emerges in the field.

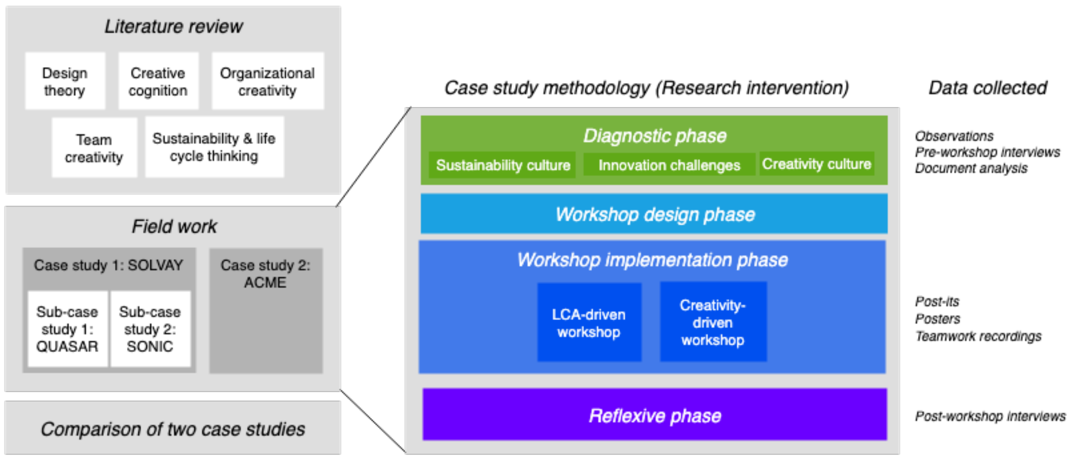

Figure 3.1– General methodological approach

The general methodology is illustrated in Figure 3.1. Beginning with a literature review to build the framework of design theory and individual, social and organizational creativity, we then moved into the field work which consisted of two case studies. The first case study at Solvay had two sub-cases (two projects, Quasar and Sonic, experienced the same methodology separately) while the second case study at ACME only consisted of one project. The field work stage, covered partially in the article in CHAPTER 5 and in CHAPTER 6, used research intervention. The intervention methodology is divided into four sub-phases: Diagnostic, Workshop Design, Workshop Implementation and Reflexive phase. Additional data from the case studies can be found in Appendix A and Appendix B. Finally, the case studies were compared in a final phase and is partially covered in the article in CHAPTER 5 and in CHAPTER 7.

The methodology for each case study used research intervention (David, 2000; Radaelli, Guerci, Cirella, & Shani, 2012), inspired by action research: an iterative process of observing, intervening, collecting data on the intervention, and reflecting on results (Coghlan & Shani, 2013; Yorks, 2005; Yström, Ollila, Agogué, & Coghlan, 2017). In the case of this project, first a *diagnostic phase*, where the "initial state" of the case study was established, followed by a *design phase* where the design brief will be constructed. Afterwards, a *workshop implementation* phase will be carried out as several co-design and knowledge building sessions with a design team composed of various stakeholders. During the final *reflexive / recommendations* phase, we recommended eco-design value creation pathways for the organization based on the outcomes of the workshops. During this final stage we also reflected on the change that occurred in the organization with the workshops implemented and compared this to our findings from the diagnostic.

Building on the theory that innovative ideas result from combining the acquisition of new knowledge with the generation of unknown concepts, knowledge-building before (and during) ideation is essential (Agogué, Hooge, et al., 2014; Le Masson et al., 2010). A method for managing the creative process of co-design workshops called **KCP** (Knowledge, Concepts, Proposal), developed by Le Masson et al. (2010), organizes the creative process into three distinct phases: knowledge building, followed by idea generation, or creation, and proposition of solutions. This methodological tool was used to ensure the design team is exposed to enough knowledge before ideation to improve their creative capacity, and to increase organizational learning.

We also used participatory design methodologies to include external stakeholders in several workshops. Some research showed that these participatory methods are conducive to creativity (Dubois et al., 2014).

The first case study at ACME consisted of an intervention in the Canadian offices over 6 months. The second case study at Solvay consisted of an intervention in Lyon and Paris in France, over 1.5 months. This explains the difference in detail for each diagnostic, where ACME's diagnostic phase was much more detailed and profound than Solvay's.

3.1.1 Diagnostic phase

At Solvay, we worked with two separate research projects who were part of the corporate growth initiatives for radical innovation. Both of these projects implicated the same staff, so the casting remained the same, but the subject matter differed for both sub-cases. The project names were Quasar and Sonic. At ACME, we worked with a local business unit in the Canadian organization. Through interviews with workshop participants, we characterized the market trends and innovation climate of the industry. We also investigated the organizational factors that might affect employees' intrinsic motivation for creativity by using Amabile (1996)'s social psychology of creativity framework. The pre-workshop interviews also served to understand the employees' perception of the sustainability and eco-design strategy at the firm. We also examined internal documentation (such as Environmental Product Declarations (EPDs) and sustainability reports) and publications, to get a larger picture of the firm's eco-design strategy evolution.

3.1.2 Design phase

This phase occurred outside the walls of the firm, where we prepared and designed the workshops that would make most sense for the participants of the study on the basis of the diagnostic performed. We also decided on casting at this stage. Using the KCP method, we decided on an appropriate knowledge building exercise (K) before the concept-generation stage (C) for each workshop.

Since Solvay already had an internal LCA-driven eco-design program, we merely observed these workshops which were piloted by the internal environmental assessment team. The two creativity-driven workshops at Solvay, as well as both LCA-driven and creativity-driven workshops at ACME were designed, facilitated and observed by the researchers.

At ACME we used the participatory design method for casting the workshops, inviting value chain actors from outside the organization to participate.

3.1.3 Workshop implementation phase

In this phase we organized and facilitated both workshops. Retrospectively, we used an ex-post C-K method (Agogué, Hooge, et al., 2014; Le Masson et al., 2010) to illustrate the reasoning of each team in an arborescence of concepts generated and knowledge used during the workshop. Then we used Le Masson, Hatchuel and Weil's assessment technique called V2OR (value, variety, originality and robustness) to judge the quality of the ideation process.

3.1.4 Propositions phase

After the workshops we conducted post-workshop interviews with the participants to get an idea of the success, team dynamic and climate.

After codifying all the concepts generated during the workshops, we synthesized the data to generate a report of final recommendations for each firm to move towards one or more sustainable innovations. This phase corresponds to the P phase in the KCP method.

The methods used for contrasting the LCA-driven eco-design approach with the creativity-driven eco-design approach aimed to shed light on the effect of the tools and workshop design on creativity.

Inspired by Le Masson et al. (2010)'s design theory, we designed a series of workshops for both case studies, which also built on the diagnostic that we performed. The workshops for which we had control (all but Solvay LCA-driven workshops) were carefully designed to provide a starting point of knowledge that at a desired distance from the dominant design of the product (ie. LCA results for workshop 1 and foreign knowledge for workshop 2), as well as providing a method or tool that is qualified as either rule-based or innovative (i.e. the Golden Rules of Eco-design for workshop 1, and C-K method or prospective innovation for workshop 2).

Clearly, the design team will have already been exposed to the LCA results in workshop 1 before workshop 2, which may in effect influence their creative reasoning. We therefore considered several alternatives to sequence the workshops in order to avoid "biasing" the design group with the LCA results. Considering Agogué et al. (2011)'s results which show that the information presented immediately before a workshop are on what the participants fixate, we felt confident that the introduction of new knowledge before workshop 2 would be more important in their creative reasoning than information they had seen one or several weeks prior (ie. the LCA results in workshop 1).

After leading the participants through the sequence workshops, we mapped the concepts proposed and knowledge activated by each team in each workshop using C-K theory, and evaluated the creativity of their exploration using the V2OR method (Le Masson et al., 2010). These results are presented in Appendix A and B.

An exploration that was high in value, variety, originality and robustness was qualified as an innovative exploration of the subject, whereas one that only built on existing knowledge, low originality of concepts was a more rule-based exploration of the subject. This analysis was done in the journal article (Chapter 4) and continued in Appendices A and B.

To evaluate individual creativity, a survey of methods was done to select which would be most appropriate for this project. Several semi-quantitative methods exist for evaluating creativity such as the Consensual Assessment Technique, where experts evaluate a creative work based on their experience (Amabile, 1996). However, this method is difficult to implement in practice since it is resource-intensive. The expert might also be a victim of cognitive fixation and unable to identify a truly innovative concept, or they might judge something to be innovative within their frame of reference, which may not be from an external point of view of the domain (Le Masson et al., 2014). We finally opted for a hybrid approach for evaluating individual creativity.

First, we evaluated the 'creative product' that emerged from the workshop using Le Masson et al (2010)'s V2OR assessment method. By establishing the dominant design and the usual way of working in the diagnostic phase, our codification of the concepts generated during the workshops consisted of identifying how they differed from this collective fixation to identify Originality, variety, value and robustness with respect to the company's individual context. We looked for elements of the K-phase presentations in the resulting concepts, and elements of what we qualified as their "dominant design" from the diagnostic. Were the participants fixated on what was presented and did this represent an expansive example or a restrictive example for their subsequent creative reasoning (Agogué et al., 2011)?

Next, we evaluated the individual's creative cognitive ability by interviewing them before the workshop to understand their creativity skills and what professional routines they might fixate on during the workshops. By interviewing them after the workshops, we looked for signs of reflexivity and if they were able to see a progression of creative learning in the workshops. We asked them to identify if they were more or less creative in each workshop, in which one they felt more comfortable, and in which one they felt easier to propose ideas. The interviews were analyzed with discourse analysis and inspired by grounded theory (Charmaz, 2014; Creswell, 2013; Patton, 2002). This analysis is presented in Chapter 6 General Discussion.

Many factors were at play concerning the team dynamic and social forces at play during the workshops that could have affected the team's creativity. From recordings and observations during the workshops, we were able to identify some power dynamics that may have taken hold. We also included some targeted questions in the post-workshop interviews to understand the team dynamic that occurred during the workshops better. Calling upon literature in the social nature of creativity (Badke-Schaub et al., 2010; Diehl & Stroebe, 1987; Paulus, 2000; Paulus & Brown, 2007; Shalley & Gilson, 2004; Stroebe & Diehl, 1994), the interviews and recordings were analyzed with discourse analysis and inspired by grounded theory (Charmaz, 2014; Creswell, 2013; Patton, 2002).. This analysis is presented in Chapter 6 General Discussion.

Organizational creativity for eco-innovation was assessed by a historical document analysis of sustainability reports, and other environment- and innovation-related publications by the company. In the case of ACME, we performed a benchmarking to understand the status quo from the competitors of the company. Interviews with the authors of these documents will also contribute data to the analysis. Many interview questions were targeted to understand the management instruments in place that may affect the employees' intrinsic motivation (Amabile, 1996). Using literature from organizational creativity, we analyzed interviews and documentation using discourse analysis and inspired by grounded theory (Charmaz, 2014; Creswell, 2013; Patton, 2002). This analysis is presented in the supplementary results (Chapter 5) and General Discussion (Chapter 6).

It should be noted that the methods used for all four objectives overlap in an intermingling web of creative dimensions that affect each other. We go into a further analysis of this in the Discussion sections of the article and of this thesis.

3.2 Data collection and analysis

For the case study at ACME, we carried out 22 semi-structured interviews with 14 employees. Each interview lasted between 30 minutes and 1 hour. We then used discourse analysis to examine the results and emerging overarching themes. We also analyzed internal documentation, including 18 sustainability reports the years from 1999 to 2016, and 62 Environmental Product Declarations (EPDs) published by the company. We conducted a literature review on the eco-design of substations, and eco-design practices based on internal publications and scientific journal publications. During each workshop, we recorded each team's conversation during the 1-hour activity, which gave us 8 hours of teamwork recordings to analyze. We also recorded the presentations by each team at the end of each workshop explaining their work, which amounted to 80 minutes of video. Finally, during the workshops we collected all the physical material used such as post-its, papers, and posters to further analyze the concepts and ideas generated.

The interview participants at ACME ranged from managers to engineers, marketing and sales experts. The external invitees who participated in the workshops did not take part in the interviews.

For the Solvay case, we carried out 24 semi-structured interviews with 13 employees. Each interview lasted between 30 minutes and 1 hour. We then used discourse analysis to examine the results and emerging overarching themes. During the LCA-driven workshops, we took notes and photos of the team's work. During the creativity-driven workshops, we collected all the physical material used such as post-its, papers and posters in addition to recording the team's conversations during the Sonic workshop. We also recorded the presentations by each team at the end of each workshop, explaining their work, which amounted to ~60 minutes of video.

The workshop and interview participants at Solvay were nearly all chemical engineering experts, most of whom had over 10 years' experience in the company. The roles represented ranged from the environmental and economic evaluation group (3E), to upper management, to laboratory and research managers to chemical engineering researchers.

The pre-workshop interview questions, found in Appendix C, were geared more to understanding the participant's background, experience and getting an understanding of their "System 1". This data was analyzed using three different categories for coding: sustainability, individual-level and organizational-level creativity and innovation. The post-workshop interview questions, also found in Appendix C, were geared towards understanding the participant's experience during the workshops. The analysis of this data used a coding for identifying their social interactions with other participants, and understanding their own perception of their creativity during the workshops.

CHAPTER 4 PRESENTATION OF THE CASE STUDIES

In this section the context of both case studies are introduced. This corresponds to the Diagnostic phase of both intervention research protocols at both ACME and at Solvay.

4.1 ACME Diagnostic

4.1.1 Market innovation challenges

Substations, large yards of electrical equipment and steel structures, are used for either stepping up voltage, in the case of preparing electricity to be transported over long distances from a generating station, or stepping down voltage, in the case of distributing electricity to homes and facilities. There are two categories of customers who buy this product: industrials, who consume more electricity than the residential grid can provide (ie. factories, hospitals or universities) and utilities, who provide electricity.

The utility customer is conservative by nature, averse to innovation, yet drives the market and establishes the dominant design. With expertise in-house to request exactly what they need from their suppliers, ACME has little opportunity to propose something innovative. Since most utilities are publicly owned, ACME cannot intervene during the design stage to propose innovation either.

On the contrary, the industrial customer is interested in getting the cheapest equipment as quickly as possible. Electricity is not their core business. When they need a substation, they do not have internal expertise and do not play by the rules and standards that the utilities have established. However, ACME does not have the resources or the time to design something innovative suited to the industrial customer's specific needs. Though these industrials are more open to innovation and impose fewer constraints on ACME, the dominant design driven by the utilities makes it difficult to invest in innovating for such a small market segment.

The innovation dilemma for the substation market is characterized by this "vicious circle": utilities have strict demands and order in large quantities, so ACME designs high end products that adhere to their exact specifications. Industrial customers have more flexibility, yet want something low cost, but ACME can't afford to design something new for them, so they sell the same product to the industrial customer that they designed for the utility customer. It seems the incentive to innovate is missing.

4.1.2 Internal innovation challenges also exist.

Beginning with the sales and marketing stage, the point of contact with the customer, these employees pick up on customer requests and needs for new features and attributes of products. The local sales and marketing staff can feed this information back up to the factory to make improvements on existing products. This is a great strategy for incremental innovation but blinds them from a larger view of the market, and from opportunities for radical innovation. Continuously adding features that become "bells and whistles" end up corresponding less to what lower-end customers like industrials really need: a simple and cheap alternative. This puts ACME at risk of minimalist and low cost incumbents taking up market share from the bigger actors like ACME (See (Christensen, 1997)).

It is clear from our interviews with employees that in the substations industry, a *creatively designed* or *innovative* substation is synonymous with being *low cost.* At ACME, the cost constraint is always encouraged, and celebrated when a design meets this criterion. PGGI is facing a lot of difficulties being competitive since the ACME products are high end, usually cost more than the competition. They usually win contracts based on innovative and creative engineering that either saves a client money or proposes a design they had not thought of in their specification. This strategy of coming up with an «option one», that surprises the customer by being an innovative design at a lower or same cost, usually wins the contract.

4.1.3 Creativity at ACME

At ACME, employees are highly competent in domain-relevant skills, some have concrete creativity skills as well though it is less common.

Amabile (1996) lists lack of resources (time and money), as a cause of low creativity of employees. Organizations that do not allow time for exploration and incubation of ideas, create an environment where employees are channeling their creativity into trying to find resources rather than finding new ideas. During the period of this investigation at ACME, "times were tough". Limited resources, resulting from low volume of new orders from customers, and from the team's inherent staffing structure led to layoffs that put the remaining employees working at overcapacity. Instead of investing in innovation by allowing employees more time to reflect on new processes and projects for long term value creation and increasing their innovation capacity, management is cutting employees who are not dedicated entirely to short-term value creation.

Despite the organizational pressures to cut back on spending, there was strong evidence for supervisory encouragement from management in the project management and engineering groups. There was an intuitive understanding among the managers interviewed that encouraging creativity among their employees is important.

4.1.4 Sustainability at ACME

ACME had been a pioneer in sustainability and life cycle management in the 1990s. At that time, the management structure for sustainability consisted of two groups: one corporate or "group level", and the other research. The corporate sustainability team dealt with high-level sustainability issues such as reporting. The corporate research group had a more hands-on mission to work with factories and product development teams to implement sustainability considerations in their products. Specialized in LCA, this corporate research group created a toolbox of eco-design tools that could be used by the factories. ACME's sustainability practices implemented throughout the company in the 1990s and 2000s reflected a high maturity level. This team helped in the publication of over 60 Environmental Product Declarations (EPDs), an ecolabel providing transparent information on the life cycle environmental impacts of specific products.

They were on a promising track until the mid-2000s, when they stopped performing LCAs internally, stopped publishing Environmental Product Declarations (EPDs) and the corporate research group dedicated to sustainability was dissolved. Today the corporate sustainability function still exists but Life Cycle Management is hardly mentioned in recent sustainability reports and publications. It seems since the 2008 economic crisis, ACME cut back on sustainability research and eco-design implementation to cut costs, and since then have only kept their corporate-level sustainability activities for reporting, marketing and public relations. The internal operations related to product design that had such impressive momentum, never came back to life.

In the past few years, recent sustainability efforts in life cycle management refer to information systems and expanding the sustainability goals of the company outside of its operations towards its entire value chain, but do not mention eco-design specifically, nor including environmental issues in product development or innovation. Recent sustainability reports also briefly mention eco-design, but are referring to the sustainability criteria integrated into the GATE Model that was established in the year 2000.

There is clear evidence that ACME had gained a lot of momentum for sustainable design up until 2008, but since the economic crisis and the dissolution of the corporate research activities in sustainability, this momentum has unfortunately remained at a halt. If they had continued to develop their rule-based eco-design practices up to the present day, they might have been on a similar path as Solvay to combining these practices with innovation management of the company.

At the present time, the local substations project group does not intentionally integrate any sustainable features in their quotes and bids to customers. The defining factor for any bid is cost, therefore reducing price and working on the bottom line is rewarded as most important part of design. An *innovative* design is synonymous with *low cost*. Price usually determines whether contracts are won and takes up the entire space of design efforts by the engineering teams. There seemed to be a consensus among employees that a sustainable product offering would necessarily come at a higher price.

Three themes of reasoning arose in interviews with the employees who participated in the study: sustainability isn't considered in substation design due to ***lack of pressure from competition***, ***customers aren't asking for it***, and ***government is not regulating*** the sustainability of the industry.

This current way of thinking evidently does not position sustainability as a lever of innovation. ACME could instead, use sustainability as a driver for creating new value through co-innovation and using innovative design to push the market instead of waiting for pressure to come externally. ACME could be empowered to create this pressure for its competitors, on the government and on customers by pressing the importance of sustainable design, by convincing customers to integrate sustainability in their scorecards, and lobbying for sustainable regulations on their products.

There was a strong theme among those interviewed that there is very little communicated on the "E" part of HSE. There is a strong focus on viewing environmental concerns as "risks" to be prevented, or as problems to address with end-of-pipe solutions. The measures are more reactive than proactive. Furthermore, environmental problems are not currently seen as opportunities for innovation. The environment is not seen as a source of value creation, but as a cost that will inevitably reduce profits if leadership is taken on these issues beforehand.

Many employees used language like "eventually" or "it will come" to refer to sustainable design, as if they had a feeling that in the next 5 to 10 years it will eventually become an important design constraint as a result of pressure from the three actors identified previously.

4.2 Solvay Diagnostic

4.2.1 Innovation at Solvay

Solvay's innovation strategy is deeply linked to their sustainability goals. In the 2017 annual report, we find the definition of their Research & Innovation Policy:

> *"Research and Innovation (R&I) policy strongly supports Solvay's ambition to grow profitably while reducing its environmental footprint and increasing the proportion of its revenue that meets the challenges of sustainable development. Global Business Units (GBUs) and Functions are working together in a cross-functional approach to provide customers with significant added value through innovative and competitive solutions tailored to the present and future needs of end-users." (Annual Report, 2017)*

Research and innovation (R&I) at Solvay takes place on the business-unit level, and on the corporate level. First, GBU R&I projects constitute incremental innovation within the existing global business units (GBU), leveraging the existing technologies within these BUs. The second are GBU-driven initiatives, in which the GBUs partner with corporate R&I to launch more radical projects that originate from market-pull demands or that challenge the existing GBU's portfolio. Finally, the **Growth Initiatives** (GI) program was created to encourage breakthrough, radical innovation that takes a more technology-push model and is managed from the Corporate R&I organization, not within any particular GBU. 17% of Solvay's total R&I budget is dedicated to these growth initiatives (2017 Annual Report), whereas the remainder of the budget is focused on GBU-driven incremental innovation.

Solvay uses an innovation management tool called **WEGO**, which is used for all three types of innovation projects: GBU projects, GBU-driven initiatives and Growth Initiatives. The WEGO innovation process is divided into two stages: Opportunity bank, and Pipe of Innovation Projects. The Opportunities phase is represented by a convergent funnel to sort the ideas from the ideation phase towards the stage-gate project management process in the Pipe stage.

Solvay tries to include representatives from the scale-up, industrialization and feasibility stages right away at the beginning of the new product development process to ensure that the development of the new projects take into account the needs of those future stages from the beginning.

This process lends well to the incremental innovation we would see in the GBUs, where an idea and opportunities that turn into project proposals can be evaluated from the beginning on their feasibility. However, for the Growth Initiatives, this type of stage-gate reasoning requires a high maturity of an idea or project that the growth initiatives do not yet have.

When it comes to surfacing creative ideas from the masses, ***Gotit*** is Solvay's bottom-up ideation management tool. It is a platform to collect ideas from any employee on anything ranging from improving the office space to ideas for new products and chemical processes. Employees can also vote on each other's ideas. Every idea is guaranteed a follow-up from upper management so there are no ideas left behind or forgotten.

However, the engineers and researchers we interviewed did not see the value in *Gotit*. First, some employees think the ideas that wind up on *Gotit* are those that are completely disconnected from ongoing businesses and needs of the company. Others think the idea evaluation process is biased because it is the same few managers who evaluate all the ideas and posts on *Gotit*, rather than the ideation process being a process to socialize ideas and get feedback from peers and affected stakeholders. Finally, *Gotit* can be discouraging if employees feel they have a creative idea in their context for their team, but when they go on the platform many other people have had the same idea in other contexts. This doesn't invalidate the creativity of the individual's idea, but it makes them feel that their idea isn't important or that it isn't likely to advance very far.

4.2.2 Creativity at Solvay

Our overall observation of organizational creativity at Solvay was that employees are extremely competent in their domain-relevant skills, though there is a lack of diversity of expertise in their brainstorming sessions. With creativity skills acquired through innovation and creativity trainings, we could say that the employees have high creativity skills. Since we were in a research &

development department, most employees interviewed were curious and creative by the nature, owing to their background as researchers. They showed signs of high intrinsic motivation, but the organizational conditions imposed on them from a strict structure and limited resources limit their expression of that creativity.

In the labs, employees felt they had the freedom to investigate a new polymer or chemical process if they felt it was interesting and would add value to the company; no one would challenge them on their exploration. However, there were no resources available for this kind of exploration: employees had to "find the time" to do it – often on their own schedule after working hours. One employee shared: *"You have to do innovation yourself at Solvay. I do it because I'm passionate about it"*.

Employees also felt that they were caught in a double bind – they were asked to be creative and innovative, but on a strict time schedule and with limited budget.

Though everyone was highly competent in their particular sub-domain of chemistry and process engineering, they recognized the lack of diversity and the similarity of their ways of thinking in brainstorming exercises.

It was clear that the GI radical innovation projects were managed in a similar way to the GBU-driven incremental innovation projects. The employees recognized that they needed more time and freedom, without a strict deliverables list for their GI projects, and this was hampering their ability to deliver. Projects are stopped in their tracks too early in the innovation process, because they are treated as part of a stage-gate system instead of as an open exploration with divergent pathways.

This "impatience" is reflected in their regular sessions for brainstorming. The employees felt like their brainstorming sessions were very conventional, and almost always converged towards the chemical processes necessary to realize their ideas instead of diverging towards exploration of those ideas to begin with.

There was also evidence of an elitist and deterministic view of creativity; those with the most of experience in the company or in the field of chemistry were the source of creative and innovative ideas, whereas the more junior employees were responsible for executing the ideas.

Those who were not experts or "research fellows" were only creative if their personality allowed them to be. There was a general lack of fconsideration for the organizational and managerial dimensions that affect intrinsic motivation of employees, and that creativity skills can be learned rather than exclusively innate to “creative people”.

4.2.3 Sustainability at Solvay

Sustainability at the corporate level is managed from Brussels, Solvay’s headquarters. The team is divided into three main axes: improving industrial activities (by working to reduce carbon emissions at the factory level, for example), reporting to stakeholders (by submitting reports to the Dow Jones Sustainability Index, for example), and portfolio management (by reviewing the environmental performance of the entire product portfolio at Solvay in their applications and along their value chain).

This third axe of the Corporate Sustainability team works in partnership with a Corporate Research & Innovation team based on Lyon, France called “3E”, or Eco-Efficiency Evaluations team. The 3E team consists of environmental LCA analysts and economic evaluation analysts, of whom most have significant experience in the chemicals industry and have worked at Solvay for many decades. These two teams work together to perform Sustainable Portfolio Management (SPM) evaluations on different products and services at Solvay.

SPM has been used since 2009 at Solvay. In 2017, 88% of their portfolio was analyzed (Solvay Annual Report, 2017). The SPM evaluation is based on the cradle-to-gate environmental footprint of the product (called Operations Vulnerability) within a specific context, as well as its position in the market for that specific application (called Market Alignment).

The SPM evaluation constitutes three dimensions: operations vulnerability, market alignment and the sales volume.

- **Operations vulnerability**
  - Either an eco-profile or a full LCA of the product in its application, compared to a reference product (corresponding to an equivalent function)
  - Impacts are monetized & compared to their overall sales volume to arrive at a final, single score.
- **Market alignment** (market signals on the sustainability of the product in its application)
  - This is a “fact-based” assessment of market signals on the sustainability of the product in its application.

- **Sales Volume**
    - Total revenues from that product

The rating places the products in three categories (see **Error! Reference source not found.**), " solutions", neutral and challenges.

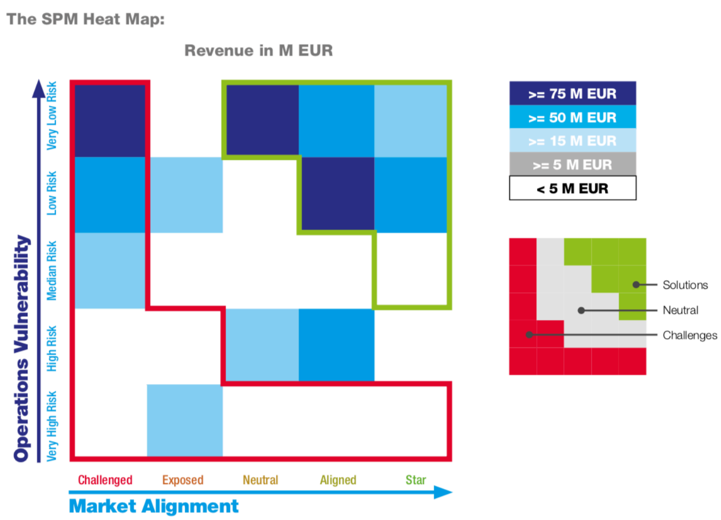

Figure 4.1 – Positioning of products evaluated with the SPM tool at Solvay (Solvay, 2017)

The SPM methodology is used in a wide range of Solvay's activities, most notably every research & Innovation (R&I) projects are evaluated before turning into a product development project in the WEGO process. During the opportunities phase, the product is evaluated with a "Fast Track SPM", a qualitative analysis of the six categories on each dimension of SPM. Before turning into a "project" in the Innovation Projects phase of WEGO, the full SPM methodology is carried out, and eventually a Full LCA is also evaluated to compare the product to a "reference" product, which already exists on the market for the same function.

The 3E team in 2017 began a pilot program called Sustainability-by-Design, which aimed "*to help innovators put sustainability at the heart of their projects: changing the mindset from sustainability as an obligation to a business advantage*" (Solvay, personal communication, April 2018). By leveraging the SPM tool, it was hoped to use these results to come up with eco-design pathways for the given PAC. The vision of this program shows a clear intention to put sustainability considerations at the heart of the R&I processes for developing new products and improving existing products.

Whereas the SPM tool alone defines a "Reference" product (existing already on the market), to compare its environmental footprint to a "Target" product (which is being developed in the current project), the SbyD methodology empowers the project team to establish an "Ambition", or a desired environmental footprint of their product that goes beyond the current reference and target's impacts.

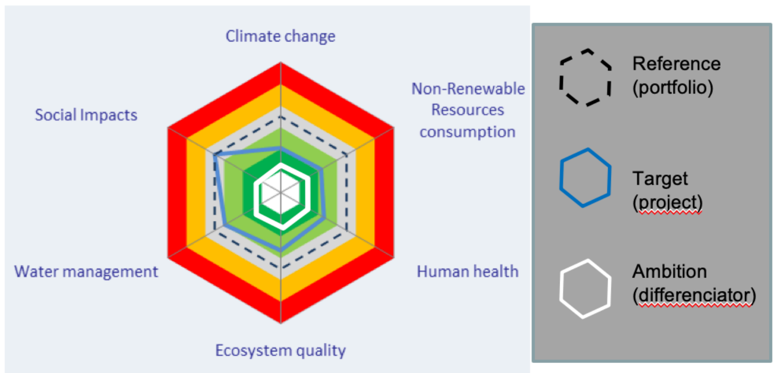

Figure 4.2 – SPM spider showing reference, target and ambition on 6 sustainability indicators (Solvay, personal communication, April 2018)

The idea is to compare the project to a reference, establish an Ambition, and then brainstorm on how to arrive at the ambition through eco-designing the product. The 3E team offers some suggestions to guide the brainstorming process, such as "Use renewable energy, recycle materials", "Look for potential hotspots in the upstream steps", "Avoid waste release", "Do more with less". These "rules" correspond to rules that are commonly found in rule-based eco-design literature (Abrassart, 2011; Luttropp & Lagerstedt, 2006).

Solvay's proposed objectives and methodology for Sustainability-by-Design consists of three steps. First, to define the "Ambition" for the project through brainstorming sessions. Second, to perform SPM analyses along the WEGO innovation management process, and third, to evaluate the project with economic assessments to validate that their Ambition creates new value.

CHAPTER 5 ARTICLE 1: IS LIFE CYCLE INNOVATION AN OXYMORON? AN EXPLORATION OF THE COGNITIVE AND ORGANIZATIONAL FACTORS THAT CONTRIBUTE TO CREATIVITY DURING ECO-DESIGN

by Andrea Gideon[1]*, Christophe Abrassart[2], Manuele Margni[1]

[1] *CIRAIG, Department of Mathematics and Industrial Engineering, École Polytechnique de Montréal, P.O. Box 6079, succ. Centre-ville, Montréal, Québec, H3C 3A7, Canada*

[2] *Lab Ville Prospective, Faculté de l'aménagement, Université de Montréal, 2940 Chemin de la Côte-Sainte-Catherine, Montréal, QC H3C 3J7*

*corresponding author email: andrea.gideon@polymtl.ca
phone number: +1-514-340-4711 #5925
address: *CIRAIG, Department of Mathematics and Industrial Engineering, École Polytechnique de Montréal, P.O. Box 6079, succ. Centre-ville, Montréal, Québec, H3C 3A7, Canada*

Keywords : Eco-design, Innovation, Sustainability, Life cycle thinking, Cognitive fixation, Creativity

Highlights :

- Life cycle thinking can have a framing effect in innovative eco-design
- Life cycle thinking can cause fixation on the dominant design
- Specific cognitive and organizational conditions can overcome eco-design fixation
- The eco-design methodology is dependent on its organizational context

5.1 Summary of the article

This article was submitted to the Journal of Cleaner Production in December 2018, co-authored by Christophe Abrassart and Manuele Margni and myself. In this article we suggest that the up-and-coming field of "life cycle innovation" poses an oxymoron where "life cycle" aims to frame the design problem and "innovation" aims to open the problem with reframing. We propose that the oxymoron exists when life cycles of existing products are a *starting point* for innovation, but can be solved when life cycles of the products of tomorrow are a *result* of the innovation process.

The results presented in this article cover the first workshop at ACME, as well as the first and second workshops at Solvay for the Quasar project. The remainder of the data is presented in Chapter 6.

In this article, first Solvay's LCA-driven workshop was compared to their creativity-driven workshop. The high creative output of workshop 2 compared to workshop 1 shows the power a tool such as LCA or C-K theory can have on the outcome of a design workshop. We identified the cognitive factors that helped to break the design team out of their fixation.

Second, Solvay's LCA workshop to ACME's LCA workshop. ACME, in a very different organizational context than Solvay, demonstrated much more creativity than Solvay when only exposed to LCA results. We then identified the organizational factors at play that suggest why ACME's workshop outcome was more creative than Solvay's.

The main conclusions of the article were that the success of an eco-design tool is dependent on its organizational context.

5.2 Abstract

"Life cycle innovation" appears to be an oxymoron whereas it implicitly collides "life cycle thinking", which structures and frames eco-design problems, with the willingness to follow an "innovative design" process, which expands the eco-design problem to explore unknown identities of products and services and reframes the problem on new value spaces. We posit that the use of life-cycle-driven eco-design methodologies that use existing products as a starting point for innovative exploration encourages path dependency and therefore limits creativity. Although quite powerful to codify rule-based eco-design approaches, life cycle thinking can be a factor of design fixation that inhibits creativity by too restrictively framing the eco-design problem. We sought to understand the fixation effect in eco-design and how it manifests in real-world corporate settings, considering the cognitive and organizational factors that also contribute to (de)fixation alongside life cycle thinking. We used research intervention and qualitative methods in a multiple case study approach with two global engineering firms. Each firm experienced two eco-design workshops; one life-cycle-driven and one creative-methods-driven. Our study shows that life cycle thinking alone may hinder creativity, but when paired with cognitive conditions for creativity and specific organizational contexts, eco-design fixation can be overcome. We also show that the framing effect of the eco-design methodology does not exist independently of its organizational context. This has profound implications for the sustainable innovation community who is often reliant purely on the frames inherent in life cycle approaches to strive for radical innovation for sustainability. We suggest that to break the oxymoron of "life cycle innovation", we should read "innovation of new life cycles" by which life cycles of the products of tomorrow need to be a result of the innovation process, rather than "innovation within the existing life cycle", using life cycles of current products as a starting point for innovation.

5.3 Introduction

The field of "Life Cycle Innovation", otherwise known as eco-innovation or sustainable innovation that specifically takes a life-cycle approach, is gaining excitement and bringing together a growing community of scholars and practitioners (see for ex. Life Cycle Innovation Conference in Berlin, 2018). Challenges such as energy transition, decarbonisation and circular economy have put pressure on firms to develop products and services that are sustainable but also highly innovative to have a radical impact (Ceschin, 2014; Ceschin & Gaziulusoy, 2016; McAloone & Pigosso, 2017; Nill & Kemp, 2009; Tukker, 2008; Tukker & Butter, 2007). While life cycle thinking (LCT) structures and frames the way we tackle environmental issues by helping to select eco-design rules, innovative design seeks to freely expand the design problem to explore new identities of products and services without the limitations of a particular frame such as the functional unit of the existing object (Abrassart, 2011). For example, if we use LCT to eco-design the conventional vehicle, we might choose a functional unit of "conveniently transporting a person 15 km to work", where the hotspot is fuel consumption during the use phase (CIRAIG, 2016). Rule-based eco-design reasoning would lead us to address the hotspot by developing the clean-powered electric car. Whereas with innovative eco-design we might question the implicit notion of "convenience" as "wasted time in transit", and instead design an experience where mobility provides an enriched experience (i.e. for health, social interaction, mindfulness, aesthetic impressions) and therefore enables a "convenient slow mobility" system to reduce emissions. We might even go as far as questioning the purpose of "transporting", if for example we abstract the function as "communicating for work", we can then imagine re-designing the conventional vehicle as a video-conferencing device in smart cities.

With this perspective, the collision of "life cycle thinking" and "innovative design" may appear contradictory. Our hypothesis is that LCT can be a factor of design fixation that inhibits creativity during eco-design by thinking exclusively within the existing function of the object (product or service) under study, therefore creating the framing problem and reinforcing the dominant design. This fixation effect manifests in the *creative reasoning* (Cassotti & Agogué, 2016) used during the design process when influenced by life cycle assessment (LCA) results.

Life cycle thinking is extremely valuable for treating environmental issues and offers a robust starting point for the eco-design process. Its framing effect is effective for disseminating rule-based eco-design at a large scale, yet it bodes ill for innovative eco-design. LCT reinforces path dependency (Dosi, 1982) and is too dependent on inherited frames to address the systemic environmental issues facing society today. Scholars in innovation management emphasize the need for innovative design processes to open new value spaces and overcome these path dependencies (Le Masson et al., 2010). If innovative design aims to design the rule-based design of tomorrow, we propose that innovative eco-design aims to design and frame the unknown life cycles of tomorrow. In this perspective the oxymoron problem can be solved. When the starting point of the design process is the life cycle of an existing product, the eco-designer is in a frame of path dependency, and “life cycle innovation within the existing life cycle of the object” is an oxymoron. On the contrary, if the life cycles of unknown objects of tomorrow are imagined and explored through the design process, then new life cycles are a *result* of the design process (Abrassart et al., 2016). If the eco-designer explores the innovative design frames of tomorrow, then “life cycle innovation” should be understood as the “innovation of new life cycles”.

Before reaching this conclusion, this oxymoron of “life cycle innovation” begs the question, what cognitive and organizational factors contribute to the framing problem during eco-design to enable more creativity and innovation?

5.3.1 The framing problem

The designer’s approach to eco-design is abductive, exploratory, transformative and reflexive, which differs from the engineer’s approach that is more deductive, rule-based, incremental and technically rational (Abrassart, 2011; Cucuzzella, 2016). For a designer, problem framing is a common heuristic used in abductive reasoning to define the *design space* of an unknown object, responding to a *design brief* with a *working principle* (Dorst, 2011). Abductive reasoning is analogous to an inspector who imagines scenarios to give coherence to a clue by relying on laws. For the engineer, it is more familiar to use deductive reasoning on known objects and functions with the help of conceptual models and catalogues of rules (Dorst, 2011).

Abrassart (2011) relays these two kinds of design reasoning with Le Masson et al.’s (2010) theory of innovative design to contrast the engineer’s rule-based eco-design with the designer’s innovative eco-design. The engineer’s rule-based eco-design is embedded in the systematic design approach (Pahl & Beitz, 1996; Ulrich & Eppinger, 2011b). This approach starts with LCA results of an existing object, continues with the selection of relevant *Design for Environment* rules, and ends with a detailed design; all in a deductive manner (Luttropp & Lagerstedt, 2006; Ulrich & Eppinger, 2011a). In contrast to the engineer’s approach, the designer’s innovative eco-design opens the identities of objects by exploring unknown meanings, functionalities and sometimes new *working principles*.

Cucuzzella (2016) also demonstrates this dichotomy of eco-design by relaying Schön’s (1983) *reflection-in-action* to a more transformative approach to eco-design, and *technical rationality* to a more incremental approach to eco-design. Another study on eco-innovation (Tyl et al., 2014) stresses the lack of importance attached to the ideation phase during eco-design, suggesting that creativity is often limited in rule-based eco-design as a result.

We do not want to subdue the value of a life cycle-driven eco-design approach. Though it has many characteristics of rule-based design today, LCT was ground-breaking in the 1990s and 2000s, for reframing the design problem on the entire value chain of a product instead of only on the manufacturing phase for which the producer was responsible (Hunt & Franklin, 1996). In fact, life cycle analysis results are most interesting when they are counterintuitive and demonstrate unexpected hot spots, creating a trigger for creative solutions.

However, life cycle-driven, rule-based eco-design rarely questions the functional unit, a representation of the *dominant design*, where the product's identity and key features have become a de facto standard (Abernathy & Utterback, 1978; Utterback & Abernathy, 1975). This approach to design therefore uses for example, analytical tools like LCA (Jolliet et al., 2016), guidelines like the golden rules of eco-design (Luttropp & Lagerstedt, 2006) or other eco-design tools (Bellini & Janin, 2011; Rossi et al., 2016) that seek to improve the existing functional unit's environmental impacts. In contrast to this, innovative eco-design seeks to constantly challenge the dominant design of a product to create new identities of new objects; designing the unknown (Le Masson et al., 2010). In Figure 5.1 we illustrate the different approaches to framing the eco-design problem in both rule-based and innovative eco-design.

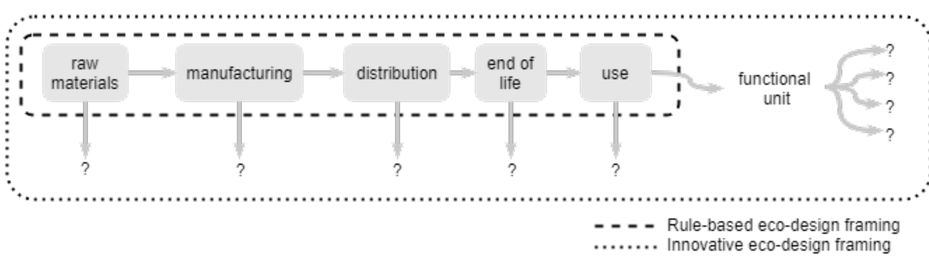

Figure 5.1 – Framing the problem in different schools of eco-design

While extremely beneficial for deductive reasoning used in rule-based eco-design for product improvement, detailed information such as LCA causes us to fixate on the dominant design and is therefore not adequate for enabling the abductive reasoning needed in innovative eco-design (Abrassart, 2011).

5.3.2 The cognitive factors

These cognitive barriers stem most notably from the *fixation effect* (Jansson & Smith, 1991), and limit creative reasoning (Cassotti & Agogué, 2016). Cognitive fixation is an observed phenomena in creative idea generation, where individuals tend to propose solutions from knowledge easily accessible by memory (Cassotti & Agogué, 2016). When applied to the process of design, we can then define design fixation as being a "blind […] adherence to a limited set of ideas" (Jansson & Smith, 1991). This happens because the mind is "lazy" and follows the "path of least resistance", using its *fast thinking* in settings where it might be inappropriate (Cassotti et al., 2016; Kahneman, 2011). Cassotti and Agogué (2016) define creative reasoning as a process of inhibitory control (Houdé, 2014) to purposely inhibit the *fast thinking* system to access the *slow thinking* system (Kahneman, 2011) where creative ideas can emerge.

In professional environments, fixation, or being stuck in the *fast thinking* system, is observed as *technical rationality* (Schön, 1983): using routines or rules of thumb, relying on past experience and existing knowledge to solve problems. This is useful for incremental design, but inappropriate for transformative design, where we would rather access our *slow thinking* system to consider things differently. We must therefore inhibit our *fast thinking* to de-fix, access our *slow thinking* system and trigger *reflexivity* (Schön, 1983) with heuristics and access to new knowledge to explore the unknown.

Cognitive inhibition for creative reasoning is a learned skill that takes practice, but some studies have shown that it can be stimulated by different tools, methods or triggers in a creativity workshop setting. It has been shown that the examples or information shown to individuals right before ideating or brainstorming has a significant fixation effect (Agogué et al., 2011; Cassotti et al., 2016). For eco-design, this means we need expansive, not restrictive, triggers to activate our *slow thinking* system before ideating in order to be creative. When we thus expose ourselves to LCA results before ideation, we are showing a restrictive example that is not enough to trigger creative reasoning.

Some researchers have demonstrated the fixation effect during eco-design with an experimental approach in a controlled environment (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010, 2011). By giving different groups of students environmental information with varying levels of detail before ideation, those with a general starting point (i.e. a journal article) proposed the most creative ideas compared to those who were given detailed LCA results as inspiration (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010, 2011). This study is promising for our hypothesis that LCT frames the possible set of solutions and therefore is a tool that causes fixation. Yet this study is limited in terms of real-world application; a controlled environment is insulated from the organizational pressures and routines that professionals experience when doing eco-design.

5.3.3 The organizational factors

The tools and triggers used to stimulate creativity before ideation affect the cognitive process of the participants, but what about their social interactions with each other and the corporate context in which they are ideating?

Pragmatically, organizational creativity is the result of the interaction of individual capabilities and the organisational context in which they take place. Individual creativity rests upon a balance of three dimensions: domain-relevant skills (ie. technical knowledge), creativity-relevant processes (i.e. cognitive style and skills in taking new perspectives on problems and in generating ideas) and, most importantly, intrinsic motivation (Amabile, 1988, 1996, 1998, 2012). Creativity training to increase individual creativity has been shown to have a positive effect on intrinsic motivation and contribute overall to the development of organizational creativity (Rampa et al., 2017). On the other hand, the organizational context can have a strong influence on individual creativity (Amabile, 1996; Rampa et al., 2017). Organizational culture, systems of evaluation, reporting tools, and organizational structure often highly influence individual routines, with a range of possible effects, from normalisation of conducts to stimulation of learning (F. Aggeri & J Labatut, 2010; Aggeri & Labatut, 2011).

Those in charge of implementing sustainability with an LCT approach (i.e. by performing LCAs to inform product development), are rarely involved in innovation strategy, while those in innovation strategy rarely have sustainability requirements when boosting the firm's creativity. While this is a common organisational feature, there is often an intention to inspire creativity with a life cycle approach to find new ways of doing business and improving products. However, those who manage the creative process often do not communicate with or valorise these domain relevant-skills. By marrying the processes of innovation and life cycle thinking, we hoped to create better interactions between organizational factors and individual creative capabilities in order to better understand eco-design fixation.

5.4 Methods

The methodology was designed on the premise of comparing two eco-design workshop settings, one LCA-driven and the other creative-methods-driven. Different tools were introduced as inspiration for brainstorming, while the social and cognitive factors that affect the participants' creativity were observed.

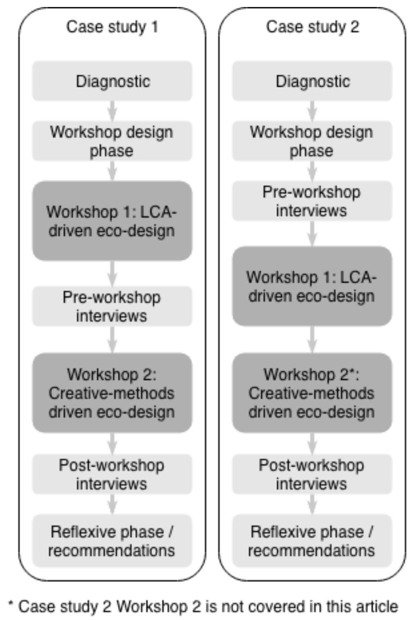

Figure 5.2 – Research intervention methodology

We therefore chose a multiple case study approach (Yin, 2009) in a corporate environment, using research intervention (David, 2000) and qualitative methods based on grounded theory (Charmaz, 2014; Patton, 2002) to investigate our hypothesis. Two case studies were developed in two global engineering companies: Solvay and ACME[5].

Research intervention is a method derived from action research, which requires the researcher to participate in the environment they are observing (David, 2000). The methodological steps of the intervention are illustrated in Figure 5.2. Each case study began with a *diagnostic phase*, where the organization and the market in which they operate were analyzed in terms of innovation, creativity

[5] Our second case study partner chose to remain confidential for the purpose of this article. We will refer to them by the fictional name "ACME" for the entirety of this piece.

and sustainability. We evaluated the framing in which the organization was immersed (answering questions such as “What is their experience with LCA?”, “What is their conception of the dominant design, or the rule-based design of the product?”). We also contextualized the *fast thinking* system (Kahneman, 2011) of the group on a cognitive level (answering questions such as “What professional routines do they use on a daily basis?”). Finally, we investigated the organizational setting, relationship between the environmental experts and strategists, and the organizational structure that enables intrinsic motivation (Amabile, 1996; Rampa et al., 2017).

Based on the diagnostic, we began the *workshop design phase*, where we, the researchers and authors of this paper, used the information from the diagnostic to structure the two eco-design workshops with tools and methods that would respond best to the design team’s framing and their cognitive and organizational setting. This was followed by a *workshop implementation phase*, in which each team experienced the two workshops tailored to their organisational contexts. The workshops were either observed and facilitated by the researchers or only observed in cases where the company already had an LCA-driven eco-design method established internally. For the scope of this article, Solvay workshop 1 and workshop 2 will be compared, as well as Solvay and ACME workshop 1. The second workshop at ACME will not be covered. Finally, a *reflexive phase* followed the workshops where we evaluated the participants’ experience and the results of the workshops.

Interviews were conducted with most participants before and after both workshops, and were analyzed using an adaptation of discourse analysis and grounded theory (Charmaz, 2014; Patton, 2002). The reasoning of each team was illustrated by C-K diagrams (Le Masson et al., 2010) in order to codify and represent the reasoning of the teams.

Concept-Knowledge (C-K) Theory is a model of innovative design reasoning (the creative process) by the co-expansion of two spaces: the Knowledge space (K) and the Concept space (C). The C-space is formed by a tree representing the rational exploration of concepts, whereas the K-space is represented by a network of knowledge activated for the generation of new concepts. C-K theory can demonstrate the fixation effect by a limitation in the expansion of C and K spaces (Agogué et al., 2011).

From these C-K transcriptions illustrating the design reasoning, a V2OR (Value, Variety, Originality and Robustness) analysis (Le Masson et al., 2010) was used as a series of indicators to evaluate the quality of the team's exploration. In the concept space, we evaluate the Variety (number of different branches explored) and Originality (number of expansive partitions that challenge the dominant design). In the knowledge space, we evaluate the Value (new value spaces that unite actors who did not previously work together) and Robustness (the validity of the propositions when the context changes). In our case, the success of the workshops rested upon the exploration of new value spaces, such as the life cycles and frames of tomorrow, and on the originality of concepts, in challenging the dominant design.

It should be noted that C-K theory is a research program on design theory (Hatchuel & Weil, 2008), but can also be used as a tool to structure the brainstorming process (Agogué, Hooge, et al., 2014; Le Masson et al., 2010).

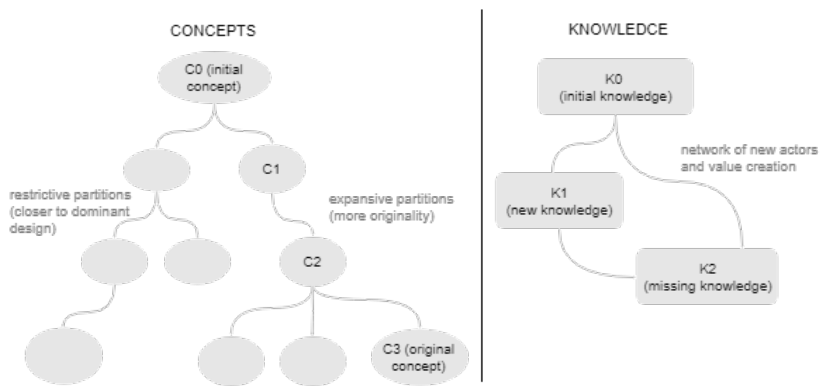

Figure 5.3 – C-K Theory (Adapted from (Agogué & Kazakçi, 2014; Le Masson et al., 2010))

5.5 Case study 1: Solvay

5.5.1 Diagnostic

The first intervention took place in France in the corporate research & development division (called the Research & Innovation Center) of Solvay, a chemicals company headquartered in Brussels. Solvay has acquired an expertise in LCA internally and has channeled this expertise into an internal LCA-based eco-design tool for product evaluation called "Sustainable Product Management" (SPM). The SPM tool and LCAs performed internally often only consider the cradle-to-grave impacts of the product in question, since a chemical product can have many uses and be used in many different markets. These tools are the professional routines that represent Solvay's *technical rationality*.

Solvay has recently launched a strategic initiative called “Sustainability-by-Design” (SbyD), whose aim is to include sustainability considerations in the design of all their chemical products. In parallel to this initiative, the corporate research team instituted a radical innovation strategy remain on the cutting edge of research and product development. The object of our intervention at Solvay was one of these innovative research projects, demonstrating a clear effort to merge life cycle thinking with innovation strategy.

Despite Solvay’s high eco-design maturity level (Pigosso, Rozenfeld, & McAloone, 2013), the inclusion of a creative approach with sustainability was not directly supported by upper management. The process had to be negotiated internally by the sustainability team with different business and research groups for their buy-in.

Through this process of negotiation, the research project chosen as the object of study for the eco-design workshops was on downconversion nanoparticles. Also known as quantum dots, these particles’ main functionality is to absorb photons and re-emit them at a higher wavelength. This project was in early phases of design, where they had many degrees of freedom, but little knowledge on the final design parameters (Midler, 2004).

5.5.2 Workshop 1: LCA-driven eco-design

Since piloting the SbyD program, the LCA team had experience running eco-design workshops based on the SPM tool. We therefore acted as observers and did not intervene in the preparation, organization or facilitation of the LCA-driven workshop. Facilitated by the leader of the LCA team, only internal engineers and managers were present for the workshop which began with presentations on the LCA results, followed by a group discussion, and ending with a common brainstorming session.

Emerging technologies and nanotechnologies like downconversion particles, are both struggles for the LCA community in dealing with their high uncertainty (Berube, 2013; Miller & Keoleian, 2015; Wender et al., 2014). The workshop was based on a cradle-to-gate life cycle assessment of a solar panel containing the downconversion nanoparticles. The study was performed by the internal LCA team using preliminary design knowledge, steeped in uncertainty.

At this stage in the project, the research team was developing the nanoparticles for a specific application: to increase the efficiency of solar panels. By converting unused ultraviolet (UV) rays into visible rays, more light could be converted into energy by the panel. For this function, as shown in

Table 5.1, the nanoparticle itself represented an insignificant amount of relative impacts, which relied mainly on the parameter of increased efficiency of the solar panel's energy production by means of the particle. The main eco-design trade-off was therefore between the avoided impacts by the increased efficiency of the solar panel (more clean energy produced in the use phase) and the impacts of the nanoparticle (additional impacts on the raw materials and production phases).

Table 5.1 - Starting point for Solvay workshop 1: summarized LCA results of the solar panel with the downconversion nanoparticle

Relative contribution of nanoparticle to overall impacts of solar panel	<1% *
Relative cradle-to-gate impacts of nanoparticle alone	~50% raw materials ~50% production

*(dependent on increased energy efficiency of solar panel due to the nanoparticle)

Regardless of the life cycle approach, two elements led the discussion to re-center on the manufacturing process for the nanoparticle. First, the high uncertainty around the efficiency parameter caused discomfort in the group discussion. Does the nanoparticle contribute to a 6% or a 20% increase in energy production? Some participants did not feel as though a life cycle approach was appropriate since the effect of their nanoparticle on the entire product system was dependent on a speculated parameter. Second, a recent internal market study showed that the solar panel market had evolved quicker than expected, and the standard commercial solar panel now absorbed the UV spectrum, meaning there was less market pull for the product Solvay was developing.

Solvay reframed the eco-design problem, using *technical rationality* (Schön, 1983), renouncing their intention to use life-cycle-driven eco-design, and reverting to their core expertise and familiar territory: chemical processes. Our understanding of the reasons for this are:

- LCA results were based on technical assumptions outside of Solvay's expertise. This "new knowledge" territory was subsequently avoided.
- Discomfort with high levels of uncertainty. The LCA of the emerging technology was not "perfect" (ie. with all the required data and technical assumptions verified) which caused a lack of confidence in the life cycle approach.
- New market information on the application of the nanoparticle questioned the goal and scope of the LCA.
- Implicit company rules, priorities, hierarchy and power structures were present and unchallenged because the participants and facilitator were all internal to Solvay and assuming their usual role.
- Cooperation between the LCA team and the research team was based on an agreement backed by differing interests, which created a fragile environment to explore the unknown.

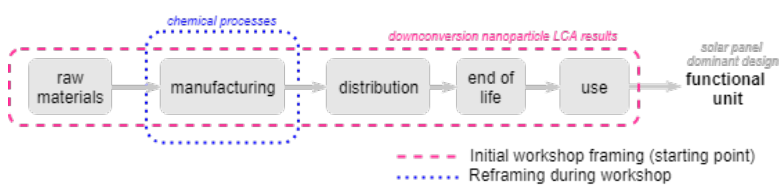

Figure 5.4 - Solvay reframes the problem by confining it from the life cycle to the manufacturing phase

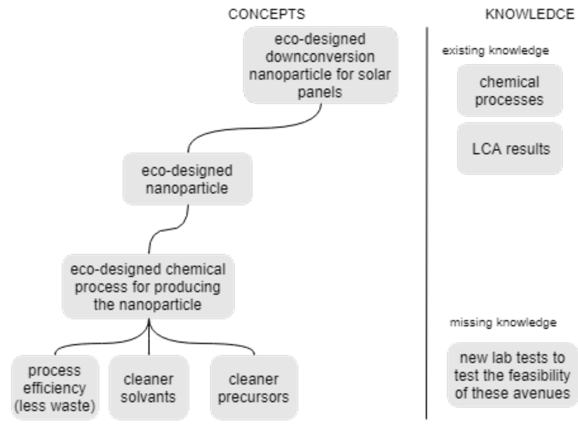

Figure 5.5 – Ex-post C-K diagram of Solvay's reasoning in workshop 1

The C-K diagram in Figure 5.5 demonstrates little variety, no originality, no new value created and a low level of robustness. Solvay reframed the problem in a restrictive way, yet they could have continued to use the life cycle approach despite the unfavorable conditions (ie. new market information, lack of knowledge and high uncertainty in the LCA, and stringent political interests) to reframe on another point in the life cycle. For example, they could have explored niche photovoltaic markets such as the retrofit market, where they could have an impact on the end-of-life phase of existing solar panels by prolonging their lifetime. It was clear that their *technical rationality* and *fast thinking* system was moving at full speed to re-center the problem around their core expertise, and there was no creative trigger present to encourage them to access their *reflexivity* and *slow thinking* system.

5.5.3 Workshop 2: C-K theory

While the first workshop did not question the functional unit, as is customary in rule-based eco-design, the aim of the second workshop was to do just this, using innovative eco-design (Abrassart, 2011). The workshop began by an introduction to C-K Theory (Le Masson et al., 2010). The goal was to imagine new sustainable functions for the downconversion nanoparticles. It is also customary in innovative design to introduce new knowledge or unknown concepts before the brainstorming session, to stimulate the participants' reflexivity.

This workshop at Solvay was designed and facilitated by the authors of this article (i.e. by external experts), however, the casting of the participants remained the same as the first workshop; only internal engineers and managers participated. In contrast to the first workshop where the entire group discussed together and brainstormed individually, in this workshop we asked the participants to break into teams of two or three to discuss and brainstorm with the C-K method, and to share their ideas with the group at the end of the session.

In contrast to the first workshop where LCA results were used as the "trigger" for framing the eco-design discussion, the facilitators used a pre-C-K diagram suggesting possible divergent pathways from the dominant design. Building on Agogué et al.'s (2011) idea that expansive examples would stimulate creativity, we presented pathways of innovative reasoning that diverged from what caused their fixation in the first workshop. The pre-C-K diagram was used as a common starting point for the smaller teams in parallel. One example was the "bifunctionality of light", a provocative twist on the initial concept by relating to an external piece of knowledge (a study by Gençer et al. (2017)).

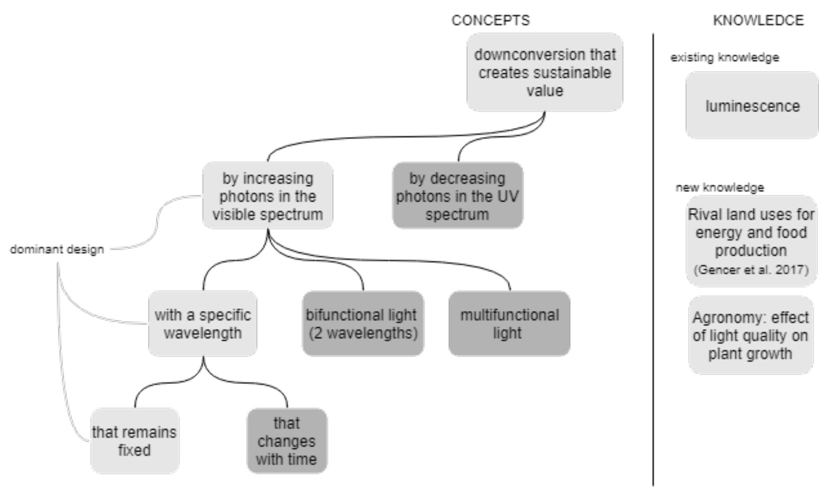

Figure 5.6 - Pre-C-K diagram as a creative trigger for workshop 2 at Solvay

Using the C-K method, the participants successfully reframed the problem around new possible functional units, and therefore radically questioned the solar panel application of the downconversion nanoparticles they had taken for granted in the first workshop.

For example, one team played with the idea of using the light of the moon instead of the light of the sun, which led to a conversation on extracting value from reflected light. This led them to imagine a concept of using the downconversion particles for smart windows. Another example was a team who used a reversal heuristic to ask why we are looking exclusively at *down*conversion, when we could also look at *up*conversion. These highly divergent ideas triggered a more realistic concept that built on the idea of the multifunctionality of light: selecting wavelengths for human well-being. This opens up possibilities in the smart window space (where certain wavelengths could be filtered) or for luminotherapy.

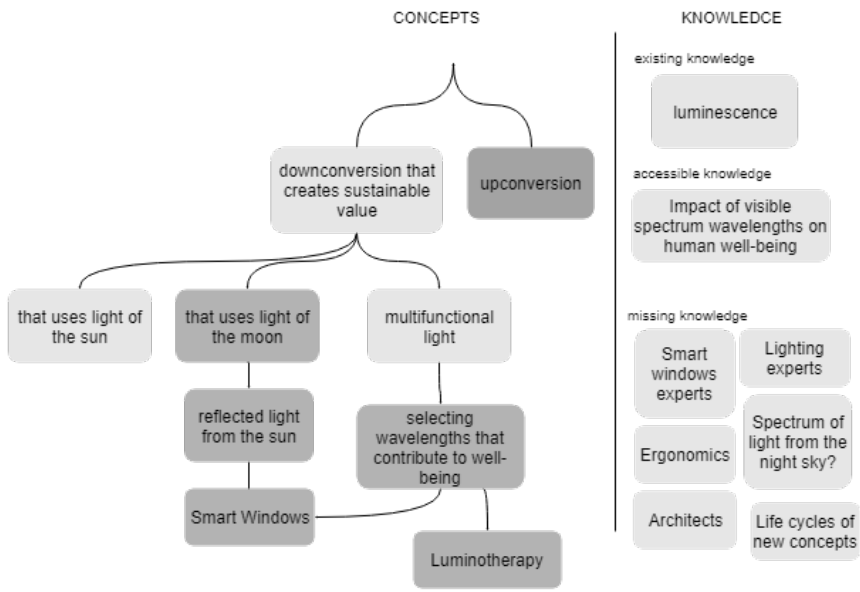

Figure 5.7- C-K diagram of Solvay workshop 2 results

Solvay's exploration in this workshop had a high level of variety and originality in the concept space. They identified new value spaces in the knowledge space and robustness was also high. For the specific examples shown in Figure 5.7, the new value space of using light for human well-being through smart windows and luminotherapy defines an entirely new life cycle and framed the problem in a surprising and unprecedented way for Solvay.

Many new pathways of value creation and potential for new networks of actors were developed by the teams that were not explored in the first workshop. Our interpretation of reasons for this are:

- Presence of external facilitators flattened the hierarchy and implicit company rules that might inhibit creativity
- Presentation and use of a creative trigger at the beginning of the workshop (the pre-C-K tree) encouraged an exploratory reframing of the problem during the brainstorming exercise

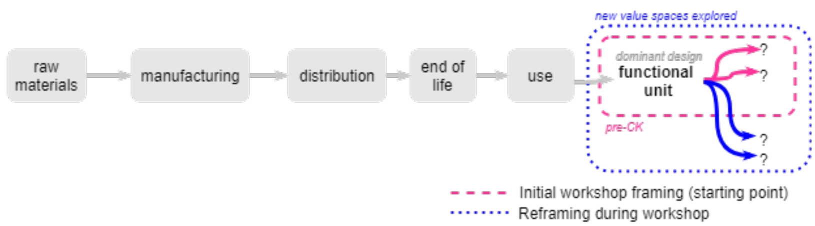

Figure 5.8 - Solvay frames the problem around new spaces of value creation, challenging the functional unit

5.6 Case study 2

5.6.1 Diagnostic

The second case study took place at an electrical equipment manufacturer. In contrast to Solvay where we worked with a corporate R&D team, in this case study we worked with a local business unit who sells integrated substation systems to the Canadian market. Neither this team nor anyone in the Canadian organization had an expertise in LCA, however their corporate research center in Sweden historically had this expertise internally in the 1990s until the mid-2000s. Since this period, LCA is not frequently practiced and no longer used on a strategic level. Eco-design is also an area of potential improvement in the sustainability strategy of the company, which focuses more on health & safety, a socially responsible supply chain and ensuring all the facilities have an environmental management system. For these reasons, the company's eco-design maturity level is quite low (Pigosso et al., 2013).

On a local level, the environmental management team felt as though they were consulted only for end-of-pipe solutions and seen more as risk managers than as potential creators of sustainable value. There was however, direct support from upper management for this collaborative project between the local environment team and the local business unit, which historically had never been done before in Canada. There was momentum backing an evolution of the environment team from a passive to an active role in terms of value creation.

The local team with whom we worked viewed their design engineers as their "local R&D". Each system was designed specifically for the needs of each project and customer, largely based on pre-defined specifications, but engineers did have some room to propose innovative and creative solutions. For example, using their expertise to propose something the customer hadn't thought of that might save time, space or money, designed with the usual set of rules and codes for substation design but rearranged in a creative way to create new value. From interviews with employees, the business is viewed as highly reliant on their ability to be creative, which we qualify as *enriched* deductive reasoning (Dorst, 2011). Most often, the contracts won when they creatively challenge the customer's specification.

Substations, a key technology in the transmission of electricity, are large yards of steel structures and electrical equipment that step voltage up (e.g. to be transported from a remote generating station over long distances) or step voltage down (e.g. to be used by a city or a large factory once the electricity has arrived). The key issue in substation design is the distance between the cables that carry such high voltages in a small surface area – put them too close together and the electromagnetic fields emanating from the cables could arc. Common design trade-offs of a substation are therefore whether to design a large surface area where distances are respected, known as an air-insulated substation (AIS) or to insulate the system with SF6 gas, compressing it on a smaller surface area, known as a gas-insulated substation (GIS). Substations are an archaic technology that has only incrementally evolved since the 1970s. The electrical infrastructure market relies on huge investments and is run by large corporations; its high technological momentum (Hughes, 1987) makes it difficult to radically innovate. The products that make up the system and the system itself have therefore maintained a stagnant identity. Due to this resistance to change in the industry, we chose an up-and-coming market that wasn't so fixated on the usual ways of working: the data center market. The subject chosen for the workshops in this case study was therefore large electrical infrastructure (ie. substations) for data centers.

5.6.2 Workshop 1: LCA-driven eco-design

Since the company did not have an internally realized life cycle assessment of a substation, an LCA for a similar system was used (Laruelle, Ficheux, Kieffel, & Huet, 2013), as a basis for identifying hot spots to work on during the workshop. Given the lack of internal knowledge and eco-design tools, the LCA-driven workshop was facilitated by the main author of this study.

Many participants learned about LCT for the first time and had never worked with LCA results before. As summarized in

Table 5.2, the LCA showed that the eco-design trade-off between GIS and AIS is the impact on ecosystem quality from higher land use, and impact on climate change from higher energy losses in the AIS, versus the highly potent SF6 emissions that contribute to climate change in the GIS (Laruelle et al., 2013). Both systems also showed significant impacts in the raw materials used. In addition to the LCA of a substation, we also showed the life cycle assessment results of a data center in the UK (Whitehead, Andrews, & Shah, 2015), which demonstrated that the most significant impacts occurred during the use phase, and were attributed to the important amount of energy used by the data center.

Table 5.2 - Starting point for workshop 1: summarized hotspots from LCA results (adapted from (Laruelle et al., 2013; Whitehead et al., 2015))

	Air-insulated substation	**Gas-insulated Substation**	**Data center**
Hotspots	Higher energy losses during the use phase Larger land use Raw materials	SF6 leakages during the use phase Raw materials	Energy usage

The workshop casting was highly interdisciplinary. ACME had an interest in using a participatory design methodology, where we invited external actors to participate. Customers were invited from the data center and utilities industries as well as environment experts specialized in LCA.

The structure of the workshop began with intensive knowledge sharing seminars. The group of participants split into four teams. Each team was first tasked with defining the eco-design problem (based on LCA results), using divergence (brainstorming) and convergence (categorizing and eliminating ideas). The task to define the problem was an opportunity for the participants to reframe freely the problem (Dorst & Cross, 2001). They were then asked to propose solutions to the problem. Halfway through the workshop, the Eco-design Golden Rules (Luttropp & Lagerstedt, 2006), a classic rule-based eco-design tool, was presented as a tool that could be used, or not, by the teams.

The first team focused on a sustainable supply chain and better materials for the substation only. The second team focused on energy efficiency, while the third focused on design-for-recycling and the fourth on reducing the impact on the local environment. Though each of these problems represent classic eco-design problem framings, only the first team, composed entirely of ACME employees, remained in the dominant design paradigm and framed the problem on life cycle phases of the substation alone. The other three teams, composed of an interdisciplinary mix of ACME employees and external actors, framed their discussion on the interaction between the substation and the data center and imagined new combined services. Unknowingly, they challenged the dominant designs of the substation and of the data center. For example, the three interdisciplinary groups all saw the data center as a heat source that could channel the heat for different applications. Another creative concept that emerged was to increase user awareness on the energy consumption of data, a foreign concept outside of ACME's expertise, requiring a new network of actors and creating new value for ACME.

The implicit company routines, priorities and hierarchies (and therefore their *fast thinking* or *technical rationality*) were challenged by the presence of external participants and the playful nature of the highly creative energy that arose during the activity.

.

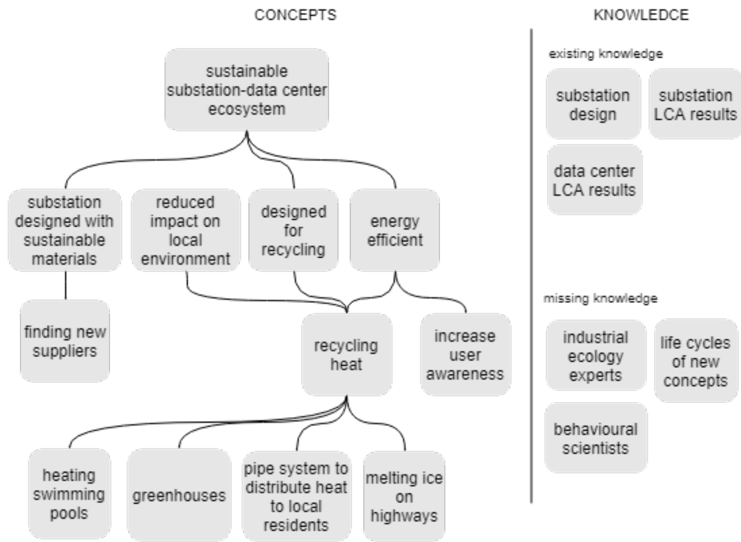

Figure 5.9 – Ex-post C-K diagram of ACME's reasoning in workshop 1

In Figure 5.9 we codified an excerpt of the reasoning patterns of the four teams using C-K theory. The first partitions on the concept side demonstrate each team's chosen problem, and the following partitions demonstrate a handful of solutions they found. We found some variety, and some originality in the concept-space, and a high exploration of new value and robustness in the knowledge-space. Save for the first team, the overall exploration in this workshop was quite creative.

The high creativity of participants was a contradictory result to our initial hypothesis – we had originally understood the effect of tools such as LCA as having a rule-based framing effect on eco-design workshops, but this case study showed that other organizational and cognitive factors were at play that influenced the creativity of the participants, independent of the eco-design tools imposed on them.

From interviews and observations during the workshops, our understanding of why the participants in ACME's LCA-driven eco-design workshop went beyond the life cycle view to challenge the dominant design are as follows:

- The presence of external actors changed the tone. The usual way of seeing problems was challenged by external interests that are not always the same as ACME's

- LCAs of two potentially complementary objects were presented: substations and data centers. Although these LCAs were presented separately, a broader initial framing was created than only considering the substation object.
- Support of the initiative from ACME Canada's upper management.
- Employees felt as though incremental eco-design was already being done by the R&D groups located in overseas factories. They felt they had little influence on these product design decisions.
- LCT was new for everyone, except the external LCA experts in the room. The participants did not feel attached to the results. They wanted to go further.
- Starting the activity with *problem setting* instead of *problem-solving* encouraged *reflexivity* and abductive reasoning, since engineers, who usually work with strict specifications, were destabilized by this task (Dorst & Cross, 2001).

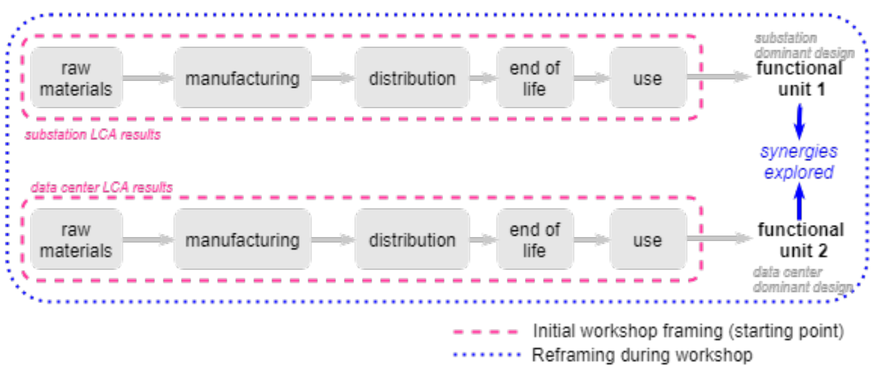

Figure 5.10 – ACME reframes the problem from the life cycle to imagine new value spaces

5.7 Results & discussion

The previous section detailed both case studies individually; in this section we share our insights and findings by comparing the three workshops to one another and sharing our understanding of the cognitive and organizational factors that affected creativity during eco-design.

Table 5.3- Context comparison

	Solvay workshop 1	**Solvay workshop 2**	**ACME workshop 1**
Facilitators / workshop organization	Internal	External	External
Internal interdisciplinarity	low	low	high
External participants	none	none	3 customers & 2 environment experts
Tools used	Internal SPM tool & Internal LCA results	C-K theory	Similar product LCA results, Eco-design rulebook (Golden rules)
No. participants	10	12	15
Political support from upper management	Negotiated		Direct
Eco-design maturity level	High		Low
LCA competency	Acquired, internal		External
Location	Europe		North America
Department	Research & Innovation		Local business unit

5.7.1 Cognitive factors

5.7.1.1 Framework

Three cognitive factors contributed to (de)fixation of participants and determined whether they adhered to their technical rationality or accessed their reflexivity.

The first cognitive factor is the **ability to reframe the design problem**. Are the participants able to use reflexivity to reframe the problem in an expansive way and question the dominant design? Or are they reluctant to explore new knowledge and unknown concepts, thereby resorting to their technical rationality? The different tools proposed during the workshops were designed to trigger this reframing – were they effective?

The second factor is the participants' **creativity skills**. Do they have formal knowledge of creativity techniques and how to use inhibitory control?

The final cognitive factor is participant's **distance to the identity of the object**. Are they an expert in the field, very familiar with the technical intricacies of the product, where their technical rationality impulse might be very strong? Or are they a neophyte, seeing the product from an outsider's perspective to bring insight from a new domain?

5.7.1.2 Comparison of LCA-driven and creativity-driven workshops at Solvay

Solvay demonstrated a classic progression into creativity, from rule-based to innovative eco-design, showing support for our first hypothesis that eco-design with cognitive stimulation can lead to higher creativity.

When exposed to LCA results of the downconversion particles as part of the life cycle of a solar panel, the participants were fixated on imagining solutions that would optimize that for which they had an internal expertise: the chemical process. They refrained from exploring new knowledge and unknown concepts, staying in the realm of the known. By reframing the problem in a restrictive way, from the life cycle to the manufacturing phase only, they did not generate many creative ideas in the concept space. There was also a resistance towards using the LCA results because of high uncertainty in the data and technical assumptions due to the product being in early stages of development. The participants judged the LCA tool to be irrelevant if it is not used "perfectly" (ie.

with minimized uncertainty). This shows another way LCA might create a framing effect in eco-design.

During post-workshop interviews, some employees expressed that they felt the brainstorming was redundant in the LCA-driven workshop and that the ideas they came up with did not have innovation potential. Some participants also expressed that they did not feel capable of being innovative because they were not technical experts. However, this distance from domain-relevant skills proved to be very useful in the creativity-driven workshop. Those who were unfamiliar with the technical intricacies of the product were able to abstract it in ways that triggered creative ideas for the group (e.g. the moonlight example). In contrast to the first workshop with an open group discussion and individual brainstorming, the second workshop disseminated the participants in smaller groups, where those who felt less technically competent would brainstorm together with an expert. This enabled the non-experts to feel permitted to share their ideas.

The creativity-driven workshop began with a brief training on creativity skills and innovation theory. Though many participants already had strong creativity skills, the introduction to creativity theory enabled them to use those skills in a safe, exploratory environment.

With the introduction of the C-K method, which is designed to structure the brainstorming process, the participants were able to reframe the problem on new functions by partitioning aspects of the dominant design in the concept space and accessing new knowledge in the knowledge space. The pre-CK tree triggered creative ideas, whereas the LCA / SPM only activated their *fast thinking*.

The starting point of LCA of the product in one specific application on which they were fixated, was put aside to frame the eco-design problem on Solvay's core expertise in the manufacturing phase. On the other hand, the starting point of a pre-CK tree that elucidates the dominant design and suggests ways of challenging it, without LCA, resulted in identifying life cycles of new products of tomorrow.

The contrast between these two workshops demonstrates a reliance on the method used and on creative triggers presented before brainstorming in eco-design. The participants already had the cognitive skill necessary to be creative, as was demonstrated in the creativity-driven workshop, yet they were not "allowed" to use it to its full potential without the C-K method. In the creativity-driven workshop, the C-K method enabled them to reframe the problem in an expansive way, triggering creative thinking and *reflexivity*, whereas in the life cycle-driven workshop, the SPM tool and LCA results created fixation on the dominant design, causing the problem to be restricted, restraining their thinking process to *technical rationality*.

5.7.2 Organizational factors

5.7.2.1 Framework

The eco-design workshops can be considered as ephemeral organisational devices in a larger, permanent organization. As such, the organizational factors we will consider in our studies will have to consider both factors from the company (i.e. level of expertise on LCA and LCT culture) and factors describing the relative autonomy and originality of the workshop as ephemeral organizations (support from upper management to the workshop sessions, distance from usual cultural rules (e.g. a flattened hierarchy during the workshop), the new interdisciplinarity enabled by the workshop (were there only engineers or was there a variety of roles and responsibilities, interests, beyond the classical project team, represented during the workshop?), and presence of external actors and stakeholders.

The first organizational factor is **eco-design maturity** (Pigosso et al., 2013) of the company and their level of LCA competency. Is LCA being introduced for the first time, are they highly vested in the information provided by an LCA? Is eco-design a strategic priority for the company and do the outcomes of the workshop therefore have high stakes?

The second factor is **political support from upper management**. Is the merger of innovation and eco-design processes through this research intervention project directly supported or negotiated with upper management?

Third, **distance from cultural rules** – did the environment enable them to flatten the hierarchy during the meeting? Were they in an environment where they felt playful enough to explore new concepts or was it a regular business meeting where their usual professional routines and reasoning were used?

Fourth, **interdisciplinarity** of workshop. Were there only engineers or was there a variety of roles and responsibilities, interests represented during the workshop?

The final and fifth organizational factor is the **presence of external actors**, or the use of participatory design.

5.7.2.2 Comparison of LCA-driven workshops at ACME and Solvay

LCA may be the cause of fixation in a familiar organizational context, as was observed at Solvay, but the ACME case shows that the introduction of a new organizational context could free the participants from fixation on the LCA results and unleash their creativity. This result supports our second hypothesis, that the eco-design tool does not exist independently of its organizational context, and the latter can have a tremendous effect on creativity.

ACME's low level of eco-design maturity meant that LCT was new knowledge for the participants, in contrast to Solvay, where the participants were very familiar with LCA and the SPM tool. From interviews with ACME participants after the workshop, we discovered that the LCA results did not resonate so much with them. Some Solvay participants had high stakes in the outcome of the workshop and the performance of the tool since they wanted to prove the success of their internally developed methods and value the work that had been put into generating the LCA results. There was an understood need to rely on the results during the workshop and therefore stay in the dominant design.

Full and direct support from ACME's upper management eased the participants into a more exploratory setting during the workshop. They were given "permission" to be creative and explore without strict expectations of the results. At Solvay, the LCA team had to negotiate the process with many upper levels before finding the appropriate team for whom to design the workshop. The eco-design process was under a lot of pressure to deliver results for new and innovative chemical processes. In the socio-psychological model of creativity, this aspect corresponds to supervisory encouragement for the creative process: lacking at Solvay and clear at ACME (Amabile, 1988, 1996, 1998).

The presence of an external facilitator, external participants and high interdisciplinary at ACME created distance from the employees' usual ways of working and challenged their usual reasoning and internal dynamic. By splitting the group up into four smaller teams, this also flattened the usual hierarchy present at ACME, making the interactions between participants more fluid and open. In interviews with Solvay participants, they frequently referred to the first session as a "meeting", which holds a connotation of familiar rules and conventional hierarchies. Facilitated internally, with only internal Solvay employees participating, there was no outside perspective to challenge the *technical rationality* of Solvay.

The comparison of the LCA-driven workshops in both ACME and Solvay show that the eco-design tool is not independent of its organizational context.

5.8 Limitations

Though our approach was robust in using a multiple case study design, only two case studies in two different industries and departments is not enough evidence for extrapolation.

The choice for using intervention research (David, 2000) was crucial since we wanted to observe the interactions between life cycle thinking and creativity in a real organizational environment. This proved however difficult to control for many variables such as casting and timing of workshops. Due to this method choice, we could not directly compare the two case studies using quantitative measures.

The nature of qualitative research used for this project required that the researchers themselves are a part of what they were observing, which could be the source of some confirmation bias. However, the multiple levels of analysis and multiple case studies add rigour to the results we obtained. Even the best practices in quantitative assessment of creativity are dependent on the opinion of experts (see for ex. Consensual Assessment Technique (Amabile, 1996)) or measure peripheral aspects of the ideation process such as number of ideas or frequency of ideas (Brem, Puente-Diaz, & Agogué, 2017).

Another common criticism of this project is that we may have "contaminated" the participants with LCA results in the first workshop, since the same people participated in the second workshop. *"Why did you not use different participants for workshop 1 and workshop 2?"* We made this choice, firstly because we wanted to offer all the participants an experience where they could learn about the two regimes of eco-design. We did not want to give special privileges to some participants over others. Second, we did not want to objectify the participants of the study, but rather provide them with knowledge and training that would be beneficial to their work, while simultaneously observing the aspects we needed for our data collection. Third, as Agogué et al. (2011) showed, the examples shown immediately before ideation have an important impact on creativity, so we assume that LCA results presented two weeks prior did not "contaminate" the second workshop.

If we could repeat the experience, it would be interesting to see if ACME would have been fixated in the LCA-driven workshop had there not been any external participants. It would also be interesting to see if the same outcomes would have arisen if the creativity-driven workshops were done before the LCA-driven workshops.

It is important to note that we are not recommending the methodology we followed in this study as a pathway for firms to achieve innovative eco-design. We simply chose a progression from an LCA-driven to a creativity-driven workshop to answer our research questions. We discuss a potential hybrid eco-design method in the following section.

The final limitation of our study is the cultural differences between the Canada and France in our two cases. This project did not follow an extensive anthropological methodology to evaluate the corporate culture differences of each country and how they may have affected our results. However, we do recognize that for example, in Canada the management hierarchy does not have the same significance as in France, where one's superior has a lot more power and authority. We also recognize that companies in France are subject to stricter environmental regulations than in Canada, which may explain a more important reliance on LCA results at Solvay than at ACME.

5.9 Overall discussion and new questions

Coming back to our initial question, is life cycle innovation really an oxymoron? *Not necessarily!* We have shown that LCT may cause fixation with rule-based eco-design because it frames the problem in a restrictive way, without challenging the dominant design, as seen in Solvay's LCA-driven eco-design workshop. With innovative eco-design, which uses reframing as a vehicle for exploration, fixation is no longer a problem but requires specific reasoning tools to stimulate cognitive processes and *reflexivity*, as seen in Solvay's creativity-driven eco-design workshop. However, LCT paired with an exercise in problem setting, interdisciplinary casting and a political distance from the LCA results, as seen in ACME's LCA-driven workshop, the organizational context was conducive to creativity even with rule-based eco-design tools.

These results have led us to new questions and propositions for new research on this topic. For one, what do these results teach us about eco-design methodology? What hybrid workshop could be proposed as a method for those eager to stimulate creativity during eco-design, considering all of the factors mentioned here.

Another question that arises from these results is, at what point in the creative process is it ideal to introduce LCA results, to avoid fixation? We chose to begin our workshop with a presentation of results, but perhaps an initial phase of reframing before exposure to the results could lead to more creativity.

We focused on LCT and rule-based eco-design as a restrictive type of framing, but what about newer contexts like circular design (Ellen MacArthur Foundation & IDEO, 2017), socio-design based on social LCA, or eco-socio-design based on life cycle sustainability assessment? Are the conditions the same? Do they frame the problem in the same way that environmental LCA does?

Another issue that surfaced in our study was how participants deal with uncertainty in LCA, and the consequences of uncertainty on eco-design. Especially in the field of nanotechnology and other emerging technologies, it would be interesting to have a more profound inquiry into fixation during eco-design caused by the discomfort with uncertainty and complexity, building on the works of Arpin and Revéret (2016), Cucuzzella (2011), Berube (2013), Miller and Keoleian (2015) and Wender et al. (2014).

This study also suggests an evolution of the role of the sustainability professional in the corporate world. The sustainability professional needs to be well-versed in innovation and creativity if they want sustainability to be at the heart of the innovation process, otherwise it will remain an after-thought or used as an evaluation at the end of the innovative design process. By merging sustainability considerations and innovation processes, the sustainability professional can concretely create business value. On the other hand, innovation professionals also need to acknowledge that sustainability can be used as a lever for creativity if it is included early in the innovation process, and not in the after-math of innovative design.

5.10 Conclusion

We began this article with the hypothesis that life cycle thinking creates fixation during eco-design by limiting reflexivity of designers and forcing them to use their technical rationality. Through two case studies, we were able to decipher that it is not only the eco-design tool that creates fixation on a cognitive level, but other cognitive factors and organizational contexts can tremendously affect creativity. The framing effect of the eco-design tool therefore does not exist independently of its organizational context. We showed that by teaching participants creativity skills, showing the value of non-expertise (distance to the object) and the ability to abstract the problem, they are able to de-fix, unleash their creativity and use re-framing to explore new value spaces and generate the life cycles of tomorrow. “Life cycle innovation” is therefore an oxymoron if LCT is a point of entry of innovation, not if new life cycles of tomorrow are the result of an innovative process. We also showed that despite using a rule-based eco-design tool to guide the reflection of participants, where LCT is a point of entry to the innovation process, they might gravitate towards an innovative eco-design paradigm if the organizational context is favorable, thereby overcoming the framing effect of LCA. This context is propelled by interdisciplinarity, participatory design, presence of an external facilitator, support from upper management and eco-design maturity. This has profound implications for the emerging life cycle innovation community, who relies exclusively on life cycle tools as enablers of innovation. It takes favourable cognitive and organizational environments to unleash creativity when using these tools, to fully bring them to their innovation potential. The modern sustainability professional needs innovation knowledge and creativity skills if sustainability is to be truly at the heart of the innovation process.

CHAPTER 6 SUPPLEMENTARY RESULTS

In order to keep the article concise and target the results presented to our main conclusions presented, we could not cover all six workshops in the scope of the article. This section presents complementary results to what was presented in the article in Chapter 4. The raw data including C-K diagrams of the workshop results and V2OR analyses can be found in Appendix A and Appendix B.

6.1 Workshop 2: Creativity-driven eco-design workshop at ACME

The creativity-driven workshop at ACME was facilitated and designed by the researchers of this project, using the prospective innovation method. Four prospective scenarios of the substations and data centers market in the year 2040, based on the observations made in the Diagnostic phase, were presented to the group. We divided the participants into four teams, each using one scenario as a "rational myth", to imagine the substation-data center eco-system in the future.

For example, one scenario was to build on the contrasting lifespans of the substation (40 years) and the data center (10 years), to imagine synergies between them and their surrounding environment through the frame of industrial ecology. The team who worked on this scenario consisted of three engineers who all had a common language and technical knowledge of the substation, as well as one external environmental expert. The team originally felt quite stuck – this topic had already been addressed in the first workshop and they had already easily identified the potential flows of material and energy that could be reused (excess energy, excess heat, excess materials from computers). Recognizing their fixation, they took some time to find another piece of foreign knowledge they could use to bisociate. With the idea of optimized intelligent transportation in the year 2040, they built on the *fictional* piece of knowledge, that bridges and tunnels would no longer be needed. Their idea was to leverage this transportation infrastructure in cities to better distribute heat from the data center.

The second piece of knowledge they used to bisociate was considering noise and light emanating from the substation as an energy flow in industrial ecology. Their second concept was an Electronic Music Festival using these flows in Parc Jean Drapeau.

The participants in the other three groups were similarly very playful, without fear of exploring the unknown. Most teams imposed fictional knowledge to expand on the foresight scenario they were given, and used this to bissociate when they were fixated, and reason creatively. Though this creative spirit was encouraged, the results of this workshop were almost too creative. The participants seemed to lose their footing on reality in reasoning in 2040 and had trouble coming back to the present to propose something realistic after going so far outside the box.

Another team consisted of three ACME employees from different domains, and one external expert from a utility. The utility expert dominated the conversation by sharing his extensive knowledge on the subject, that was foreign to the internal ACME employees. The brainstorming session was completely at a halt because the ACME employees felt they could not challenge the knowledge of the expert, and exploration of the unknown was always met with judgement from the expert who could say “No, this idea will not work. We tried it already”. This negativity made the internal participants feel as though they had not done the exercise correctly and had not had the chance to express their creativity at all. There seemed to have been not enough knowledge overlap on the foresight scenario, so the ACME employees didn’t feel as though they could share their knowledge or propose creative concepts.

The detailed accounts of all four teams’ reasoning are available in Appendix A.

6.2 SONIC Project at Solvay

The SONIC project is part of the Sulfide Growth Initiative, like Quasar, but this project aims to use sulfide-based chemistries to develop a solid electrolyte for solid-state batteries. This battery technology is not yet on the market but promises advantages in terms of safety (lower risk of explosion from the liquid electrolyte), and efficiency (higher energy density of the battery). Solvay has established an open-innovation network with major battery producers, start-ups and academics to realize this project, but for the purpose of the workshops, we worked only with the GI innovation project specific to the development of the solid electrolyte.

The casting for these workshops was similar to that of Quasar, with the exception of some engineers dedicated to this specific project.

6.2.1 Workshop 1: LCA-driven eco-design workshop for SONIC at Solvay

This workshop, referred to as the “meeting” by the employees, was organized and facilitated by the 3E team, and as researchers we only observed.

First, LCA results of the battery containing the solid electrolyte were presented and compared to the state-of-the-art liquid electrolyte battery to determine its overall environmental performance.

The LCA results showed that the overall contribution of the solid electrolyte relative to the battery cell is quite minimal, and dependent on the energy density of the cell. In **Error! Reference source not found.**, a sensitivity analysis varying the energy density shows that the bigger the energy density (due to the addition of the Sonic solid electrolyte), the lower the single-score environmental profile of the entire battery, when compared to its reference.

During the two-hour discussion prior to the brainstorming exercise, two major themes were discussed by the group: difficulty with uncertainty in the LCA, unclear focus on life cycle approach and political pressure that created an urge to re-center on the chemical process (i.e. the manufacturing phase of the electrolyte, isolated from its larger context within the battery.)

The LCA was heavily based on technical hypotheses and consequently, the high uncertainty rendered the team uncomfortable with the conclusions of the study. Despite the order-of-magnitude results that showed the electrolyte contributed quite little to the overall impacts of the battery, the contribution depended on a technical assumption.

With pressure from a manager who proposed framing the meeting exclusively on finding new processes to develop the electrolyte, other actors in the room confronted this, advocating for maintaining the life cycle approach despite all of the uncertainty in the results.

Eventually, the team centered on the same improvised methodology as the Quasar workshop and performed a qualitative SPM analysis on the electrolyte alone and used this as a basis for brainstorming ideas on how to improve the six dimensions of the SPM hexagon. They reframed the problem on the manufacturing stage and on their technical rationality: chemical processes.

The results of the brainstorming session were uncreative, limited to existing and accessible knowledge within Solvay. Though some variety was explored, there was very little originality in the resulting ideas.

6.2.2 Workshop 2 : creativity-driven eco-design workshop for SONIC at Solvay

The second workshop at Solvay was organized and facilitated by the researchers, using the prospective innovation method. Two foresight scenarios were developed, based on the observations from the diagnostic phase, to be used as "rational myths" by the participants. We divided the participants in two teams, each using one scenario as a basis for ideating on the SONIC project in 2030.

The first scenario was based on the theme of circular economy, which we titled: "June 26, 2030: Solvay leads the first circularity loop of value creation for the solid electrolyte". The second scenario, on the theme of intelligent urban mobility, which we titled: "June 26, 2030: Solvay, driving force behind new urban mobility thanks to its solid electrolyte".

For example, the team working on the circular economy scenario very quickly focused on technical parameters that could permit the recyclability of the battery and the electrolyte. They looked at the life cycle process of the battery, examining every possible circularity loop, and opened up new innovation fields on each of these loops to imagine how the battery could be redesigned to fit into this vision. The conversation stayed very focused on the technical aspects and new design criteria of the battery, and the team ideated with ease when reasoning in the year 2030. When we asked them to move towards the present and use backcasting to establish a plan for achieving that design, the team was stuck. Their propositions were very grounded in Solvay's way of working and knowledge, they were able to identify accessible and missing knowledge and make analogies that allowed for bissociation (for example, one concept was the "Post-it electrolyte" that can be unstuck from the electrodes with a triggering mechanism). There wasn't much exploration of new possible value or new networks of actors – when these ideas came up , the team quickly recentered on what they knew, and ideated on innovations for chemical aspects of the "circular electrolyte" concept.

When presented with a foresight scenario, the starting point of the exploration was the concept "circular solid electrolyte" added an element to the dominant design they already knew. They explored the aspect of circularity by reframing the problem on the entire life cycle, opening innovation fields for each one, but staying mostly focused on those that were closest to their knowledge and technical rationality.

The reasoning patterns expressed in C-K diagrams are available in Appendix A, as well as a further exploration of both teams' reasoning for this workshop.

CHAPTER 7 GENERAL DISCUSSION

It is important to note that the two case studies are distinct in their organizational contexts and the types of projects worked on during the workshops differed drastically from one another. These stark differences between the two cases make them difficult to compare to one another because there were many variables that could not be controlled for by the nature of research intervention. However, the advantage of research intervention was that we could experiment with these tools and experience them within a real organizational context rather than incubating them so that they could be more easily compared. The comparison that follows in this section draws major themes that tied together or distinguished the two cases from each other.

This section presents a discussion on the data collected: observations made during the workshops, V2OR and C-K analyses of the workshop results, and the insights taken from interviews with workshop participants which I presented in Chapter 5. Going further than the insights offered in the article, this section goes deeper in relating the data to the literature presented in Chapter 2 and compares both case studies. Beginning the discussion in Section 7.1 with design theory, I present how the participants framed or reframed the design problem, and whether they accessed reflexivity. I then discuss the political nature of the rule-based eco-design tool, its inherent difficulties in addressing innovative design problems observed in the workshops, and the extent to which the participants really integrated sustainability issues into their reflection. In Section 7.2 I discuss the cognitive factors that contributed to fixation during the workshops, showing that the presentation of new knowledge or sharing of existing knowledge (in a diverse group) can trigger creativity, and that LCA can be both an expansive and restrictive trigger depending on the context. In Section 7.3 I discuss the social factors that contributed to the collective fixation of the group, uneven power dynamics and ephemeral organizational contexts. Finally in Section 7.4, I discuss the contrast between organizational creativity, focusing on the corporate cultures at Solvay and ACME and how they transcended into the workshops to affect creativity.

7.1 Using design theory to contrast both eco-design approaches

Reflection on Objective 1 : contrast a rule-based (LCA-driven) eco-design regime with an innovative (creativity-driven) eco-design approach to understand their effects on creativity

7.1.1 How did LCT frame the problem, and were participants able to re-frame?

We showed in the article that the teams effectively reframed the problem as Dorst suggests in his design thinking framework. This section takes the analysis further and covers the additional results in ACME workshop 2, and the second sub-case study (SONIC project) at Solvay.

Our diagnostic showed that in the usual way of working at ACME, the engineers use *Abduction-1*, also known as classic problem solving, to propose the Option design, or creative alternative to what their clients request. They develop a creative proposal (WHAT) by accessing known working principles stemming from their experience and knowledge (HOW) to achieve a known and desired result for the customer (VALUE). If they were to respond exactly to what the client requests, the WHAT is usually also specified by the customer.

For example, the engineers are asked to provide an air-insulated substation which should cost around 1 million dollars. They use their creativity to evaluate all the products existing in ACME's offering that could also deliver this solution for 1 million dollars but also reduce the land space required by ten-fold and propose a gas-insulated substation instead. Though this requires their creativity to develop something that provides the VALUE the customer asks for, they are not inventing new working principles by using new frames. We could even qualify this as enriched deductive reasoning.

At Solvay we worked with researchers who are steeped in the scientific method, often in laboratory settings. Their clients are not customers outside the organization, rather they are internal questions asked by either the business units, where they might be constrained to deliver a specific answer, or from the Growth Initiative innovation projects, where they might have more liberty to explore in an innovation field. The diagnostic showed us that their usual way of working also involved Abduction-1 type reasoning. They are asked to answer a question that provides known VALUE, by accessing known working principles (HOW) that stem from their knowledge and experience as chemists.

For example, the 3E group is asked to say whether product A or B is more sustainable on its life cycle. They use the working principle of the LCA methodology to evaluate the question and provide the answer. In the laboratory, the chemist-researchers are asked to find a chemical that provides a certain function – the chemists access the literature on this topic, select which experiments to do (which working principles to use), and replicate the experiments they found in literature before tweaking them until they provide the value requested.

What we were looking for in our workshops was whether the participants used Abduction-2, where they test **new and unknown** working principles by framing and reframing the problem.

In the LCA-driven workshop at ACME, we observed the use of Abduction-2 by three out of four teams, who were presented with the frame of life cycle thinking, with the working principle of optimizing hotspots on the value chain. All but one of the teams reframed the problem using other working principles (HOW), most frequently that of industrial ecology to channel the excess heat generated by the data center to other applications, creating new VALUE that neither the data center nor the substation had provided before.

At Solvay, the participants in the LCA-driven workshops were suggested the frame of life cycle thinking, which proposed a new working principle that required them to extend past the boundaries of that which they are experts. However, they rejected this frame and opted for a known working principle: chemical processes.

7.1.2 Use of reflection-in-action and technical rationality during the workshops

Schön (1983) calls the reasoning of professionals who apply scientific principles and laws to solve problems (their usual professional routines, intuitive choices and rules of thumb), with a positivist worldview, technical rationality. He argues that professional practice, particularly in design, requires the use of reflection-in-action when faced with a surprise, or creative trigger. He saw design as a discipline with constructivist values. I chose to briefly touch on reflection-in-action in this section as a framework to demonstrate how participants distanced themselves from their usual professional routines and ways of thinking as they transitioned from workshop 1 to workshop 2, and in general from their usual way of working (established in the diagnostic) to the workshops.

The purpose of the Diagnostic phase was to establish “what IS the technical rationality of the participants?” so that we could establish the base case, and consequently identify when they are using reflexivity.

The usual ways of working at ACME and Solvay are demonstrably grounded in technical rationality. The engineer at ACME refers to standards, design manuals and engineering knowledge applied to design calculations. The chemist or process engineer at Solvay refers to known principles for process design and chemical laws of matter (Potier, Brun, Le Masson, & Weil, 2015).

When we compare ACME and Solvay's LCA-driven workshops, both cases had the tendency to reject the frame of life cycle thinking, but ACME diverged towards reflexivity, allowing the life cycle frame to be a starting point from which they could explore. Solvay on the other hand, converged towards their technical rationality, remaining in the chemical knowledge, rules and principles they know best. ACME constructed a new reality in which to imagine their products in a creative way, whereas Solvay felt their existing reality of chemistry was the only space they felt comfortable creating. All creativity-driven workshops in both cases led the participants to use their reflexivity.

7.1.3 The power of the eco-design tool and its limitations

7.1.3.1 The political nature of the LCA tool

Solvay's internal experience, sustainability strategy and expertise all revolve around the life cycle approach. SPM is a clear example of an internally-developed rule-based eco-design tool, based on LCA methodology, which quantifies impacts of a product for a certain function, and benchmarks it against a product with a similar function. They have invested a lot of time, money in the tool, which now has a well-renowned reputation as a tool that proves they can create sustainable value.

Solvay is proud to share that thanks to the SPM tool, they can demonstrate that the growth rate of products in the 'solutions' category is positive, whereas the rate of growth of products in the 'challenges' category is negative. The tool allows them to justify investments in sustainability initiatives because it has correlated economic growth to a decrease in environmental impacts. They have internally demonstrated that "decoupling" is possible. For this reason, the tool is revered for its potential to justify sustainability initiatives, especially for innovation, which is also a potential source of economic growth for the company.

Clearly, the SPM tool had a lot of momentum and it was logical to exploit it further and inject it into the innovation process. In a large company like Solvay it is difficult to introduce new tools and methodologies once the existing ones have been transmitted across the different businesses and research groups.

When we contrast this with ACME, who did not have an already established eco-design framework on the local level as sophisticated as Solvay, who were not experts in product development (rather assembling off-the-shelf products into systems), we see clearly the importance of the organizational context in the use of an LCA-driven tool or methodology for eco-design.

Though the design of the workshop purposefully framed the ACME participants in this rule-based eco-design paradigm (with the Golden Rules (Luttropp & Lagerstedt, 2006), LCA hotspots of both the substation and the data center clearly stated as starting points), there wasn't a strong attachment to exploiting the LCA results. As we saw at Solvay, the SPM tool had a higher political value; using the results was very important to the success of the workshop, to the 3E team, whereas at ACME the participants took the LCA results with a grain of salt and reframed the problem.

It was surprising to us that ACME employees for example chose *not* to exploit the SF6 emissions pathway[6] - after all, we offered it them on a silver platter! Some employees at ACME also justified their choice to reframe outside of the LCA results by saying that the factories and people responsible for product development in other countries were probably already doing something about this, and that in the future they expect that SF6 gas won't be a problem anymore because regulation will eventually come.

Ironically, the lack of accountability and ownership from ACME employees for eco-designing their product actually helped them to be more innovative and not be stuck in trying to find ways to improve the product. They felt they could channel their creativity elsewhere. At Solvay, the employees felt a strong sense of accountability and ownership for the LCA results and therefore were highly attached to extracting value from them in the workshop.

---

[6] We found this interesting when compared to a "practice workshop" we did before the workshop at ACME, with graduate students and LCA experts at the CIRAIG as participants. The CIRAIG participants gravitated almost exclusively to the LCA hotspots for their eco-design ideation, predominantly focusing on the SF6 emissions that contributed to climate change in the substation. We therefore expected this pathway to be exploited at ACME, but to no avail. It should be noted that the "practice workshop" at the CIRAIG was performed only to gain experience as a facilitator and does not contribute to our data collected or methodology of the project in any way.

7.1.3.2 The clash of applying rule-based tools & methods to an innovative product

During the LCA-driven workshops for both the Quasar and Sonic projects, there seemed to be a clash between the two regimes of design. The 3E team imposed a rule-based tool and methodology on two highly innovative projects that were still in rudimentary states. These projects required a more innovative approach because they had such high uncertainty and were very early in the development stage (refer to Midler's diagram Figure 2.1).

The 3E team is not only to blame, there was a lot of evidence in interviews that the innovation processes are rushed and moved too quickly in general at Solvay. The Quasar and Sonic projects were managed with a project management approach (Ulrich & Eppinger), with strict targets and expectations of what was to come out of them.

There seemed to be a blindness on behalf of Solvay towards the need for separate creativity & innovation management processes for projects like Quasar and Sonic; they applied the tools and knowledge they were familiar with for more developed and advanced projects. For example, in Quasar the team fixated quickly on one potential application of the nanoparticles, and quickly imposed this as a dominant design to converge on a product, without taking the time to explore the other possible applications pathways. They jumped too quickly into a rule-based framing of the problem rather than exploiting the innovative nature of the project to fully extract the full potential value.

7.1.3.3 What level of sustainable design was reached?

In relation to the sustainable design literature, Solvay stayed in the realm of Product Improvement (Brezet & van Hemel, 1997) on the Product level (Ceschin & Gaziulusoy, 2016) during the LCA-driven workshop. On the contrary, in the creativity-driven workshop, Solvay reached the product redesign, function innovation and system innovation realms (Brezet & van Hemel, 1997), where they explored the product-service systems level of eco-design (Ceschin & Gaziulusoy, 2016).

With the lens of Brezet and van Hemel (1997), in ACME's LCA-driven workshop, three out of four teams entered right away into system innovation territory, (for example, by proposing to create a network of pipes to re-channel heat form the data center). The one team that stayed in a product improvement paradigm (by, for example, proposing a process to find sustainable suppliers and materials to build their substations), had strong attachment to the outcomes of the workshop and put ideas on the table that they had been thinking about for a long time. They were the only team to cling to one of the LCA hotspots (resource use & climate change impacts of materials in the substation). The second workshop at ACME also went straight to system innovation territory.

With the lens of Ceschin and Gaziulusoy (2016), ACME gravitated towards a product-service-system level in their ideas for the first workshop, but in the second workshop with foresight scenarios that put them in a context displaying and encouraging consideration of the social nature of the system, they were able to venture further into the spatio-social level.

7.2 Individual creativity level: what cognitive factors were at play?

Reflection on Objective 2 : On an individual level, investigate the cognitive factors that also contribute to fixation during eco-design.

This part of the discussion is an analysis of when participants were fixated, on what and for how long. Grounded in studies in creative cognition (Agogué et al., 2011; Agogué, Le Masson, Dalmasso, Houdé, & Cassotti, 2015; Agogué, Levillain, & Hooge, 2015), it was expected that by giving restrictive or expansive examples in the K-phase or introductory presentations before ideation, the participants would fixate on what we presented to them. We expected that the workshop design would dictate a trajectory for the teams by shedding light on a design space with a specific frame. From the starting point we provided, were the participants able to use their reflexivity and inhibitory control to move the spotlight to another part of the design space, and reframe the problem?

7.2.1 LCA: expansive or restrictive trigger for ideation?

The overarching objective of this thesis was to apprehend how LCA causes cognitive fixation and why. LCA results can be qualified as a “restrictive example” because they present a suggestion as to how to solve the problem of “eco-designing product X”, by optimizing hot spots on that product’s life cycle. In relation to C-K design theory’s framing of a “creative idea” as one that challenges the dominant design, the LCA results do not nudge participants towards this by keeping the functional unit stable. However, in relation to the ability to reframe the problem from the manufacturing stage to the entire life cycle of that product, this would be an expansive suggestion or example to show before ideation.

At Solvay, the life cycle frame was restrictive; life cycle thinking was well-known to the participants. What surprised us in showing the life cycle results as inspiration for ideation was that participants restricted the problem framing even more than what was presented. They converged towards the manufacturing stage only, and showed clear signs of fixation, though it wasn't specifically on the LCA. The LCA triggered them to fixate even more on what they knew best, chemical processes in the manufacturing stage. **At ACME, the life cycle frame was expansive**; no one in the room had heard of life cycle thinking before so its novelty triggered creative thinking and out-of-the-box solutions.

7.2.2 Knowledge-sharing and presentation of new knowledge in the K-phase

In ACME's first workshop, we used participatory design and many actors did not have common knowledge base on each other's fields. We started the day with presentations (in the K-phase of KCP) on substations, data centers and life cycle assessment so that everyone started from common ground. Through this knowledge-sharing session, most participants claimed in post-interviews to have "learned new things" and really appreciated the opportunity to expand their knowledge-base during the introductory presentations.

Solvay did not have this opportunity to share knowledge since everyone in the room was familiar with each other's expertise and knowledge spaces. Even the LCA practitioners at Solvay were seen as "technical experts" rather than "sustainability experts". There was almost too much overlap of existing common knowledge, to which they stuck during workshop 1 for both Quasar and Sonic. In interviews after the workshops, many participants at Solvay questioned why they did not have access to new knowledge during the workshop. For example, in the Sonic project, there were many unknowns on the design criteria for the battery cell; the participants did not know what was important for a battery manufacturer or other actors in the life cycle stages.

For the creativity-driven workshops at ACME and Solvay, we started the workshop, in the K-phase of KCP, with presentations on new knowledge with which most participants were not familiar. All three creativity-driven workshops led to highly creative performance and de-fixation.

7.2.3 Expansive triggers

For the Quasar project at Solvay, the expansive trigger we presented was a pre-CK tree, where we clearly identified the dominant design and suggested pathways to break out of it. This proved to be an excellent trigger for creative exploration of the concept-space and for accessing new knowledge in the knowledge-space. Working with the C-K tool also proved to be excellent to structure the brainstorming process, which had occurred almost haphazardly in the LCA-driven workshop. Many participants interviewed afterwards were very happy with the C-K method and its power for structuring their exploration, not constraining them from exploring a concept because they lack knowledge in that field. The participants effectively used inhibitory control and reframed the problem several times in the concept space. For example, we showed the heuristic of "the state of the non-art" (Le Masson et al., 2010) in our pre-CK tree, which one team re-appropriated to explore the concept of Up-conversion instead of Down-conversion.

Another team explored the concept of the light of the moon instead of the light of the sun. These concepts were not specifically suggested in the C-K tree, so there were no signs of fixation, however it was clear that the "non-art" heuristic gave the participants permission to explore and de-fix.

At ACME, four foresight scenarios were presented as expansive triggers. Though the participants were de-fixed from the dominant design of the substation and data center with the help of the scenarios, they redirected their fixation on the foresight scenarios.

One team's ideas reflected many of the aspects found in the scenario they used and had trouble going further. (Data Quebec)

The team working with the industrial ecology scenario quickly recognized their fixation and asked for help from the facilitator. They took the opportunity to reframe the problem using the idea of "transportation", suggested as a pathway from the facilitator, which led them to some ethereal concepts that were almost too crazy to be realistic. They went so far outside the box and were so de-fixated that they lost a grasp on what was realistically possible. Though ACME's creativity workshop did lead to high expression of creativity by the participants and clear ability to de-fix from the dominant design, they took the workshop to be more of a fun and playful game rather than a serious game (Agogué, Levillain, et al., 2015).

7.3 Social nature of creativity: how did the team dynamic affect creative expression during the workshops?

Reflection on Objective 3 : On a team level, when working on eco-design ideation in groups, investigate the team dynamic that affects creativity.

7.3.1 The "ephemeral organization" of the workshop & cohesiveness

The workshop environment we created during the workshop design consisted of casting, location, and warm-up exercises to set the tone for the day. For example, for Solvay's second worskhop we started the day with an ice breaker question "If you were an element of the periodic table, which would you be and why?" This set a clear tone of conviviality and ease among participants, allowing them to feel they were no longer bound by the rules, regulations and hierarchies usually present in their day-to-day.

A key difference that distinguishes Solvay's workshop 1 (in both projects) from all other workshops in both case studies is that the participants referred to the activity as a "meeting" and not a "workshop". It felt like a routine part of their job where their usual pressures, issues and problems were present and the social dynamic between the participants reflected the existing hierarchy of Solvay. By contrasting this to the "ephemeral organization" we created at ACME by inviting external actors, we created a setting where the usual rules no longer applied, and the hierarchy was flattened by the presence of external actors. This disruption to the usual setting of what constitutes a "meeting" proved to be extremely effective in increasing creativity.

The ephemeral environment of the workshops led many participants to feel like they got closer to their colleagues. There was a sense of team-building and disruption of existing relationships to create new collectives (Dubois et al., 2014).

7.3.2 Loafing and dominating personalities: interference of politics

For most of the groups in both of ACME's workshops and in most groups in Solvay's creativity workshops, participants expressed good collaboration and a respective, fruitful working environment for idea generation. When asked specifically about "evaluation apprehension", all participants said they felt comfortable sharing their ideas openly and were not afraid of judgement.

There were two cases however where we saw one person dominating the conversation, and some cases where social loafing was also present.

First, in both of Solvay's LCA-driven workshops, we saw that hierarchical power in a culture where organizational structure is highly respected, shifted the conversation towards their political interests. This had a profound effect on the creativity of the group.

One manager had very specific expectations of the value that the LCA results and SPM tool could bring. There was a misconception that the life cycle assessment would shed light on inefficiencies in the manufacturing process, which would lead to opportunities for innovation in the chemical processes. The idea that eco-design would serve a specific purpose and lead to a specific result by one person with high level of hierarchical power in the team made the rest of the group frustrated yet obligated to follow their lead. This manager's stark imposition that the group turn towards chemical processes was what led the group to reframe the problem.

Second, we saw the dominance of the "technical expert" constrain the creativity that might emerge from the "non-expert", leading to social loafing (Stroebe & Diehl, 1994) from that non-expert. During Solvay's creativity-driven workshop for SONIC, the experts in the team were judgemental of novel ideas from non-experts. For the team working on the "circular economy", one non-expert felt that the experts were judging the ideas too quickly. They felt like their ideas were being discarded and invalidated. After trying to participate, this participant felt helpless and retreated from participating for the remainder of the workshop. We also saw this at ACME's LCA-driven workshop, where the "fixated team" was composed of two technical experts and one marketing expert. The marketing expert knew intuitively that they had to redirect the conversation towards something more innovative, but felt inadequate to question the expertise of the experts (Le Masson et al., 2014).

Third, we saw that an external expert with a dominant personality felt they needed to share their knowledge with the internal participants. Particularly during the ACME creativity-driven workshop, for the team working with the foresight scenario on "revitalizing Northern and abandoned mining communities with blockchain mining" that was designed to be a triggering piece of new knowledge. It wasn't anticipated that the external actor part of the team would already be an expert in this field. The external expert therefore spent most of the time in the group sharing their knowledge and experience in first nations communities, and the ACME team members retreated to merely asking this participant questions rather than using their creativity to explore concepts. The team stayed heavily in the knowledge-space and did not capitalize on it to explore the concept-space. When some concepts were suggested, the external expert would often say “No”, and explain why their idea wouldn’t work based on their experience.

During interviews after the workshop, the participants conceded that they felt they hadn’t done the exercise properly, they felt like they weren’t creative and felt inadequate to share ideas since they were in the present of such a dominant person imposing so much new knowledge on them. The external expert said “no” to ACME’s ideas, and no one at ACME felt empowered to challenge their knowledge and judgement. This same external participant did however challenge ACME’s conception of the dominant design of the substation business model. During a discussion about Product-Service-Systems, the ACME participants were more likely to say “we don’t do this” or “this would never be possible for substations”, whereas the external expert challenged them to seriously reconsider this option as they see a need for it in the market.

7.3.3 Collective fixation

Due to the lack of diversity in the casting for the workshops at Solvay, we saw a collective fixation in both the concept-space and knowledge-space (Le Masson et al., 2014). At ACME, the nature of the participatory design casting led to breaking both the concept-space and knowledge-space collective fixation.

At Solvay, the homogeneous team with differing levels of expertise did not trigger new ideas since there was an underlying belief from most participants that the “expert” was the source of creative ideas.

Participatory design at ACME was particularly helpful in breaking collective fixation. The exposure not only to different knowledge, skills and concepts, but to different political interests, values and points of view of the value chain of the product allowed for high creativity. Especially with respect to a life cycle approach, having stakeholders from all life cycle stages around the table during a design exercise helps in creating joint accountability for the impacts along the value chain. At Solvay, the absence of actors from the life cycle stages blinded them from those interests and led them to feel unaccountable for them.

7.4 Organizational creativity: structures and culture

Reflection on Objective 4 : On an organizational level, investigate the institutional factors that contribute to fixation during eco-design

Organizational culture is listed an important factor of organizational creativity in the literature (Nyström, 1990; Woodman et al., 1993). Particularly cultures that favour risk-taking and challenges. Solvay's organizational culture is quite authoritarian, the divide of power between manager and employee is given great importance. Hierarchy and structure of the organization are respected, compared to organizations we saw at ACME, where employees and managers worked together and found common ground. The distinct societal norms of France and Quebec may have also affected each company's respective organizational culture.

The contrast observed in Solvay's succession from an internally managed workshop to one facilitated by external actors, is reflected in both the creativity of the ideas generated and perceptions of participants. From an environment steeped in the usual organizational culture of high importance associated to hierarchy, to an ephemeral environment for exploration where the hierarchy was intentionally flattened, there seemed to be a dormant creativity that was awakened in the second round of workshops. Along with high technical skills and domain-relevant knowledge, employees also had high creativity skills; they just didn't have the right organizational context provided for them to demonstrate it (Amabile, 1996).

Some employees confessed that they felt they had freedom to explore and be creative in their day-to-day jobs but didn't have the resources to do so. Even in managing innovation projects where they needed time to fully explore the subject, they were given strict deadlines to deliver results, and projects were cancelled before the employees felt necessary.

At ACME, the organizational culture was quite somber; there were budget cuts and colleagues were being laid off, putting more pressure on the remaining employees to do more work with the same amount of time available to them. They were motivated by short term goals and deadlines to meet sales targets that blinded them from developing an innovative and creative strategy to attack their market. In the ephemeral organization of the workshop, we also saw, similarly to Solvay, a chance for the employees to unleash their creativity since they were given "permission", however, not many employees had formal creativity training. They subsequently went too far in their exploration, as we saw in ACME creativity-driven workshop.

Solvay's organizational tool called *Gotit* was meant to collect creative ideas from employees, but most employees interviewed did not feel empowered to contribute to it. They felt as though it was biased since the same constrained group of managers evaluated the ideas, there was no socialization of the ideas placed in *Gotit*. Though this tool is an attempt by Solvay's management to foster organizational creativity, and managers' perceptions from interviews were that it was effective, the employees expected to input ideas did not find it useful.

Solvay is also quite avant-garde in their innovation management structure, since they created the *Growth Initiatives*. The GI program resembles the "I" structure in R-I-D (Hatchuel et al., 2001a, 2001b), since this is a source of value creation and to identify new competencies. For example, the sulfide GI was intended to bring new markets to Solvay by developing competencies in sulfide chemistry, which to this day was not already developed.

However, there was evidence that the GI programs were managed much like regular innovation projects in a classic project management style, constrained to delays and budgets that aren't appropriate for highly innovative subjects like the GIs were dealing with.

Hatchuel et al. (2001a, 2001b) also suggest moving from Innovation as a "quality" to innovation as a "process" that can be managed. Though Solvay as an organization took a step in this direction, ACME participants interviewed were not aware of this distinction. At ACME, innovation was seen as a quality of projects and had a very narrow sense (ie. low cost, meets customer requirements but proposes one new element, etc.)

CHAPTER 8 CONCLUSION AND RECOMMENDATIONS

There seems to be a new eco-design paradox: life cycle thinking presents a frame that reinforces the dominant design, contributes to design fixation and inhibits creative reasoning. radical sustainability challenges facing the world today require innovative design to bring radical reductions in impacts we have on the planet, but firms are applying the frame of life cycle thinking to those issues. While this is a step forward, I qualify this "engineering" approach which use quantitative analyses like LCA and optimizing systems for eco-efficiency, as "restrictive" in the context of being able to radically challenge existing systems. Design offers a transformative and constructive way to approach eco-design, especially when the issues in question are to radically reduce environmental impacts.

In this thesis in particular, I addressed the way life cycle thinking can affect creativity during ideation by imposing a frame that causes fixation. If not overcome with cognitive skills like inhibitory control, social factors like participatory design, and organizational conditions like creating ephemeral organizational contexts for innovation, eco-design ideation solely based on rule-based life cycle thinking can be limited. Some major conclusions can be summarized as follows:

- A life cycle assessment is a political object within the organization; the way it is socialized can affect how the results are used during ideation. Firms with internal competencies acquired for LCA, and whose political interests and strategy are built on a foundation of LCA are far more likely to be fixated in the frame of LCT, and less prone to radical innovation.
- Combining LCA with participatory design not only breaks collective fixation by increasing diversity of interests, knowledge and concepts, but also increases accountability and visibility for all life cycle stages, when the stakeholders from those life cycle stages are brought together to co-create.
- The role of the sustainability professional can no longer only be the "sustainability expert" (nor only the "technical expert" as we saw at Solvay), but must also acquire innovation and creativity expertise if they are to put sustainability issues at the heart of innovation processes, rather than just evaluating the innovation process at certain time frames.

- There is a need for tools that are built on a foundation of innovative design principles for eco-design, since life cycle thinking is built on a foundation of rule-based design principles, it is not compatible with exploratory innovation processes.
- There are common goals for the innovation manager and for the sustainability manager: they both want the firm to think about its impact and place in society on the long term, rather than only focusing on short term objectives. Life cycle thinking needs to reflect that if there is to be a fruitful conversation between aligning sustainability and innovation goals for the firm.

BIBLIOGRAPHY

Abernathy, W., & Utterback, J. M. (1978). Patterns of Industrial Innovation. *Technology Review, 80*(7).

Abrassart, C. (2011). *La naissance de l'écoconception: acteurs, raisonnements, enjeux de pilotage et horizons d'une rationalisation industrielle (1990 - 2010).* (PhD Thesis), École Nationale Supérieure des Mines de Paris, Paris. Retrieved from https://pastel.archives-ouvertes.fr/pastel-00712974 (pastel-00712974)

Abrassart, C., Margni, M., Beaulieu, L., & Imbeault-Tétreault, H. (2016). *L'étude de créativité en ACV: quel apport de la conception innovante (théorie C-K) pour la phase d'interprétation de l'ACV?* Paper presented at the Cycle 2016 - Implementing sustainability through life cycle thinking, Montreal, QC.

Aggeri, F., & Labatut, J. (2010). La gestion au prisme de ses instruments. Une analyse généalogique des approches théoriques fondées sur les instruments de gestion. (n°3), 5-37. Retrieved from https://halshs.archives-ouvertes.fr/halshs-00639963.

Aggeri, F., & Labatut, J. (2010). La gestion au prisme de ses instruments. Une analyse généalogique des approches théoriques fondées sur les instruments de gestion. *Finance Contrôle Stratégie*, 5-37. Retrieved from https://hal.archives-ouvertes.fr/halshs-00639963/.

Aggeri, F., & Labatut, J. (2011). *Looking at management through its instruments: A genealogical analysis of instrument-based approaches of management*. Retrieved from https://hal.archives-ouvertes.fr/hal-00639734

Agogué, M., Hooge, S., Arnoux, F., & Brown, I. (2014). *An Introduction to Innovative Design. Elements and Applications of C-K Theory.* Paris: Presses des Mines.

Agogué, M., & Kazakçi, A. (2014). 10 Years of C–K Theory: A Survey on the Academic and Industrial Impacts of a Design Theory. In A. Chakrabarti & L. T. M. Blessing (Eds.), *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations* (pp. 219-235). London: Springer London.

Agogué, M., Kazakci, A., Weil, B., & Cassotti, M. (2011). *The impact of examples on creative design*. Paper presented at the International Conference on Engineering Design, Denmark.

Agogué, M., Le Masson, P., Dalmasso, C., Houdé, O., & Cassotti, M. (2015). Resisting classical solutions: The creative mind of industrial designers and engineers. *Psychology of Aesthetics, Creativity, and the Arts*, 10.1037/a0039414. Retrieved from https://hal-mines-paristech.archives-ouvertes.fr/hal-01199938. doi:10.1037/a0039414

Agogué, M., Levillain, K., & Hooge, S. (2015). Gamification of creativity: Exploring the usefulness of serious games for ideation. *Creativity and Innovation Management, 24*(3), 415-429. doi:10.1111/caim.12138

Agogué, M., Poirel, N., Pineau, A., Houdé, O., & Cassotti, M. (2014). The impact of age and training on creativity: A design-theory approach to study fixation effects. *Thinking Skills and Creativity, 11*, 33-41. Retrieved from http://www.sciencedirect.com/science/article/pii/S1871187113000710. doi:10.1016/j.tsc.2013.10.002

Alcott, B. (2005). Jevons' paradox. *Ecological Economics, 54*(1), 9-21. Retrieved from http://www.sciencedirect.com/science/article/pii/S0921800905001084. doi:https://doi.org/10.1016/j.ecolecon.2005.03.020

Amabile, T. (1988). A model of creativity and innovation in organizations. *Research in Organizational Behavior, 10*, 123-167.

Amabile, T. (1996). *Creativity in Context*. Boulder, CO: Westview Press, Inc.

Amabile, T. (1998). How to Kill Creativity. *Harvard Business Review, 76*(5), 76-87.

Amabile, T. (2012). *Componential Theory of Creativity*. Boston, MA: Harvard Business School.

Arpin, M.-L., & Revéret, J.-P. (2016). *Between scientific orthodoxy and informal epistemology: how is the tension between LCA knowledge and purpose resolved in practice?* Paper presented at the Cycle 2016, Montreal, QC.

Badke-Schaub, P., Goldschmidt, G., & Meijer, M. (2010). How Does Cognitive Conflict in Design Teams Support the Development of Creative Ideas? *Creativity and Innovation Management, 19*(2), 119-133. Retrieved from https://doi.org/10.1111/j.1467-8691.2010.00553.x. doi:10.1111/j.1467-8691.2010.00553.x

Bellini, B., & Janin, M. (2011). Écoconception: état de l'art des outils disponibles. *Techniques de l'ingénieur*. Retrieved from https://www.techniques-ingenieur.fr/base-documentaire/procedes-chimie-bio-agro-th2/industrialisation-des-procedes-et-usine-du-futur-42602210/ecoconception-etat-de-l-art-des-outils-disponibles-g6010/approches-des-outils-d-ecoconception-g6010v2niv10001.html.

Berube, D. (2013). Socialis Commodis and Life Cycle Analysis: A critical examination of uncertainty. In N. Savage, M. E. Gorman, & A. Street (Eds.), *Emerging Technologies: Socio-Behavioral Life Cycle Approaches*: Pan Stanford Publishing Pte. Ltd.

Bhander, G. S., Hauschild, M., & McAloone, T. (2003). Implementing life cycle assessment in product development. *Environmental Progress, 22*(4), 255-267. Retrieved from https://doi.org/10.1002/ep.670220414. doi:10.1002/ep.670220414

Brem, A., Puente-Diaz, R., & Agogué, M. (2017). Creativity and Innovation: State of the Art and Future Perspectives for Research. In *The Role of Creativity in the Management of Innovation* (pp. 1-12): World Scientific.

Brezet, H., & van Hemel, C. (1997). *Ecodesign : a promising approach to sustainable production and consumption*. Paris, France; The Hague; Delft, Netherlands: United Nations Environment Programme, Industry and Environment, Cleaner Production ; Rathenau Institute ; Delft University of Technology.

Brooks, A. L., Wang, S., & Jambeck, J. R. (2018). The Chinese import ban and its impact on global plastic waste trade. *Science Advances, 4*(6), eaat0131. Retrieved from http://advances.sciencemag.org/content/4/6/eaat0131.abstract. doi:10.1126/sciadv.aat0131

Cassotti, M., & Agogué, M. (2016). Sur quoi la créativité repose-t-elle? *L'Intelligence, 18*, 50 - 53.

Cassotti, M., Camarda, A., Poirel, N., Houdé, O., & Agogué, M. (2016). Fixation effect in creative ideas generation: Opposite impacts of example in children and adults. *Thinking Skills and Creativity, 19*, 146-152. Retrieved from http://www.sciencedirect.com/science/article/pii/S1871187115300353. doi:https://doi.org/10.1016/j.tsc.2015.10.008

Ceschin, F. (2014). Transition Towards Sustainability: The Need of Radical Innovations. In F. Ceschin (Ed.), *Sustainable Product-Service Systems: Between Strategic Design and Transition Studies* (pp. 1-15). Cham: Springer International Publishing.

Ceschin, F., & Gaziulusoy, I. (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design Studies, 47*, 118-163. doi:http://dx.doi.org/10.1016/j.destud.2016.09.002

Charmaz, K. (2014). *Constructing Grounded Theory* (2 ed.). London: SAGE.

Chesbrough, H. (2003). *Open Innovation: The New Imperative for Creating and Profiting from Technology*. Boston, MA: Harvard Business School Press.

Christensen, C. (1997). *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (2016 ed.). Boston, MA: Harvard Business Review.

CIRAIG. (2015). *Circular Economy: A critical literature review of concepts*. In L. Beaulieu, G. van Durme, M.-L. Aprin, J.-P. Revéret, M. Margni, & S. Fallaha (Eds.). Retrieved from http://www.ciraig.org/en/v.php?id=396&locale=en&year=2015&type=2

CIRAIG. (2016). *Analyse de cycle de vie comparative des impacts environnementaux potentiels du véhicule conventionnel et véhicule électrique dans un contexte d'utilisation québécois*. Retrieved from Montreal, QC: http://www.hydroquebec.com/data/developpement-durable/pdf/analyse-comparaison-vehicule-electrique-vehicule-conventionnel.pdf

Cluzel, F., Yannou, B., Leroy, Y., & Millet, D. (2012). Proposition for an adapted management process to evolve from unsupervised Life Cycle Assessment of complex industrial systems towards an eco-designing organization. *20*(2), 111-126. Retrieved from https://hal.archives-ouvertes.fr/hal-00748708. doi:10.1177/1063293x12446663

Coghlan, D., & Shani, A. B. (2013). Creating Action Research Quality in Organization Development: Rigorous, Reflective and Relevant. *Systemic Practice and Action Research, 27*(6), 523-536. doi:10.1007/s11213-013-9311-y

Collado-Ruiz, D., & Ostad-Ahmad-Ghorabi, H. (2010). Influence of environmental information on creativity. *Design Studies, 31*(5), 479-498. doi:10.1016/j.destud.2010.06.005

Collado-Ruiz, D., & Ostad-Ahmad-Ghorabi, H. (2011). Influence of Environmental Information on Expert-perceived Creativity of Ideas. In T. Taura & Y. Nagai (Eds.), *Design Creativity 2010* (pp. 71). London: Springer-Verlag.

Creswell, J. W. (2013). *Research Design: Qualitative, Quantitative and Mixed Methods Approaches* (4th ed.). California: SAGE.

Cross, N. (2001). Designerly Ways of Knowing: Design Discipline Versus Design Science. *Design Issues, 17*(3), 49-55. Retrieved from https://doi.org/10.1162/074793601750357196. doi:10.1162/074793601750357196

Cross, N. (2010). *Design Thinking as a Form of Intelligence.* Paper presented at the DTRS8, Sydney, Australia.

Cucuzzella, C. (2011). What does complexity have to do with sustainable design? In L. Graham (Ed.), *Sustainability Research by Designers: An Anthology*. Illinois: Common Ground Publishing.

Cucuzzella, C. (2016). Creativity, sustainable design and risk management. *Journal of Cleaner Production, 135*, 1548-1558. Retrieved from http://www.sciencedirect.com/science/article/pii/S0959652615019010. doi:http://dx.doi.org/10.1016/j.jclepro.2015.12.076

Cummings, A., & Oldham, G. R. (1997). Enhancing Creativity: Managing Work Contexts for the High Potential Employee. *California Management Review, 40*(1), 22-38. Retrieved from https://doi.org/10.2307/41165920. doi:10.2307/41165920

David, A. (2000). *La recherche intervention, un cadre général pour les sciences de gestion ?* Paper presented at the IX ème Conférence Internationale de Management Stratégique, Montpellier.

Diehl, M., & Stroebe, W. (1987). *Productivity Loss In Brainstorming Groups: Toward the Solution of a Riddle* (Vol. 53).

Dorst, K. (2011). The core of 'design thinking' and its application. *Design Studies, 32*(6), 521-532. doi:10.1016/j.destud.2011.07.006

Dorst, K., & Cross, N. (2001). Creativity in the design process: co-evolution of problem–solution. *Design Studies, 22*(5), 425-437. Retrieved from http://www.sciencedirect.com/science/article/pii/S0142694X01000096. doi:http://dx.doi.org/10.1016/S0142-694X(01)00009-6

Dosi, G. (1982). Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. *Research Policy, 11*(3), 147-162. Retrieved from http://www.sciencedirect.com/science/article/pii/0048733382900166. doi:https://doi.org/10.1016/0048-7333(82)90016-6

Dubois, L.-E., Le Masson, P., Weil, B., & Cohendet, P. (2014). *From organizing for innovation to innovating for organization: how co-design fosters change in organizations*. Paper presented at the AIMS 2014, Rennes, France. https://hal-mines-paristech.archives-ouvertes.fr/hal-00981108

Ehrlich, P. R., & Holdren, J. P. (1971). Impact of Population Growth. *Science, 171*(3977), 1212-1217. Retrieved from http://www.jstor.org/stable/1731166.

Ellen MacArthur Foundation, & IDEO. (2017). Circular Design Guide. Retrieved from https://www.circulardesignguide.com/

Finke, R. A., Ward, T. B., & Smith, S. M. (1996). Creative cognition : theory, research, and applications. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=1709.

Fischer, G. (2004). *Social creativity: turning barriers into opportunities for collaborative design*. Paper presented at the Proceedings of the eighth conference on Participatory design: Artful integration: interweaving media, materials and practices - Volume 1, Toronto, Ontario, Canada.

FSLCI. (2018). Life Cycle Innovation Conference 2018. Retrieved from https://fslci.org/lcic2018/

Gençer, E., Miskin, C., Sun, X., Khan, M. R., Bermel, P., Alam, M. A., & Agrawal, R. (2017). Directing solar photons to sustainably meet food, energy, and water needs. *Scientific Reports, 7*(1), 3133. Retrieved from https://doi.org/10.1038/s41598-017-03437-x. doi:10.1038/s41598-017-03437-x

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., . . . Rydberg, T. (2011). Life Cycle Assessment: Past, Present, and Future. *Environmental Science & Technology, 45*(1), 90-96. Retrieved from https://doi.org/10.1021/es101316v. doi:10.1021/es101316v

H. de Coninck, A. R., M. Babiker, P. Bertoldi, M. Buckeridge, A. Cartwright, W. Dong, J. Ford, S. Fuss, JC. Hourcade, D. Ley, R. Mechler, P. Newman, A. Revokatova, S. Schultz, L. Steg, T. Sugiyama. (2018). Strengthening and implementing the global response. In P. Z. V. Masson Delmotte, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (Ed.), *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C*

above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Hatchuel, A., Le Masson, P., & Weil, B. (2001a). *De la R&D à la RID: de nouveaux principes de management du processus d'innovation.* Paper presented at the Congrès francophone du management de projet, AFITEP « Innovation, conception... et projets », Paris, France.

Hatchuel, A., Le Masson, P., & Weil, B. (2001b). *From R&D to RID: Design strategies and the management of innovation fields.* Paper presented at the 8th International Product Development Management Conference, Enschede, NL.

Hatchuel, A., & Weil, B. (2008). C-K design theory: an advanced formulation. *Research in Engineering Design, 19*(4), 181. Retrieved from https://doi.org/10.1007/s00163-008-0043-4. doi:10.1007/s00163-008-0043-4

Houdé, O. (2014). *Le raisonnement* (1 ed.). Paris, France: puf.

Hughes, T. P. (1987). The Evolution of Large Technological Systems. In W. Bijker, T. Hughes, & T. Pinch (Eds.), *The Social Construction of Technological Systems*. Cambridge, MA.

Hunt, R. G., & Franklin, W. E. (1996). LCA - How it came about - Personal reflections on the origin and development of LCA in the USA. *Int J LCA, 1*(1), 1 -7.

IEA. (2018). *Energy Transitions in G20 Countries: energy transitions towards cleaner, more flexible and transparent systems*. Retrieved from https://webstore.iea.org/energy-transitions-in-g20-countries-energy-transitions-towards-cleaner-more-flexible-and-transparent-systems

ISO. (2006a). Environmental management - Life cycle assessment - Principles and framework. In (Vol. ISO 14040:2006). Switzerland: ISO.

ISO. (2006b). Environmental management - Life cycle assessment - Requirements and guidelines. In (Vol. 14044:2006). Switzerland: ISO.

Jansson, D. G., & Smith, S., M. (1991). Design fixation. *Design Studies, 12*(1), 3-11.

Jessup, L. M., Connolly, T., & Galegher, J. (1990). The Effects of Anonymity on GDSS Group Process with an Idea-Generating Task. *MIS Quarterly, 14*(3), 313-321. Retrieved from http://www.jstor.org/stable/248893. doi:10.2307/248893

Jolliet, O., Saadé-Sbeih, M., Shaked, S., Jolliet, A., & Crettaz, P. (2016). *Environmental Life Cycle Assessment*: CRC Press Taylor & Francis Group.

Kahneman, D. (2011). *Thinking, Fast and Slow*. Canada: Anchor Canada.

Kazakçı, A., Osman, Gillier, T., Piat, G., & Hatchuel, A. (2014, 2014-06-21). *Brainstorming versus creative design reasoning.* Paper presented at the Design computing and cognition 2014, London, United Kingdom.

Laruelle, E., Ficheux, A., Kieffel, Y., & Huet, I. (2013). *Environmental impact comparison between a 220kV Gas-Insulated Substation and a 220kV Air-Insulation susbstaion*. Paper presented at the 2013 IEEE Power & Energy Society General Meeting, Vancouver, BC.

Le Masson, P., Weil, B., & Hatchuel, A. (2010). *Strategic Management of Innovation and Design*. Cambridge, United Kingdom: Cambridge University Press.

Le Masson, P., Weil, B., & Hatchuel, A. (2014). *Théorie, méthodes et organisations de la conception*. Paris, FR: Presses des Mines.

Lewandowska, A., & Kurczewski, P. (2010). ISO 14062 in theory and practice—ecodesign procedure. Part 1: structure and theory. *The International Journal of Life Cycle Assessment, 15*(8), 769-776. Retrieved from https://doi.org/10.1007/s11367-010-0228-8. doi:10.1007/s11367-010-0228-8

Life Cycle Initiative. (2018). What is life cycle thinking. Retrieved from https://www.lifecycleinitiative.org/starting-life-cycle-thinking/what-is-life-cycle-thinking/

Luttropp, C., & Lagerstedt, J. (2006). EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. *Journal of Cleaner Production, 14*(15), 1396-1408. Retrieved from http://www.sciencedirect.com/science/article/pii/S0959652605002556. doi:https://doi.org/10.1016/j.jclepro.2005.11.022

Manzini, E. (2006). *Design, ethics and sustainability: guidelines for a transition phase*. Retrieved from Helsinki: https://s3.amazonaws.com/academia.edu.documents/14670221/nantesworkingpaper.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1546485400&Signature=eK60EM1dk7pfh7jwSlV%2F9KL%2Bhns%3D&response-content-disposition=inline%3B%20filename%3DRedesign_teaching_and_learning.pdf#page=9

McAloone, T. C., & Pigosso, D. C. A. (2017). From Ecodesign to Sustainable Product/Service-Systems: A Journey Through Research Contributions over Recent Decades. In R. Stark, G. Seliger, & J. Bonvoisin (Eds.), *Sustainable Manufacturing: Challenges, Solutions and Implementation Perspectives* (pp. 99-111). Cham: Springer International Publishing.

McLeod, P., & Lobel, S. A. (1992). The effects of ethnic diversity on idea generation in small groups. *Academy of Management Proceedings, 1992*(1), 227-231. Retrieved from https://doi.org/10.5465/ambpp.1992.17515639. doi:10.5465/ambpp.1992.17515639

Midler, C. (2004). *L'auto qui n'existait pas: Management des projets et transformation de l'entreprise*. Paris, FR: Dunod.

Miller, S. A., & Keoleian, G. A. (2015). Framework for analyzing transformative technologies in life cycle assessment. *Environ Sci Technol, 49*(5), 3067-3075. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/25636136. doi:10.1021/es505217a

Millet, D., Bistagnino, L., Lanzavecchia, C., Camous, R., & Poldma, T. (2007). Does the potential of the use of LCA match the design team needs? *Journal of Cleaner Production, 15*(4), 335-346. Retrieved from http://www.sciencedirect.com/science/article/pii/S095965260500185X. doi:http://dx.doi.org/10.1016/j.jclepro.2005.07.016

Mumford, M. D., Feldman, J. M., Hein, M. B., & Nagao, D. J. (2001). Tradeoffs Between Ideas and Structure: Individual Versus Group Performance in Creative Problem Solving. *The Journal of Creative Behavior, 35*(1), 1-23. Retrieved from https://doi.org/10.1002/j.2162-6057.2001.tb01218.x. doi:10.1002/j.2162-6057.2001.tb01218.x

Mumford, M. D., & Gustafson, S. B. (1988). Creativity syndrome: Integration, application, and innovation. *Psychological Bulletin, 103*(1), 27-43. doi:10.1037/0033-2909.103.1.27

Nill, J., & Kemp, R. (2009). Evolutionary approaches for sustainable innovation policies: From niche to paradigm? *Research Policy, 38*(4), 668-680. doi:10.1016/j.respol.2009.01.011

Nyström, H. (1990). Organizational innovation. In *Innovation and creativity at work: Psychological and organizational strategies.* (pp. 143-161). Oxford, England: John Wiley & Sons.

Osborn. (1953). *Applied Imagination*.

Pahl, G., & Beitz, W. (1996). *Engineering Design, A Systematic Approach*: Springer.

Patton, M. Q. (2002). *Qualitative Research & Evaluation Methods* (3 ed.): SAGE Publications, Inc.

Paulus, P. (2000). Groups, Teams, and Creativity: The Creative Potential of Idea-generating Groups. *Applied Psychology, 49*(2), 237-262. Retrieved from https://doi.org/10.1111/1464-0597.00013. doi:10.1111/1464-0597.00013

Paulus, P., & Brown, V. (2003). Enhancing ideational creativity in groups: Lessons from research on brainstorming. In *Group creativity: Innovation through collaboration.* (pp. 110-136). New York, NY, US: Oxford University Press.

Paulus, P., & Brown, V. (2007). Toward More Creative and Innovative Group Idea Generation: A Cognitive-Social-Motivational Perspective of Brainstorming. *Social and Personality Psychology Compass, 1*(1), 248-265. Retrieved from https://doi.org/10.1111/j.1751-9004.2007.00006.x. doi:10.1111/j.1751-9004.2007.00006.x

Pigosso, D. C. A., Rozenfeld, H., & McAloone, T. C. (2013). Ecodesign maturity model: a management framework to support ecodesign implementation into manufacturing companies. *Journal of Cleaner Production, 59*, 160-173. doi:10.1016/j.jclepro.2013.06.040

Polimani, J. M., Mayumi, K., Giampietro, M., & Alcott, B. (2008). *The Jevons Paradox and the Myth of Resource Efficiency Improvements*. London: Earthscan.

Potier, O., Brun, J., Le Masson, P., & Weil, B. (2015). How innovative design can contribute to Chemical and Process Engineering development? Opening new innovation paths by applying the C–K method. *Chemical Engineering Research and Design, 103*, 108-122. Retrieved from http://www.sciencedirect.com/science/article/pii/S0263876215002014. doi:https://doi.org/10.1016/j.cherd.2015.05.040

Poudelet, V., Chayer, J.-A., Margni, M., Pellerin, R., & Samson, R. (2012). A process-based approach to operationalize life cycle assessment through the development of an eco-design decision-support system. *Journal of Cleaner Production, 33*, 192-201. Retrieved from http://www.sciencedirect.com/science/article/pii/S0959652612001928. doi:https://doi.org/10.1016/j.jclepro.2012.04.005

Radaelli, G., Guerci, M., Cirella, S., & Shani, A. B. (2012). Intervention Research as Management Research in Practice: Learning from a Case in the Fashion Design Industry. *British Journal of Management, 25*(2), 335 - 351. doi:10.1111/j.1467-8551.2012.00844.x

Rampa, R., Abrassart, C., & Agogué, M. (2017). Training for Innovative Design to Increase Organizational Creativity: A Longitundinal Study of Hydro-Québec's Research Center. In A. Brem, R. Puente-Diaz, & M. Agogué (Eds.), *The Role of Creativity in the Management of Innovation. State of the Art and Future Research Outlook.* (Vol. 27, pp. 97-113): World Scientific.

Rossi, M., Germani, M., & Zamagni, A. (2016). Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. *Journal of Cleaner Production, 129*, 361-373. doi:10.1016/j.jclepro.2016.04.051

Sanders, E. B. N. (2008). An evolving map of design practice and design research. *ACM Interactions, XV*(6).

Sanders, E. B. N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. *CoDesign, 4*(1), 5-18. Retrieved from https://doi.org/10.1080/15710880701875068. doi:10.1080/15710880701875068

Schön, D. A. (1983). *The reflective practitioner*. New York: Basic Books, Inc.

Schuler, D., & Namioka, A. (Eds.). (1993). *Participatory Design: Principles and Practices*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Shalley, C. E., & Gilson, L. L. (2004). What leaders need to know: A review of social and contextual factors that can foster or hinder creativity. *The Leadership Quarterly, 15*(1), 33-53. Retrieved from http://www.sciencedirect.com/science/article/pii/S1048984303001012. doi:https://doi.org/10.1016/j.leaqua.2003.12.004

Smith, S., Ward, T., & Schumacher, J. (1993). Constraining effects of examples in a creative generation task. *Memory & Cognition, 21*(6), 837-845.

Solvay. (2017). *Sustainable Portfolio Management Guide*. Retrieved from https://www.solvay.com/en/sustainability/acting-sustainable-business/sustainable-portfolio-management-spm-tool

Sonnemann, G., & Margni, M. (2015). *Life Cycle Management*. Netherlands: Springer.

Stamm, A., Dantas, E., Fischer, D., Ganguly, S., & Rennkamp, B. (2009). *Sustainability-oriented innovation systems. Towards decoupling economic growth from environmental pressures?* Retrieved from Bonn, Germany: http://edoc.vifapol.de/opus/volltexte/2011/3310/pdf/DP_20.2009.pdf

Stewart, D., & Stasser, G. (1995). Expert Role Assignment and Information Sampling During Collective Recall and Decision Making. *Journal of Personality and Social Psychology, 4*(69), 619-628. doi:10.1037/0022-3514.69.4.619

Stroebe, W., & Diehl, M. (1994). Why Groups are less Effective than their Members: On Productivity Losses in Idea-generating Groups. *European Review of Social Psychology, 5*(1), 271-303. Retrieved from https://doi.org/10.1080/14792779543000084. doi:10.1080/14792779543000084

Tukker, A. (2008). Sustainability: a multi-interpretable notion: the book's normative stance. In A. Tukker, M. Charter, C. Vezzoli, E. Stø, & M. M. Andersen (Eds.), *System Innovation for Sustainability 1: Perspectives on Radical Changes to Sustainable Consumption and Production* (Vol. 1). New York, NY: Greenleaf Publishing Ltd.

Tukker, A., & Butter, M. (2007). Governance of sustainable transitions: about the 4(0) ways to change the world. *Journal of Cleaner Production, 15*(1), 94-103. doi:10.1016/j.jclepro.2005.08.016

Tyl, B., Legardeur, J., Millet, D., & Vallet, F. (2014). A comparative study of ideation mechanisms used in eco-innovation tools. *Journal of Engineering Design, 25*(10-12), 325-345. Retrieved from http://dx.doi.org/10.1080/09544828.2014.992772. doi:10.1080/09544828.2014.992772

Ulrich, K. T., & Eppinger, S. (2011a). Design for Environment. In *Product Design and Development*: McGraw-Hill.

Ulrich, K. T., & Eppinger, S. (2011b). *Product Design and Development*: McGraw-Hill Education.

UNEP. (2011). *Decoupling: Natural resource use and environmental impacts from economic growth*. Retrieved from Switzerland: http://hdl.handle.net/20.500.11822/9816

Utterback, J. M., & Abernathy, W. (1975). Dynamic Model of Process and Product Innovation. *OMEGA, The International Journal of Managmenet Science, 3*(6).

Vallet, F., Eynard, B., Millet, D., Mahut, S. G., Tyl, B., & Bertoluci, G. (2013). Using eco-design tools: An overview of experts' practices. *Design Studies, 34*(3), 345-377. Retrieved from http://www.sciencedirect.com/science/article/pii/S0142694X12000634. doi:https://doi.org/10.1016/j.destud.2012.10.001

Wender, B. A., Foley, R. W., Hottle, T. A., Sadowski, J., Prado-Lopez, V., Eisenberg, D. A., . . . Seager, T. P. (2014). Anticipatory life-cycle assessment for responsible research and innovation. *Journal of Responsible Innovation, 1*(2), 200-207. doi:10.1080/23299460.2014.920121

Whitehead, Andrews, & Shah. (2015). The life cycle assessment of a UK data centre. *Int J Life Cycle Assess, 20*, 332-349. doi:10.1007/s11367-014-0838-7

Woodman, R. W., Sawyer, J. E., & Griffin, R. W. (1993). Toward a Theory of Organizational Creativity. *The Academy of Management Review, 18*(2), 293-321. Retrieved from http://www.jstor.org/stable/258761. doi:10.2307/258761

WWF. (2018). *Living Planet Report - 2018 : Aiming Higher*. Retrieved from Gland, Switzerland: https://www.wwf.org.uk/sites/default/files/2018-10/wwfintl_livingplanet_full.pdf

Yin, R. K. (2009). *Case Study Research Design and Methods* (5th ed.). Thousand Oaks, CA: Sage Publications.

Yorks, L. (2005). Action Research Methods. In R. A. Swanson & E. F. Holton (Eds.), *Resarch in Organizations: Foundations and Methods of Inquiry* (1st ed., pp. 375). California: Berrett-Koehler Publishers.

Yström, A., Ollila, S., Agogué, M., & Coghlan, D. (2017). *Developing a learning method in an open innovation project through action research*. Paper presented at the Academy of Management Conference, Atlanta. http://publications.lib.chalmers.se/publication/249722

APPENDIX A – ACME CASE STUDY

To assess the results from the workshops, we used an ex-post C-K method to codify the rationale and reasoning each team used while brainstorming. This method divides a tree of reasoning in the concept-space, from knowledge called upon to develop those concepts in the knowledge-space.

The concept tree partitions concepts that are codified on a scale from restrictive to expansive. Knowledge is codified as either internal, already mastered or external to ACME, requiring that they create a new network of actors to achieve the development of the concept. The more expansive concepts and the more external knowledge identified during the workshop, the more creative the results.

After each representation of the brainstorming session with a C-K diagram, we discuss the results briefly and provide a V2OR analysis of the content of the workshop, followed by an analysis of the social factors that most affected the team's experience. We interpreted these social factors by observations, listening to recordings of the workshop and from interviews with the participants afterwards.

A.1 ACME Workshop 1: LCA-driven eco-design

A.1.1 Workshop design

The first workshop was designed to educate the participants on life cycle thinking and its associated tools. The use of life cycle thinking is a classical method of eco-design, where the impacts along the value chain of a product are brought to light and used as a base for brainstorming on sustainable solutions.

In the K-phase, we present the substation and the data center as two separate entities, that are only linked by one concept, that the data center uses a lot of energy. We present their LCA results as two separate systems and do not suggest any way that they could create new combined value. In this workshop, we proposed that the substation and the data center now form an eco-system as a stimulating starting point for the concept-generation phase. From here the participants could translate the problem of "What is the sustainable substation-data center ecosystem of the future?" into the problem of their choice.

Table A. 1 - Summary of workshop 1

Introductory Presentations (K-phase)	**Idea-generation Exercise (C-phase)**	**Casting**
• What is a substation? • What is a data center? • What is LCA? • LCA results of an AIS & GIS substation • LCA results of a data center	What is the sustainable substation-data center ecosystem of the future? 1. Define the problem 2. Brainstorm solutions 3. Introduction of eco-design rulebook 4. Rapid prototype 5. Present to the room	Data center (1) Utility (2) ACME (11) • Engineers • Managers • Environment • Sales & Marketing • Supply chain Sustainability Consultants (1) ------------- Total: 15

The key LCA results we showed to the participants were the results of the Alstom LCA study comparing a gas-insulated substation (GIS) to an air-insulated substation (AIS). The hotspots and design tradeoffs were between the Climate change impacts of SF6 leakage in the GIS, versus the higher energy losses in the AIS. Both systems had significant impacts in their materials as well.

We also showed results from an LCA study of a data center that showed that the hotspot of the data center was its energy usage.

A.1.2 Workshop results

A.1.2.1 Team 1 : Energy efficiency

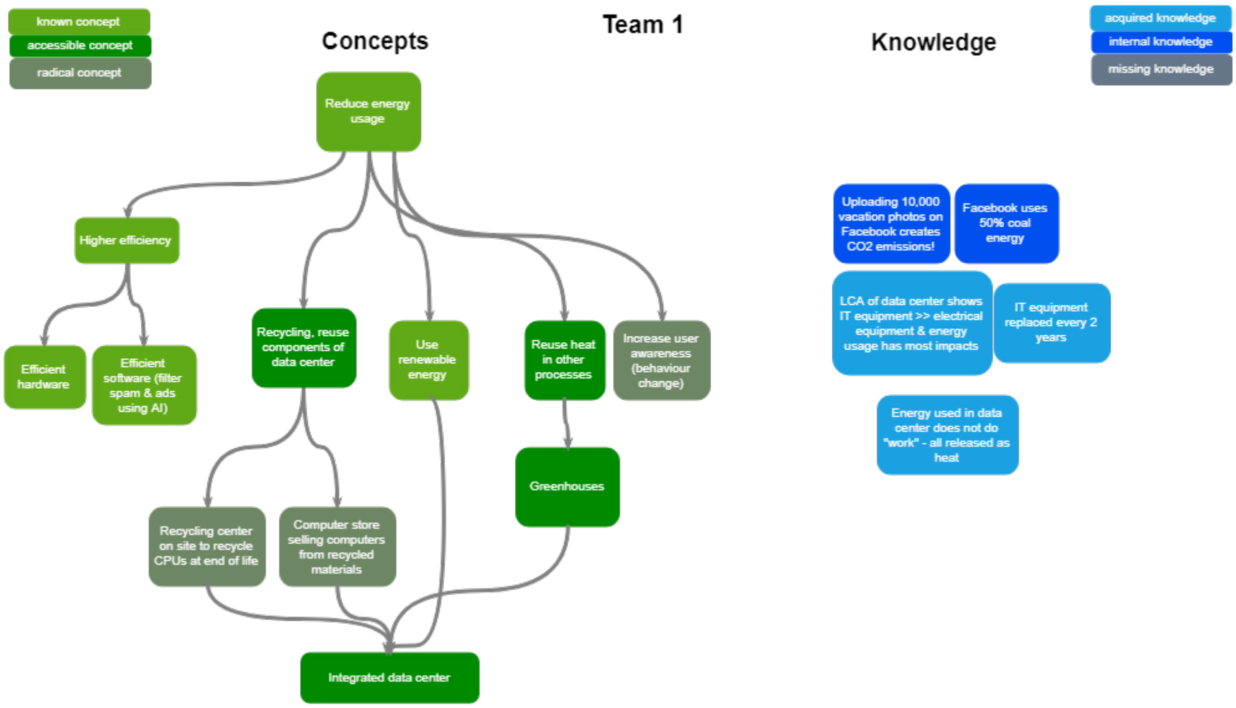

Figure A. 1 - Results of Team 1 Workshop 1 with C-K coding

This team's level of interdisciplinarity was quite high as there were participants from the utility, sustainability consultants, an ACME engineer, and an ACME HSE Manager around the table. The problem they chose to work on was to "Reduce energy usage" of the data center, which is a concept that is relatively well understood and known, therefore indicating that they might be on a rule-based design path. Some ideas that emerged, however, were rather radical. The ideas on efficiency and using renewable energy are well-known, whereas exploring the recycling of materials and heat are exploratory and new for both ACME, the utility and the data center customers. However, many other teams came up with the reuse-of-heat idea, so we classified it as an accessible concept, not radical. There are examples in industry of these kinds of projects being executed as pilot projects. The final concept that we classified as radical was to increase user awareness. This concept requires an entirely new network of actors like behavioural scientists and psychologists to come on board; a surprising and new combination for ACME.

Table A. 2 - V2OR analysis of results from team 1 in workshop 1

Variety	Good
Originality	Low. 1 radical & 2 accessible concept branches
Value	Good. New potential partnerships in industrial ecology & behavioural science identified Identified new design criteria for the data center (that they could be designed for recycling or with a pipe system to channel the heat)
Robustness	Good. Not discussed much by the team, but seems possible to redeploy this in other contexts.

This team seemed to be having fun doing the exercise, they appeared to be at ease exploring new concepts and bouncing off the ideas of others. They worked very well together and were very respectful. The different stakeholders around the table were committed to the exercise and took it seriously.

Of the introductory material presented before the workshop, this team seemed to have fixated on the energy losses present in both the substation and the data center LCAs. The setting of the problem also remained in ACME's expertise of energy efficiency.

A.1.2.2 Team 2: Substation materials

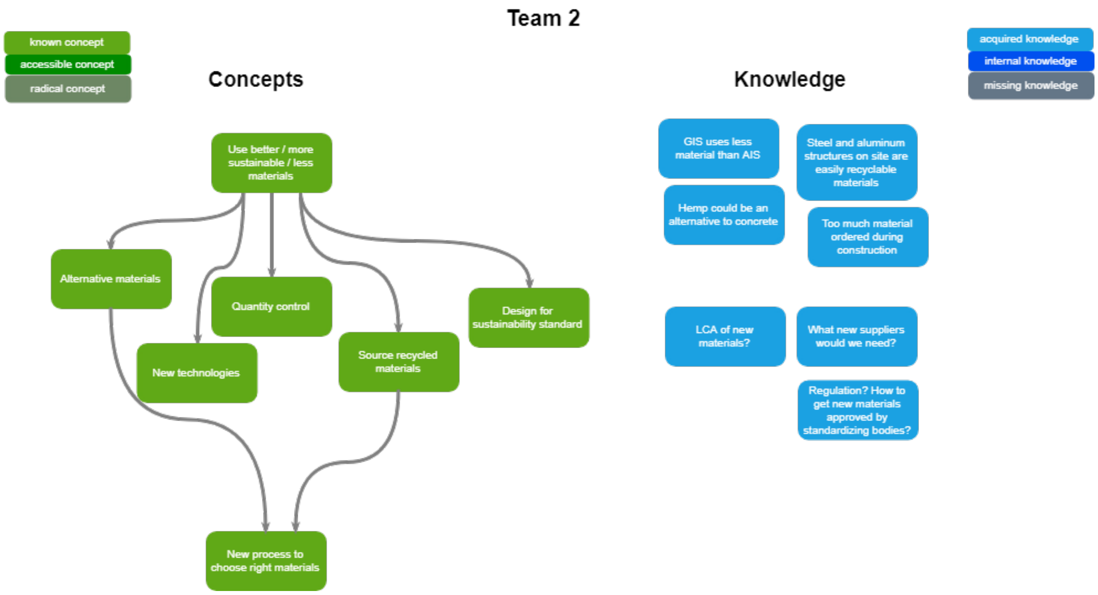

Figure A. 2 - Results of Team 2 Workshop 1 with C-K coding

This team had very low interdisciplinarity: only 3 ACME employees, where 2 were engineers and one was a marketing expert. The problem they chose to work on was "Using better / more sustainable / less materials" for the design of a substation. They failed to imagine the substation as part of its larger ecosystem or question the dominant design of the substation to imagine new possible functions that it could provide. The overall results of their brainstorming session remained in the rule-based design realm and the group was heavily fixated on the substation's existing identity. This type of reasoning was in line with what we expected when reasoning in an LCA-driven eco-design workshop. The team tried to optimize the existing design by making it more sustainable yet took for granted the *raison-d'être* of the substation itself. This represents classic eco-design reasoning that is commonplace in the transmission & distribution industry.

Table A. 3 - V2OR analysis of results from team 2 in workshop 1

Variety	Low.
Originality	Low. Remained within the dominant design of the substation
Value	Identified potential of new suppliers with sustainable materials
Robustness	Low.

In retrospect, during interviews the two engineers admitted to being fixated in this workshop but did not have the tools to enable their reflexivity to break out of it. The third participant was not a technical expert, and therefore felt inadequate to contribute to such a technical conversation that was dominated by engineer-experts.

Of the introductory material presented before the workshop, this team seemed to have fixated on the impact of materials used to build the substation. The setting of the problem also remained in their technical expertise of the engineering behind the substation, and they did not explore the unknown of the data center.

A.1.2.3 Team 3: Design for recycling

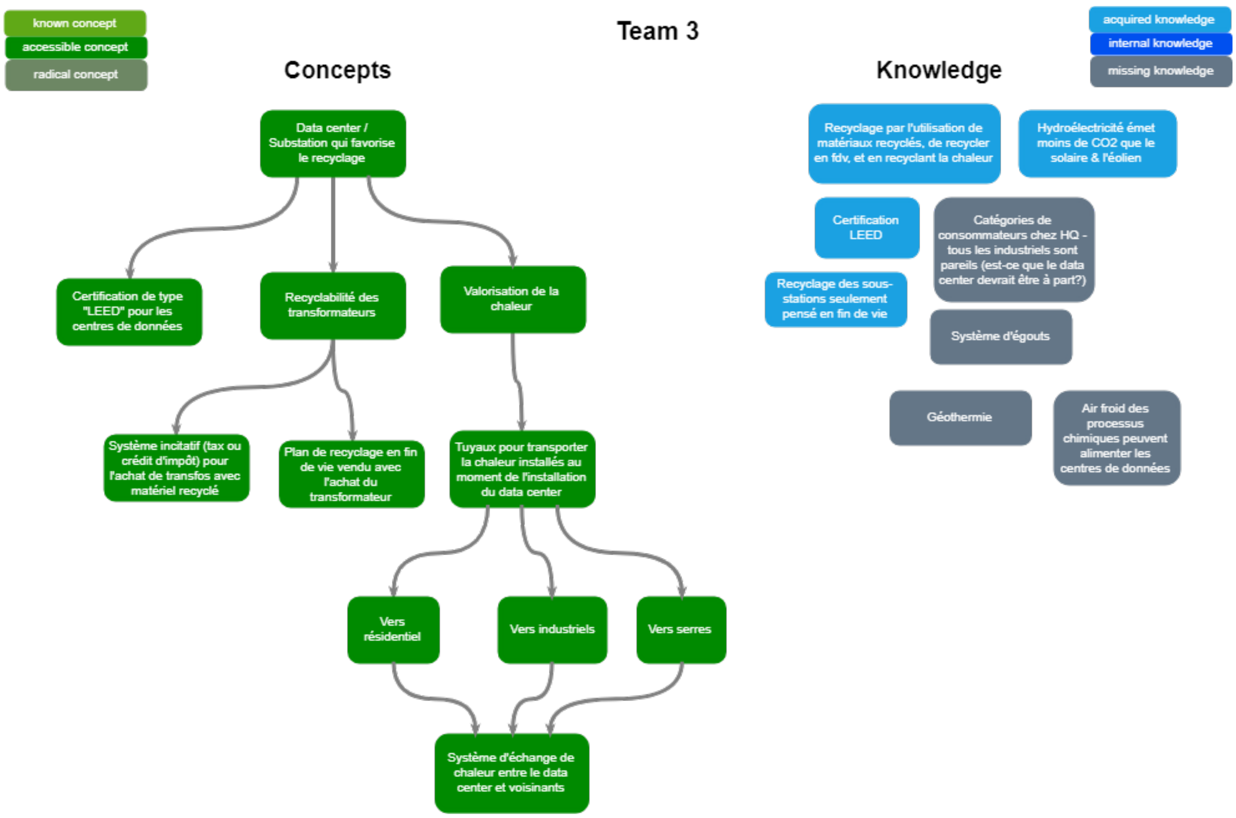

Figure A. 3 - Results of Team 3 Workshop 1 with C-K coding

This team was highly interdisciplinary, including two members from ACME, one from the utility and another from the data center. The problem they chose to work on was to design a "Data center / substation to favour recycling". This problem is abstract enough to enable radical ideas yet constrained enough to guide the discussion and brainstorming. The first set of ideas they had was around recycling heat. Again, this is not a radical concept because there are examples of pilot projects doing this already in industry, and other teams came up with the same idea. The second branch of ideas was in recycling transformers, where they thought of changing the business model of the transformer and exploring incentive policies to favor recycling in the industry. These are two accessible ideas that would add great value to ACME. The final branch was to create a standard for the data center, inspired by LEED. This is also an accessible idea for a data center, who would need to collaborate with LEED certification professionals and architects to explore this concept further.

Table A. 4 - V2OR analysis of results from team 3 in workshop 1

Variety	Good
Originality	All concepts proposed were accessible, but none were radical.
Value	Identified new actors to collaborate with such as industrial ecology experts, recycling experts, LEED building experts and governments to explore recycling policy incentives
Robustness	Good. The potential for valorizing the energy is higher in a dense, minimal urban context.

The ACME participants interviewed afterwards felt that this workshop went well. They felt creative and felt comfortable imagining new concepts for the substation and data center. Overall the team dynamic was respectful and constructive.

Of the introductory material presented before the workshop, this team seemed to have fixated on the energy losses present in both the substation and the data center LCAs, as well as the impact of the materials in the substation. They were, however, able to break out of the dominant design of both the substation and the data center and did not fixate too closely on the information presented at the beginning. The problem they chose was outside of the expertise of all participants which allowed them to explore the unknown in a safe manner.

A.1.2.4 Team 4: Local environment

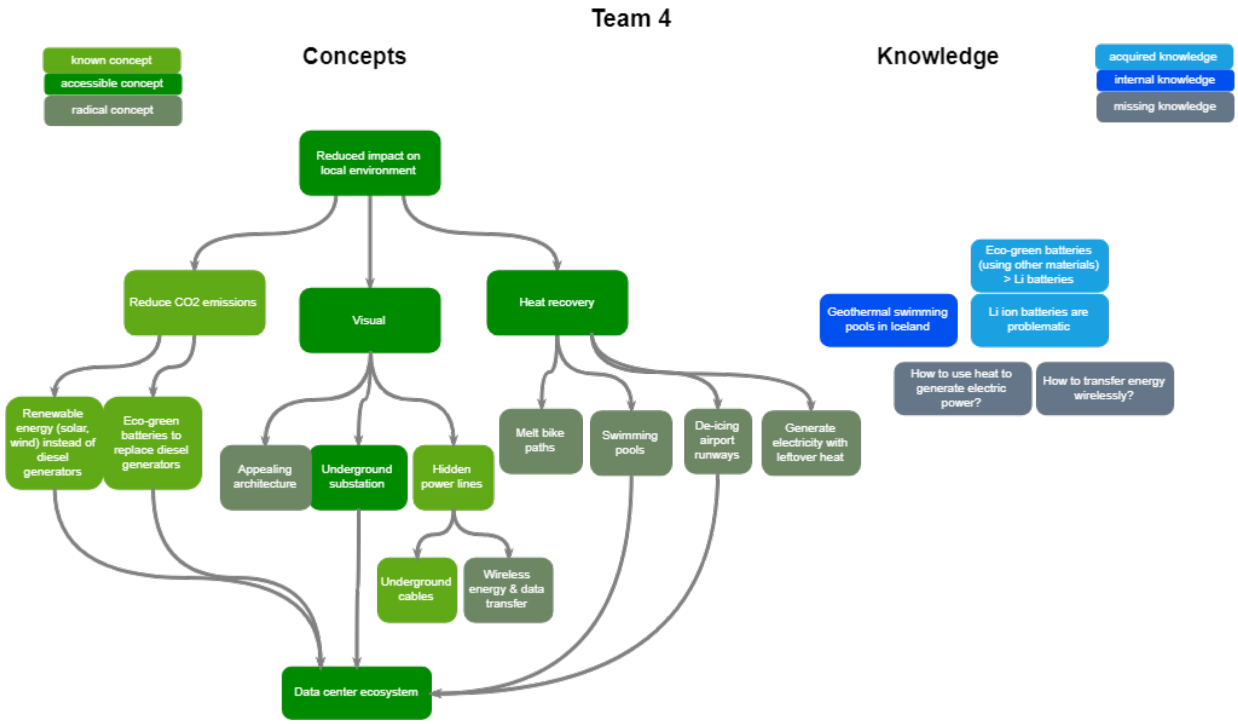

Figure A. 4- Results of Team 4 Workshop 1 with C-K coding

Though this team did not have any external participants, the roles and expertise each participant brought to the table were very diverse. One manager, one engineer, one supply chain manager and one Environment manager, all from ACME, decided to work on the problem of “Reduced impact on local environment” of both the substation and the data center. The first branch in their reasoning was to reduce CO2 emissions through renewables and replacing back-up generators of the data center with batteries, which represents a well-known concept in rule-based eco-design. The second branch, dealing with the visual impact of the combined system, was more divergent from ACME’s and the data center’s normal design criteria and priorities. The idea of “appealing architecture” was quite radical but the team did not pursue it further. They also branched into a discussion of hidden power lines, a known concept in industry, which triggered a radical idea: that of wireless energy and data transfer. However, they stopped pursuing this idea since it was so radical they were missing a lot of knowledge to explore further. The underground substation is an accessible concept because there are examples of it in the T&D industry, yet it is not something with which ACME Canada has experience.

Finally, the “heat recovery” branch led to the most radical ideas. Though heat recovery is not necessarily a radical idea (two other teams thought of the same idea and pilot projects exist in industry), they went further in imagining possible uses for the heat such as bike paths, swimming pools and airport runways which qualify as an exploratory definition of the concept.

Table A. 5 - V2OR analysis of results from team 4 in workshop 1

Variety	Good
Originality	Very good. Wireless energy and data transfer idea is very radical and provocative concept.
Value	Identified missing knowledge in the “wireless” space – would need to partner with scientists or researchers who are involved in this topic. Also identified the need for new partnerships in aesthetic or visual design of the substation.
Robustness	Good.

The employees interviewed afterwards felt like they were being creative in this workshop. They broke out of the dominant design and dug deep to find crazy ideas to put on the table. This showed that they were comfortable exploring the concept space and felt safe to do so in the workshop environment. The team dynamic was respectful and allowed for everyone to share equally in participation.

A.2 Workshop 2: Prospective innovation for sustainable design

A.2.1 Workshop design

The second workshop used strategic foresight methodology to project the participants to the year 2040, enabling them to de-fix from their present constraints. After projecting themselves to imagine the future market for data center energy needs in 2040, they were asked to back-cast to today, and to come up with a series of steps to achieve their desired vision of the future.

The 2040 strategic foresight scenarios present a different starting point than Workshop 1. We imposed four different frames suggesting the multifunctionality of the substation-data center ecosystem, each one revisiting the identity of the substation and the data center. These scenarios were the stimulating starting point for ideation.

Table A. 6 - Summary of workshop 2

Introductory Presentations **(K-phase)**	**Idea-generation Exercise** **(C-phase)**	**Casting**
• Industrial ecology • Product service systems • Blockchain • Warm-up exercise (Le cadavre exquis) Four 2040 scenarios on the integration of Substations and Data Centers (See **Error! Reference source not found.**)	Putting yourself in the context of one of four 2040 scenarios, what is the sustainable substation-data center ecosystem of the future? • Debate the scenario • Brainstorm solutions • Rapid prototype • Present to the room	Data center (2) Utility (2) ACME (11) • Engineers • Managers • Environment • Sales & Marketing • Supply chain CIRAIG (2) ------------- Total: 17

After several presentations to establish the context and offer new knowledge to the participants, a creativity warm-up exercise was introduced to encourage bisociation and prepare for the following more serious exercise.

The group was divided in four, and each group worked with one of the scenarios shown in **Error! Reference source not found.**.

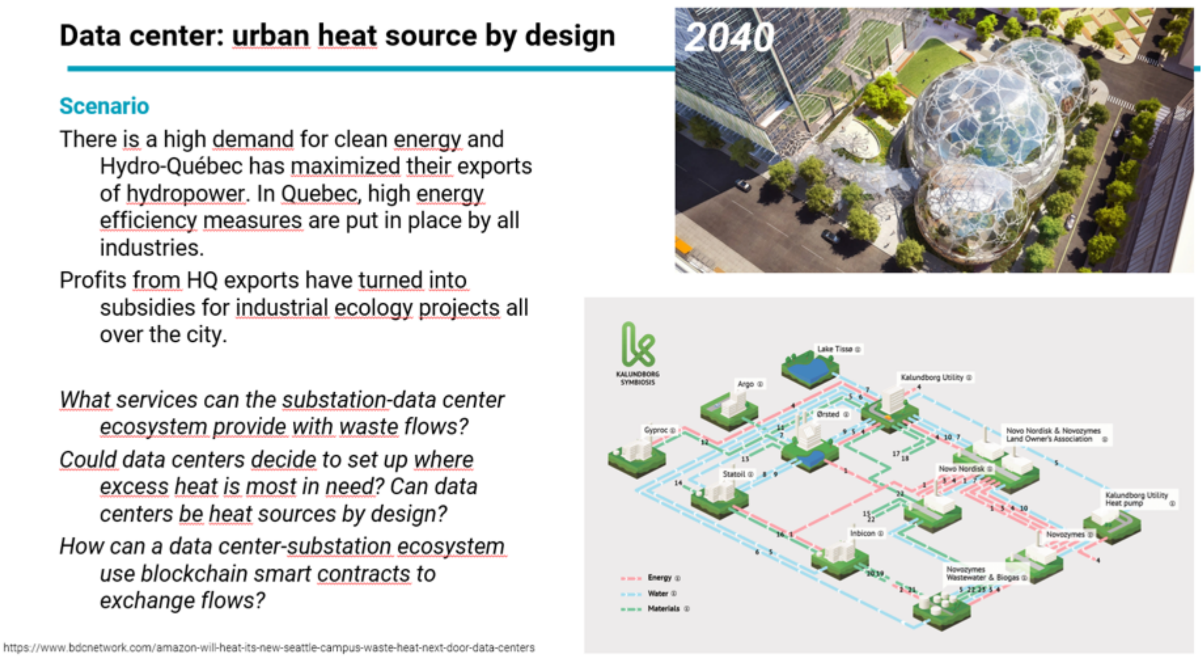

Figure A. 5

Figure A. 6

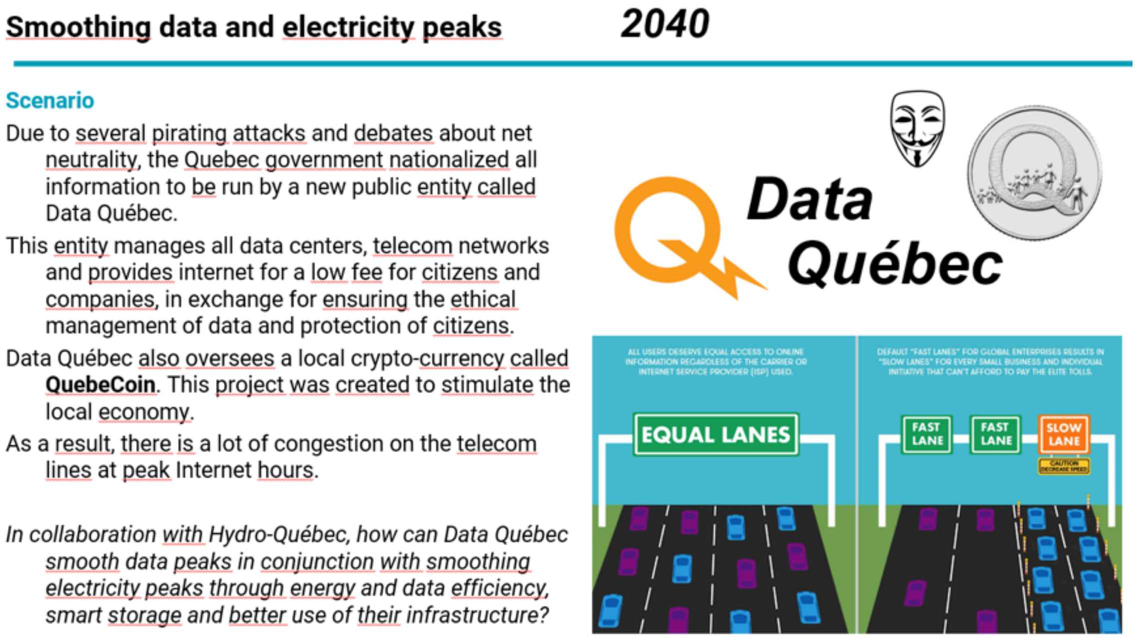

Figure A. 7

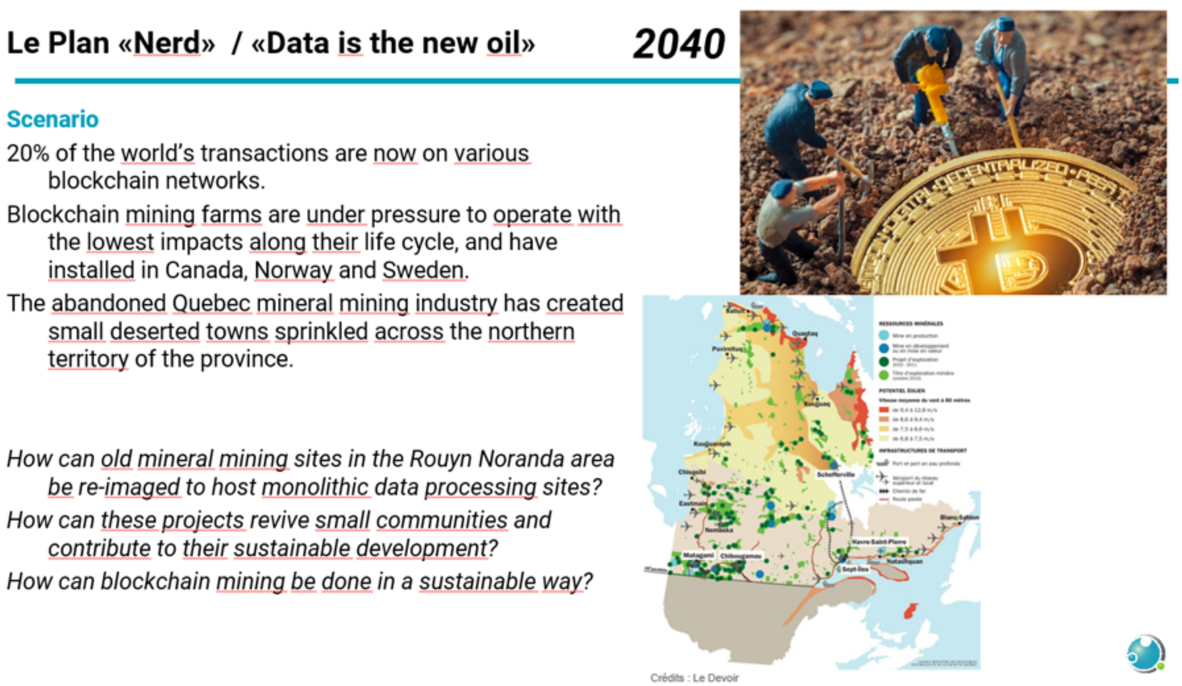

Figure A. 8

A.2.2 Workshop results

A.2.2.1 Team 1 – Industrial Ecology

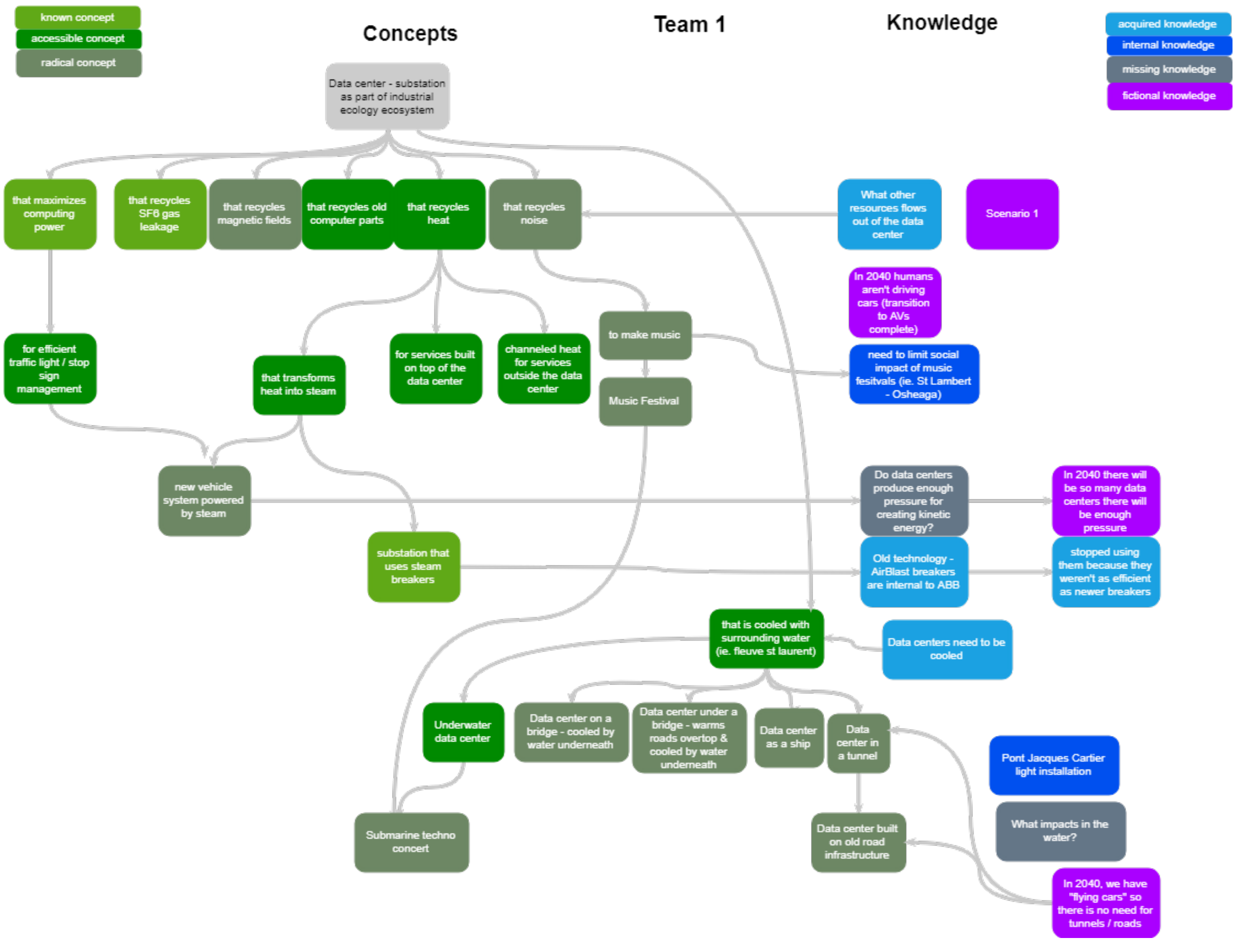

Figure A. 9 - Results of Team 1 Workshop 2 with C-K coding

This team had moderate interdisciplinarity, composed of three ACME engineers and one environmental expert from the CIRAIG. They worked with the Industrial Ecology scenario. Whereas this subject was considerably discussed in the first workshop, very quickly the team was stumped, recognizing their fixation on the ideas from Workshop 1. They listed all the flows leaving the substation-data center ecosystem and tried to imagine uses for repurposing them. Using reflexivity, the team was able to overcome this fixation hurdle a quarter way into the workshop. They accessed some expansive examples such as traffic and transportation – what could this possibly have to do with substations and data centers? This topic interestingly triggered ideas such as repurposing bridges and tunnels in which to install data centers. A crazy idea led to a more realistic concept. Though they based their reasoning on unrealistic fictional knowledge that there "would only be flying cars" in 2040, the team still managed to revive their creativity after they were "stuck-in-a-rut".

Table A. 7 - V2OR analysis of results from team 1 in workshop 2

Variety	High. Exhaustive exploration of all resource and energy flows.
Originality	Very high.
Value	Imposed fictional knowledge to continue their exploration in the concept space. Identified lots of missing knowledge and potential actors with whom to collaborate.
Robustness	Low. The ideas were very provocative and exotic but were not very realistic. Highly dependent on the fictional context they created.

The ACME participants interviewed after the workshop felt they were very creative in this workshop and seemed to be proud of overcoming their fixation. The engineers however, felt more comfortable in the LCA-driven workshop because they felt as though their expertise had brought more value. In this workshop the unknown was so hypothetical that they were playing more than being realistic. This playfulness was uncomfortable for some, though the exercise was a success. The presence of one external participant with three ACME engineers who speak the same language forced the engineers to explain their reasoning in layman's terms so that the external participant could understand. This shows they created a safe teamwork climate for everyone. This team laughed a lot and were very encouraging. They frequently affirmed each other's ideas. The external participant was able to bring to the table some ideas that provoked the engineers as well, such as the idea of recycling electromagnetic radiation, or noise, which were outside of the dominant design of the substation. The engineers ruled out the magnetism idea, saying that the field would not be strong enough in a substation, but built on the noise idea and together they came up with a very radical concept of creating a music festival inspired by the noise.

A.2.2.2 Team 2 – Cultural experience in limited space

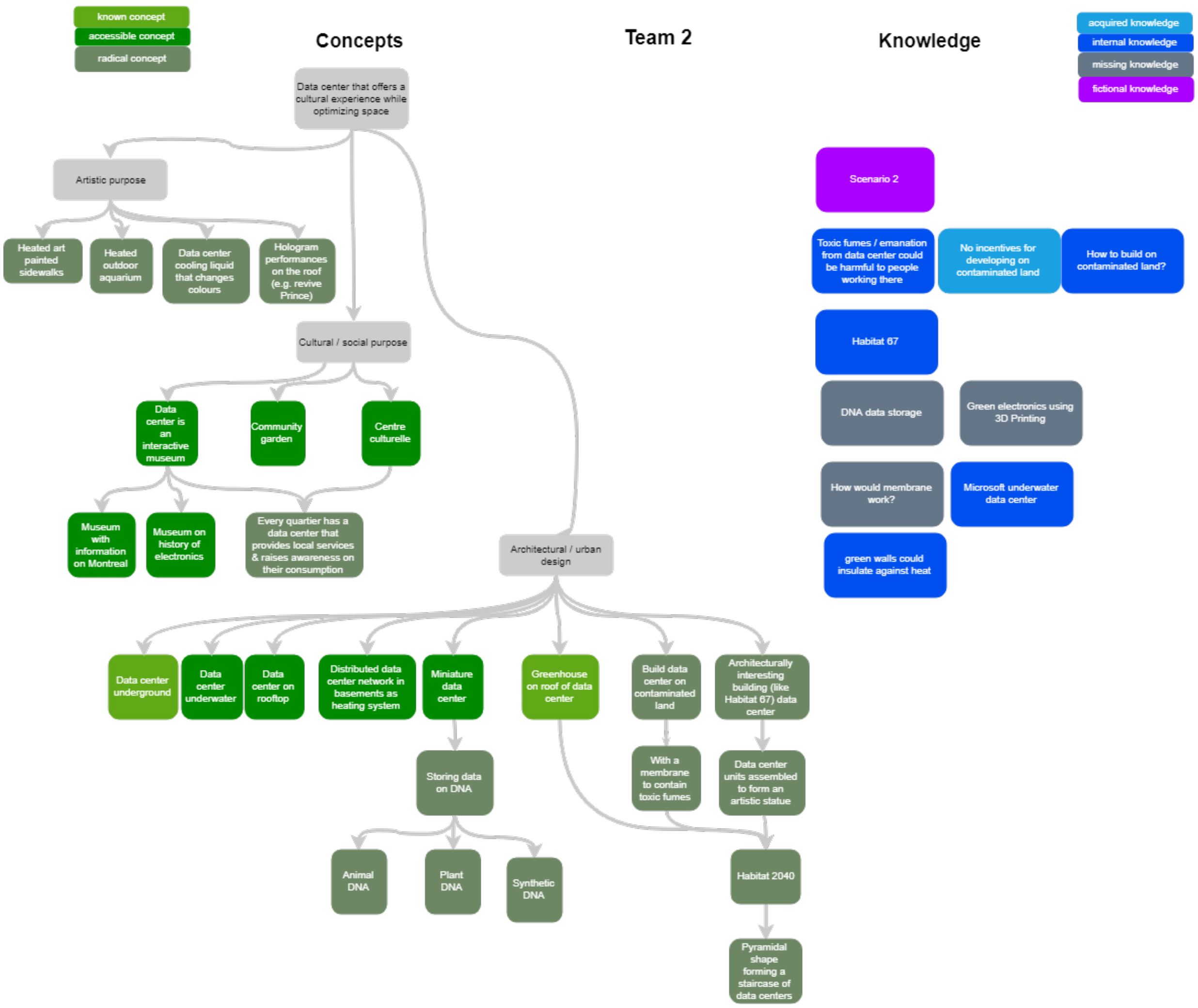

Figure A. 10 - Results of Team 2 Workshop 2 with C-K coding

This team was highly interdisciplinary, with two representatives from ACME (one engineer and one environment manager), one representative from the utility and one sustainability consultant. They worked with the foresight scenario of a data center that offers a cultural experience while optimizing space. The team did not categorize the ideas by themselves, so we assigned three main categories to the types of ideas they explored in Figure A. 10. The first branch is an artistic purpose of the substation-data center ecosystem. Some «crazy concepts» were evoked by the teams such as using the excess heat for an aquarium or changing colours on a sidewalk. Though these artistic ideas emerged and were quite far removed from the expertise of those around the table, they did not have an element that created substantial value for ACME. The second branch they explored is a cultural or social purpose for the data center / substation ecosystem. Here the ideas ranged from creating a museum to a community garden to a local data center that provides incentives for communities for saving energy. This last idea was very radical and had a lot of potential value but was not further explored by the team. The final branch explored is an architectural concept for the substation-data center ecosystem. The team imagined many new functions of the data center and substation by repurposing the exterior with plants, building the system on contaminated land and containing the contamination with a membrane. They also explored the notion of miniaturizing the substation and the data center, from which emerged the radical concept of storing data on DNA.

Table A. 8 - V2OR analysis of results from team 2 in workshop 2

Variety	High.
Originality	High. Many radical concepts such as Storing data on DNA, Building the data center on contaminated land, “Habitat 2040”, and all concepts related to turning the data center into an artistic installation.
Value	High. Identified lots of missing knowledge and new partnerships, yet did not add any fictional knowledge to complement the scenario given to them.
Robustness	Good.

The participants interviewed afterwards felt safe exploring concepts but felt that their exploration was too surreal. They interpreted the creativity exercise as jumping as far outside the box as possible but did not try to come back in to a more realistic proposition at the end. Their very radical, crazy ideas could have triggered a “back-to-reality” concept but instead left them frustrated with the overly creative process. The team dynamic was very positive, and everyone worked well together.

A.2.2.3 Team 3 – Data Quebec

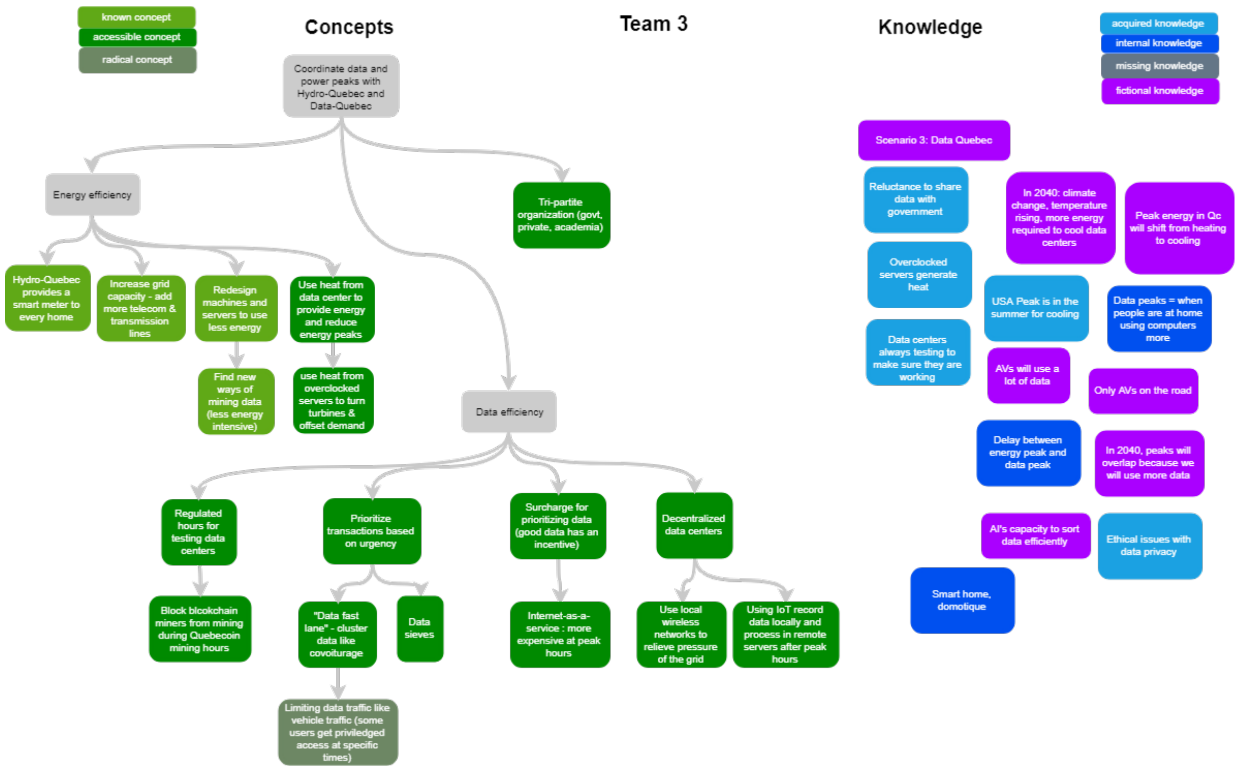

Figure A. 11 - Results of Team 3 Workshop 2 with C-K coding

This team was composed of two data center participants, two ACME participants (one HSE Manager and one Supply Chain Manager) and were facilitated by one of the researchers leading this project. The facilitator helped them to organize their thoughts and was better able to lead the discussion, and reformulate the concepts put forth by the participants. The foresight scenario they worked with was to "Coordinate data and power peaks", in a future where data management was nationalized. Their reasoning begins with some known concepts on the left, relating to energy efficiency measures. One accessible branch emerged: to use the heat from the data center to provide energy and turn turbines for electricity-generation (a recurring concept in most teams in both workshops). The second branch in their reasoning we labeled as "Data efficiency". Since half the actors around the table were from the data center industry and the other half from ACME (though none from ACME engineers nor technical experts) it made sense that the discussion centered mostly around data efficiency measures.

The first concept branch stemming from "Data Efficiency" is to regulate hours for running tests on data centers. This concept qualifies as accessible because it isn't currently done. The second is to prioritize transactions based on urgency with analogies like data “sieves” or imagining data in “traffic lanes” with priority for certain data types. This was the most radical concept the team came up with, though it was suggested in the introductory scenario (See Figure A. 11).

The final two concepts they imagined for “data efficiency” were to surcharge consumers for using data at peak hours, like peak energy pricing structures, and to have decentralized data centers, where data is processed locally instead of sent to a server at peak hours. These are all accessible concepts since they represent recent and upcoming software advancements.

The team was fixated on prioritizing data or giving ranks to different types of data and were able to use reflexivity to also discuss the ethical issues implicated in this kind of approach.

Table A. 9 - V2OR analysis of results from team 3 in workshop 2

Variety	Good
Originality	Good. One radical idea and many accessible concepts.
Value	Good. Added fictional knowledge to the scenario presented. Identified missing knowledge of partnerships in smart homes.
Robustness	Low.

The group dynamic was positive and created a safe space for exploration. The participants were comfortable being creative in the concept space and the facilitator was able to encourage their reflection on what missing knowledge they would need to complete their ideas.

A.2.2.4 Team 4 – Revitalize northern mining towns with data

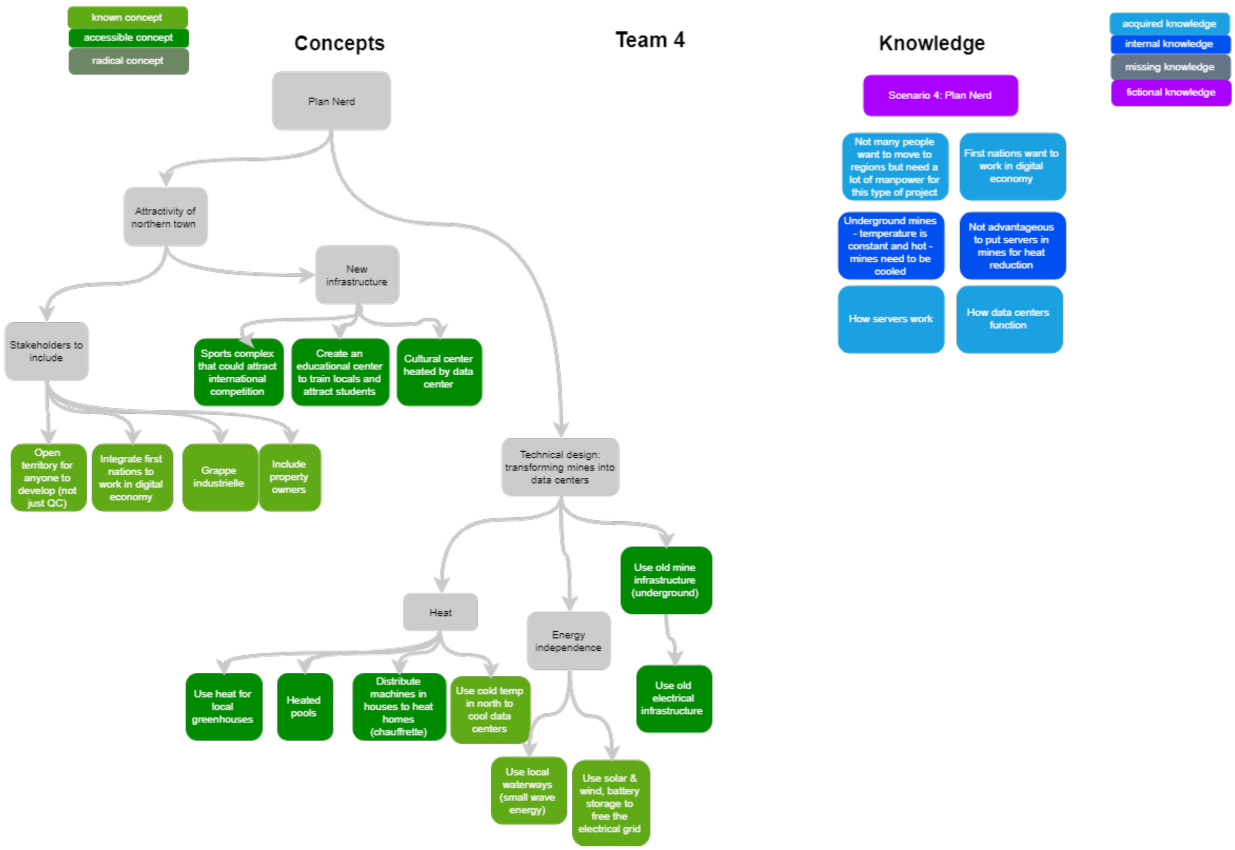

Figure A. 12 - Results of Team 4 Workshop 2 with C-K coding

This team was composed of three ACME participants (two project managers and one salesperson) and one utility participant who leads the strategic initiative for data centers at that utility. Their brainstorming session began with ideas from the ACME participants on how to make the northern towns more attractive, by adding sports complexes and increasing community infrastructure. The utility participant, who is an expert in the field and has already explored a similar pilot project, was however convinced that the desirability for these projects in Northern towns was already set in stone. The conversation then moved towards technical feasibility. The idea of recycling the heat of the data centers or blockchain mining facilities, and the idea of abstracting the data center as a distributed heater in residential homes came up again. The team talked about energy generation to make the fictional town run on renewables, a quite well-known concept and representative of rule-based eco-design. They reflected briefly on using old infrastructure, however, they were not able to get very far in these concepts because the utility participant disqualified them almost immediately. He repeatedly judged ideas with his knowledge of their technical feasibility. For example, one participant suggested exploring the idea of putting the data center underground in an old underground mine, but the utility participant said it would not work because the temperature is too high in the mine. Another participant wanted to explore working together with First Nations and building a community around the new data infrastructure that would be built, but the utility participant said he already had their buy-in from his experience visiting a town for his pilot project. Though his insights were valuable, the strong judgement on the ideas of others led to diminished creativity of the group. They did not feel comfortable exploring the concept space because there was someone present who would immediately judge their ideas. Instead, the conversation quickly shifted towards the technical details of blockchain mining infrastructure, and at least half of the brainstorming session was occupied by the utility participant sharing their knowledge on technology. Instead of being imaginative and brainstorming, the result of their work are steps to make the utility participant's vision a reality, which resembles a more rule-based design way of thinking.

Table A. 10 – V2OR analysis of results from team 4 in workshop 2

Variety	Low.
Originality	Good.
Value	Low.
Robustness	Low.

The group dynamic of this team was quite negative compared to the seven other teams in both workshops of this project. In interviews afterwards, the ACME participants admitted to feeling inadequate, like they had "failed" the exercise, and like their ideas were invalidated. The working environment was almost hostile, since the utility participant frequently said the word "No" and was quick to explain his vision of the world instead of acknowledging the value of a non-expert point of view, which has a lot of value in this kind of exercise. All ACME participants in this team preferred the first workshop because they did not feel they had succeeded in being creative in Workshop 2, due to the overbearing presence of the "expert".

This observed fixation and refusal to explore could be linked to a "diplomatic bias". Since a utility is the subject of this scenario, the one representative from the utility felt obliged to maintain a diplomatic discourse (and therefore quite uncreative) since he felt he had to represent his institution. It is not the foresight tool nor the co-design context that come into play on the fixation in this situation. The presence of an external expert may be positive if we are discussing what is internal to ACME, but here the opposite occurred with this “diplomatic bias”. The scenario placed the team on utility’s ground, which destabilized and subsequently blocked the utility participant’s creativity.

APPENDIX B – SOLVAY CASE STUDY

B.1 QUASAR

In this section we present the design and results of the eco-design workshops done for the Quasar project.

B.1.1 LCA-driven workshop

B.1.1.1 Workshop design with Sustainability-by-Design method

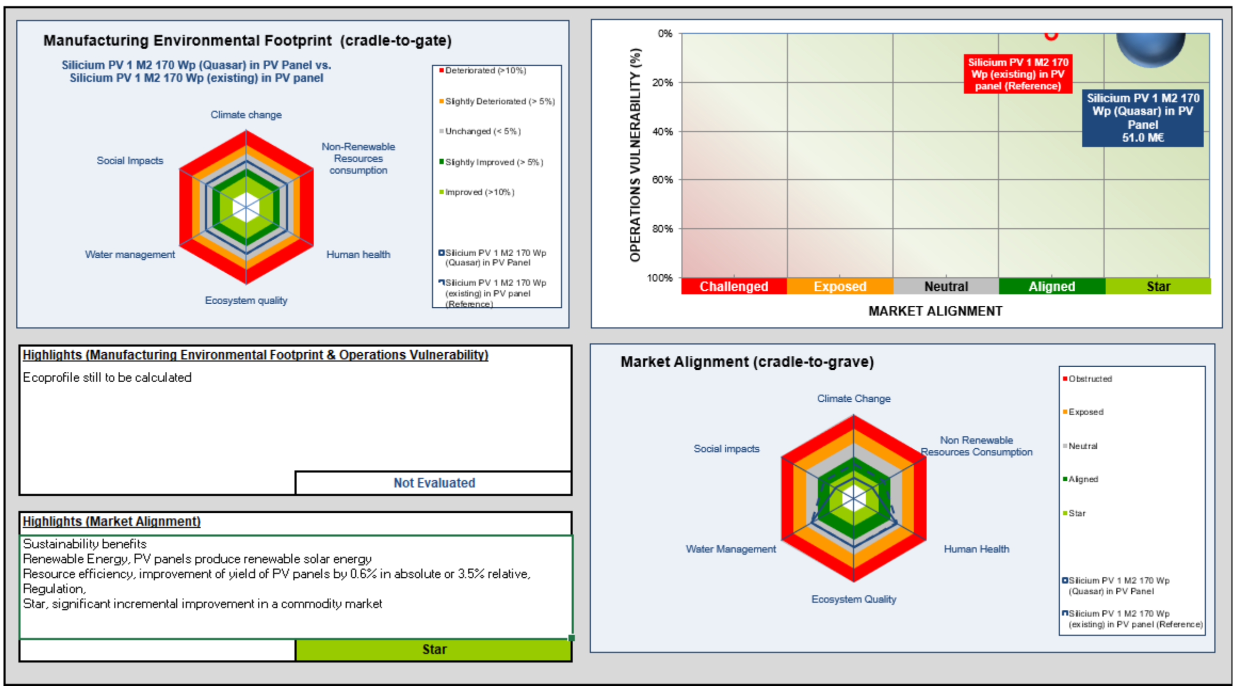

Figure B.1- Quasar SPM Results used as a starting point for LCA-driven eco-design workshop (Solvay, personal communication, June 2018)

The SPM positioning of Quasar shows that with the addition of this nanoparticle to solar panels, the sustainability market alignment of the solar panel increases, since it is expected to increase the efficiency of the solar panel.

The **reference product** that was chosen by the team was a state-of-the-art photovoltaic (PV) solar panel, whereas the target product was the same solar panel including the Quasar nanoparticle and increased energy efficiency (ie. more renewable energy can be produced with the same solar panel in the use phase with the addition of Quasar).

The **functional unit** chosen was 1MWh of energy, to compare the reference to the target product.

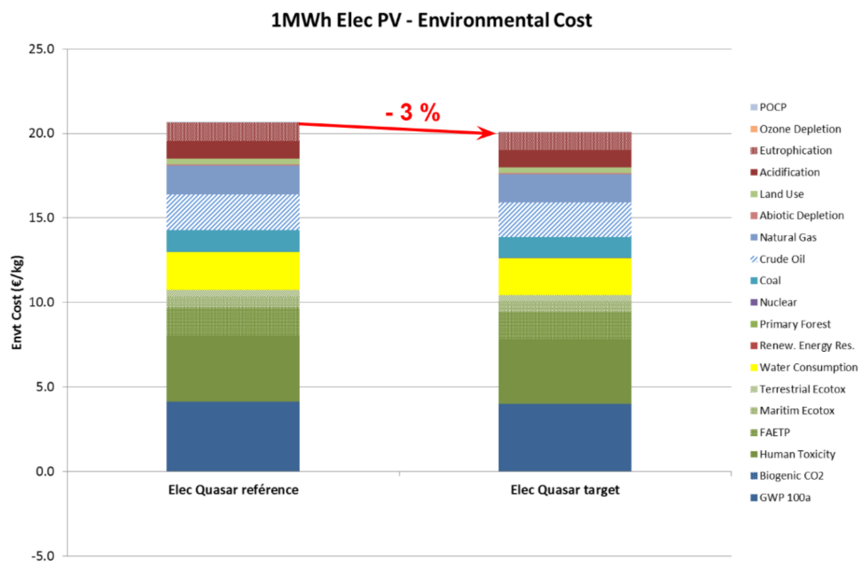

Figure B.2 - Quasar single-score LCA results used as a starting point for LCA-driven eco-design workshop (Solvay, personal communication, July 2018)

The LCA results show that the relative contribution of the Quasar nanoparticle is very minimal. The overall single score rating of the monetized impacts, a weighting that Solvay uses internally to compare all of its products, only reduces the impacts of the solar panel by 3% with the addition of the nanoparticles.

B.1.1.2 Workshop results

During the two-hour discussion prior to brainstorming, three major themes were discussed by the group: difficulty with uncertainty in the LCA, new market conditions, and political pressure that created an urge to re-center on the chemical process.

Step 1 : With a group brainstorm and based on the chemical process flow diagram (ie. only the manufacturing phase of Quasar), the group identified the environmental problems associated with six sustainability indicators on the SPM hexagon. The SPM diagram was drawn on a flip board.

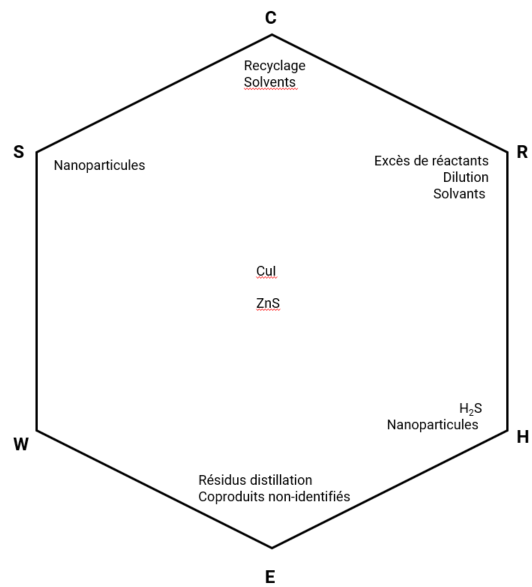

Figure B.3 – SPM diagram of environmental risks in the chemical process for Quasar, created during the LCA-driven eco-design workshop as a modified starting point

Step 2: The group was then encouraged to spend 10 minutes brainwriting (individual brainstorming) to find potential solutions to address the problems identified in Step 1. Each participant placed their proposed solution on the environmental problem they were addressing, ie. on a corner of the hexagon on the flip board.

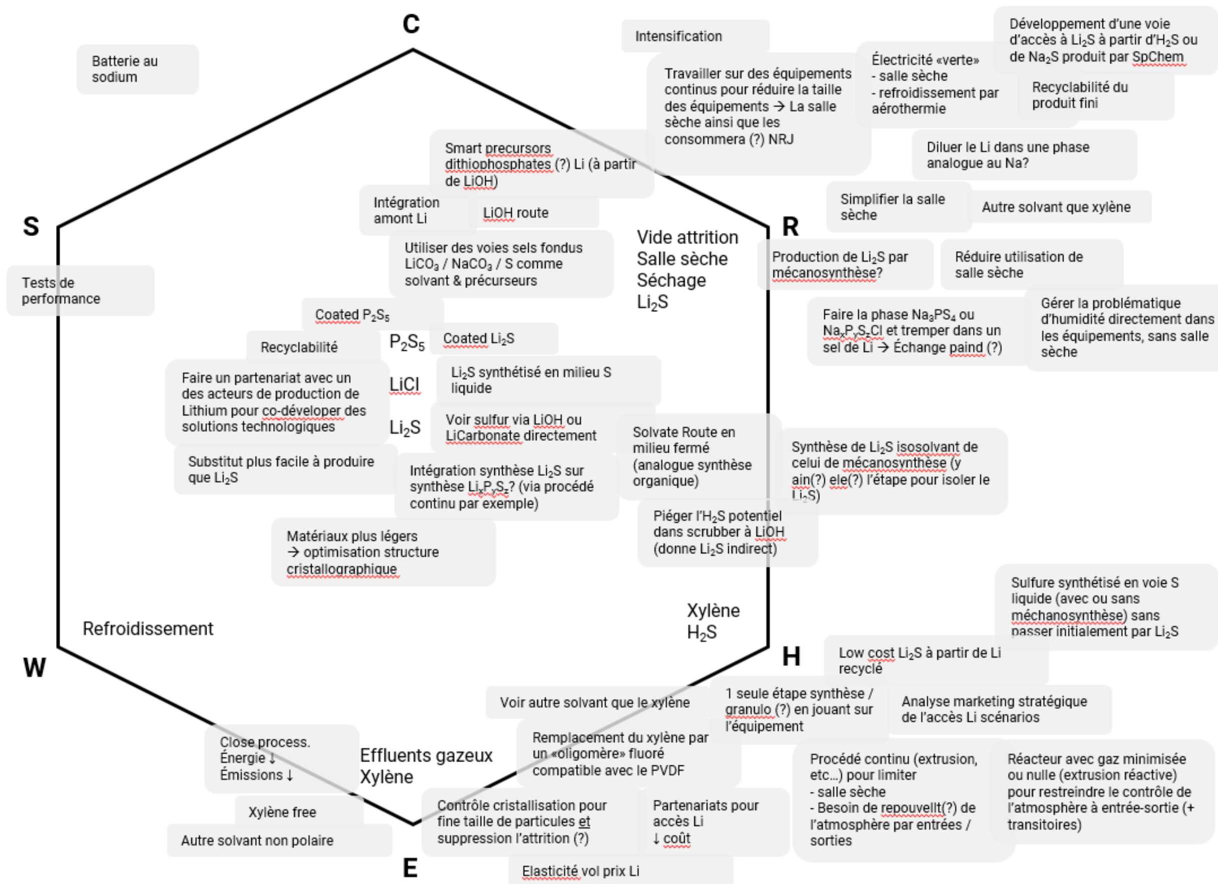

Figure B.4 - SPM diagram of environmental risks in the chemical process for Quasar, covered with post-its containing ideas to address each environmental risk

Step 3: The facilitator of the group then categorized the ideas and placed them on a graph indicating their perceived attractivity level and feasibility level for Solvay.

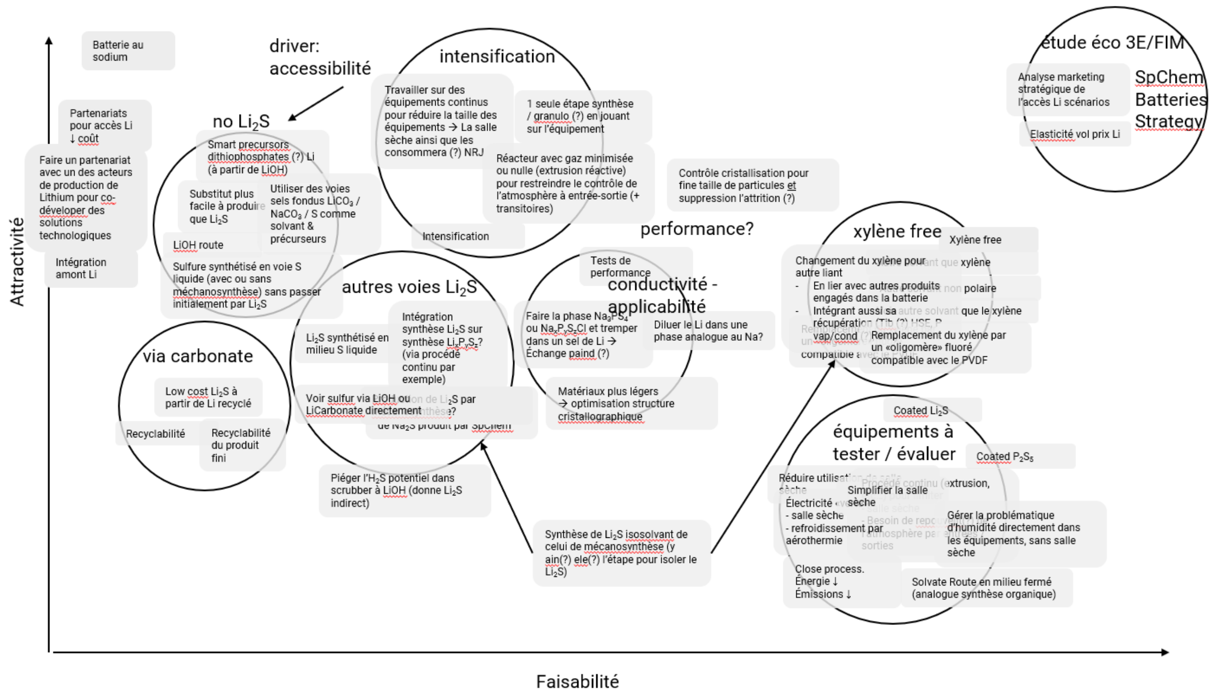

Figure B.5 – Quasar ideas classified in terms of attractivity and feasibility for Solvay, and grouped by overarching categories

11 - V2OR analysis of results from Quasar LCA-driven workshop

Variety	Mediocre
Originality	Low
Value	Low
Robustness	Low

B.1.2 Creativity-driven workshop

B.1.2.1 Workshop design with C-K Theory

For the creativity-driven workshop on the Quasar project, we used the C-K method. We began the workshop with presentations on innovative eco-design and the starting point for the activity. We did not want to leave the groups to work on an empty C-K diagram from scratch because it was their first time working with the method. Therefore, we started building the C-K tree for them, outlining the dominant design already mastered by Solvay, and suggesting different innovative pathways for eco-design. See Figure B.6 for the Pre-CK tree we formulated to trigger the creativity of participants during the workshop.

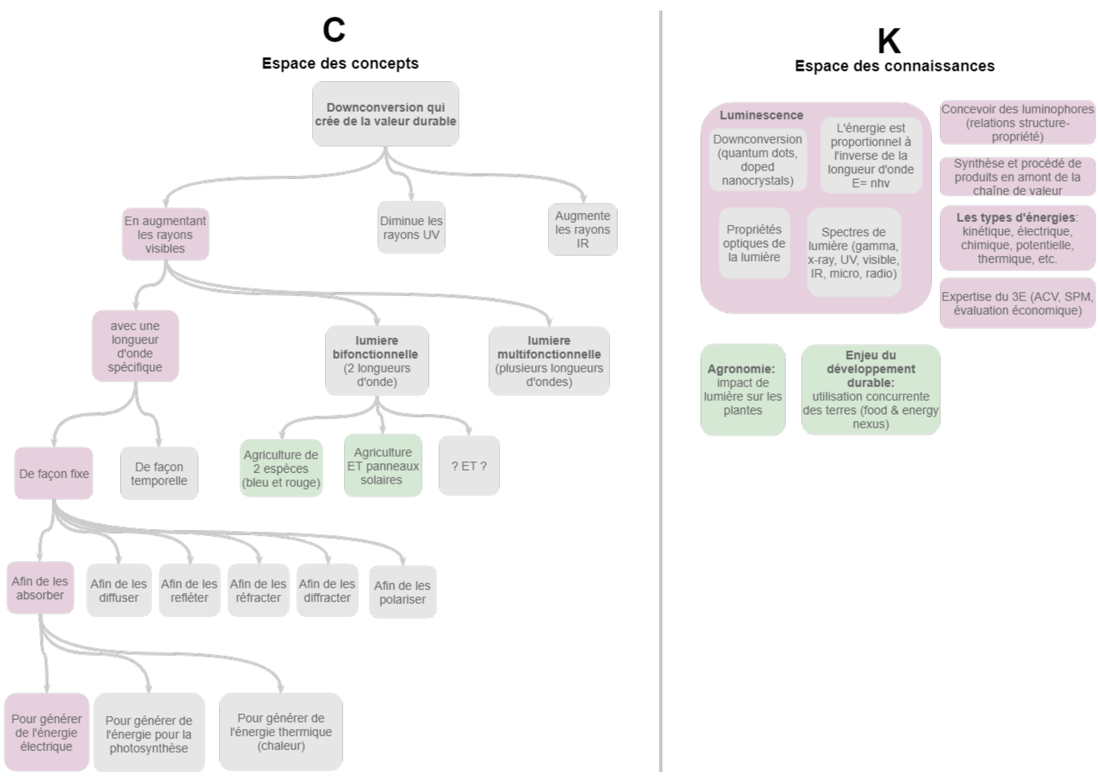

Figure B.6 - Quasar Pre-CK diagram used as a starting point for Creativity-driven workshop

By outlining the assumed functions of the downconversion nanoparticles, we were able to illustrate five properties that make up the dominant design, which can be played with to trigger creative ideas that challenge this dominant design. The first branch of the Concept tree therefore consisted of:

Downconversion particles that:

- increase visible rays
- with a specific wavelength
- at a fixed time
- in order to absorb the rays
- and convert them into electric energy.

We also illustrated the acquired knowledge-base that Solvay used to arrive at these properties and functions of downconverters. By introducing *new knowledge*, such as the sustainability debate on the rival uses of land for food and energy production, as well as the knowledge that might come from the agronomy world on the impact of light on plants, we were able to partition the Concept tree with suggestions for challenging the properties that make up the dominant design. For example :

- **why only** increase visible rays **when we can** decrease UV rays, or increase IR rays?
- **why only** with a specific wavelength **when we can** have bifunctional light, or multifunctional light?
- **why only** at a fixed time **when it can** change with time?
- **why only** in order to absorb the rays **when we can** reflect, refract, diffuse, diffract, polarise rays?
- **why only** convert them into electric energy **when we can** convert them to photosynthesis energy or thermal energy?

-

We asked the room to split into pairs or groups of three to work on this pre-CK tree to continue to identify new knowledge and add more partitions to the concept side. After one hour of brainstorming with the C-K method, the groups all shared their work with the rest of the room and the entire group shared their feedback.

During the final presentations, we asked the teams to reflect on the concepts that were most surprising to them, and the sustainability considerations they could identify in their final concepts.

B.1.2.2 Workshop results

B.1.2.2.1 Team 1

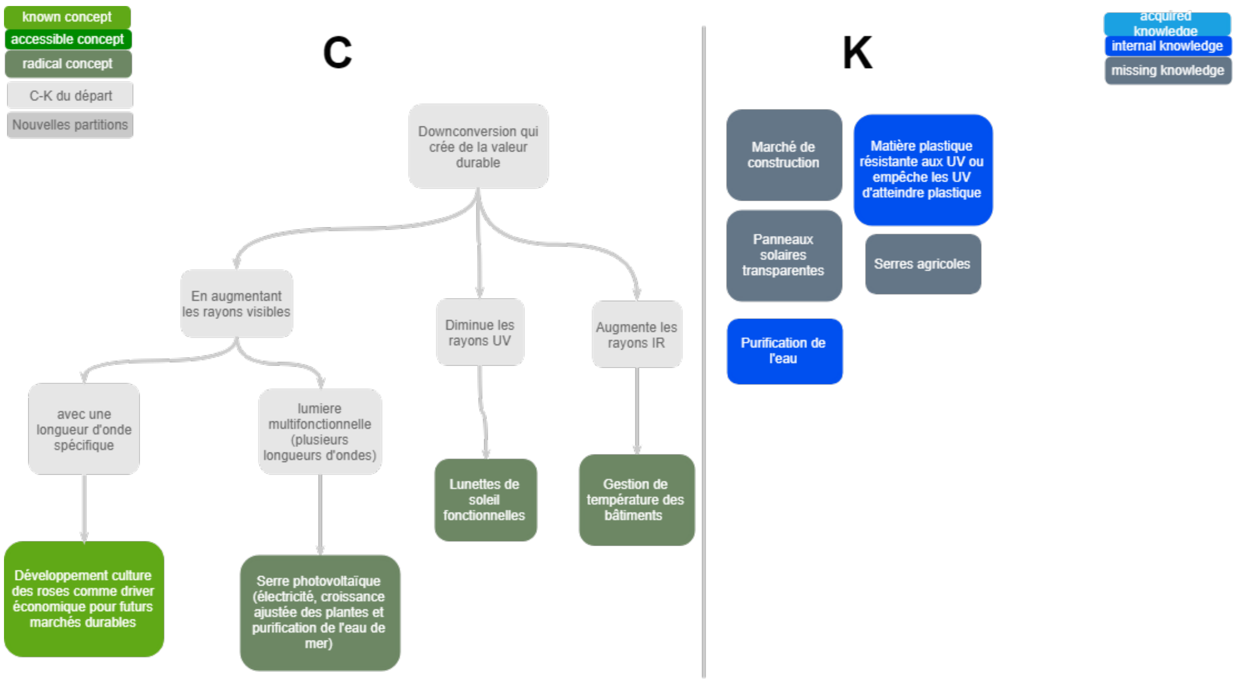

Figure B.7 - Results of Team 1 Workshop 2 with C-K coding

Table B. 1 - V2OR analysis of results from team 1 in workshop 2

Variety	Low.
Originality	Mediocre. Of their three “radical concepts” two were also addressed by the other groups. Only the sunglasses concept was unique to this team.
Value	Mediocre. Identified new value spaces for Solvay that were not considered until now: sunglasses and building /construction markets. However, they were fixated on the cultivation of roses (reappeared from the first workshop) as well as the bifunctionality of light which was presented as the creative trigger at the beginning of the workshop.
Robustness	Mediocre. The idea of “functional” sunglasses and heat management in buildings are quite vast and can be transposed to other markets.

B.1.2.2.2 Team 2

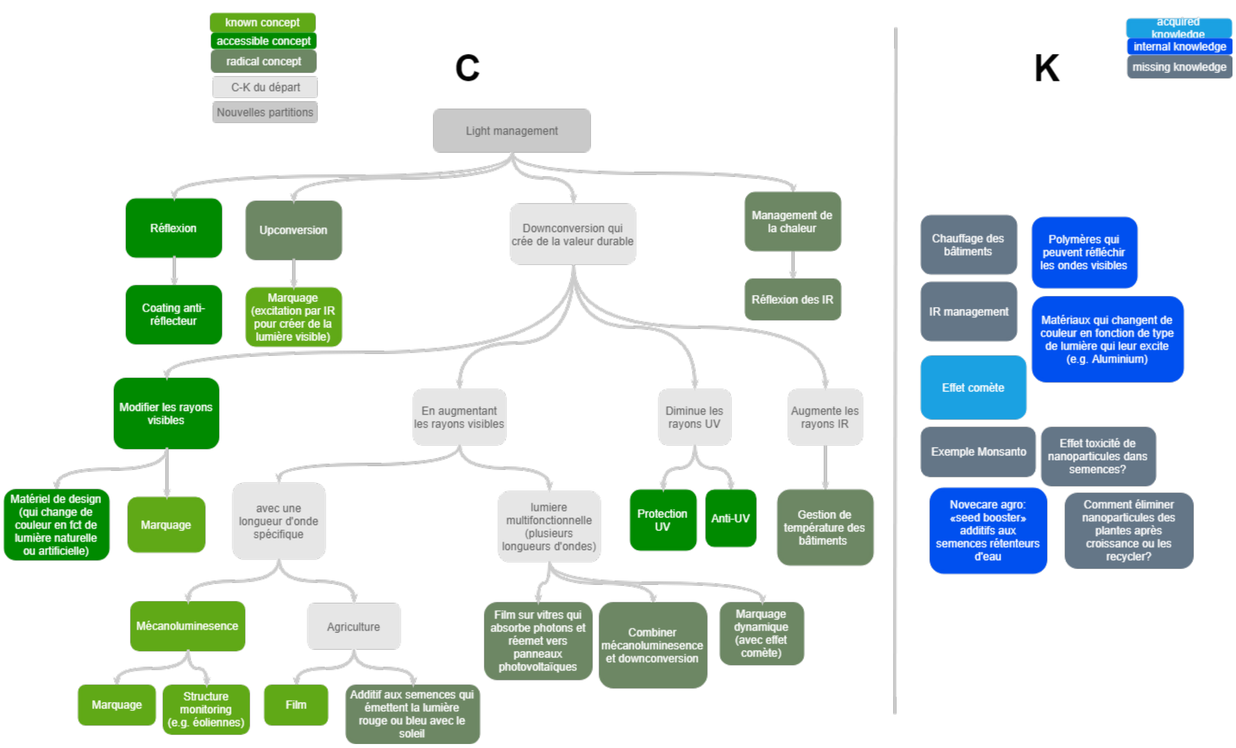

Figure B.8 - Results of Team 2 Workshop 2 with C-K coding

Table B. 2 - V2OR analysis of results from team 2 in workshop 2

Variety	Very high.
Originality	High. However somewhat fixated on the “marquage” idea. Created a new combination of “mecanoluminescence AND downconversion” which up until now were considered separate projects at Solvay.
Value	High. Recognized internal knowledge of the “comet effect” of the nanoparticles that could be useful for other applications. Identified new value spaces that required external knowledge such as agriculture, design, heat management, anti-reflective coatings.
Robustness	High.

B.1.2.2.3 Team 3

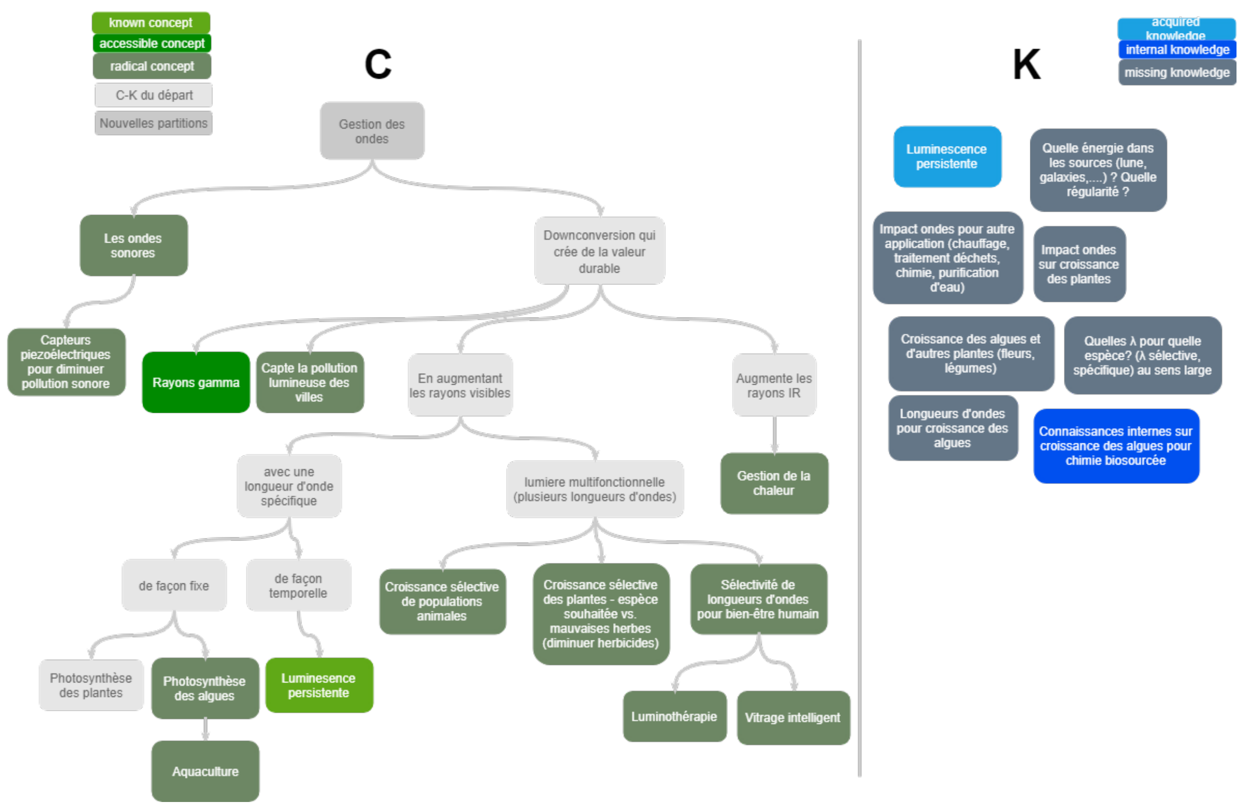

Figure B.9 - Results of Team 3 Workshop 2 with C-K coding

Table B. 3 - V2OR analysis of results from team 3 in workshop 2

Variety	Very high. Their exploration was vast and they explored many different pathways.
Originality	Very high. The majority of their concepts were highly original and were not found in other teams. The idea of managing sound waves, considering photosynthesis of algae, and a light-based pesticide or herbicide, luminotherapy were all unique to this team. However, smart windows and heat management, though original concepts, were also thought of by the other teams.
Value	Very high. Identified new value spaces such as exploring the management of sound, aquaculture, light-based herbicides and pesticides, and human well-being. They identified a lot of missing knowledge on the impact of certain wavelengths on living species.
Robustness	High.

B.1.2.2.4 Team 4

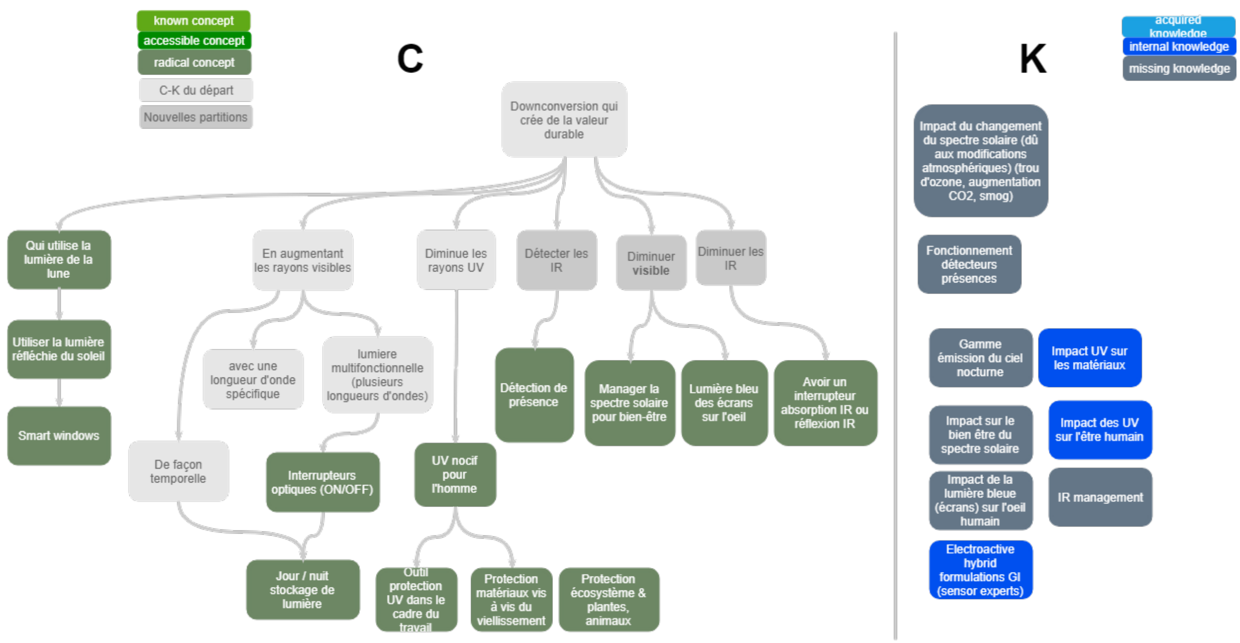

Figure B.10 - Results of Team 4 Workshop 2 with C-K coding

Table B. 4 – V2OR analysis of results from team 4 in workshop 2

Variety	High
Originality	Very high. Every single aspect they wrote down was original.
Value	High.
Robustness	High.

B.1.2.2.5 Team 5

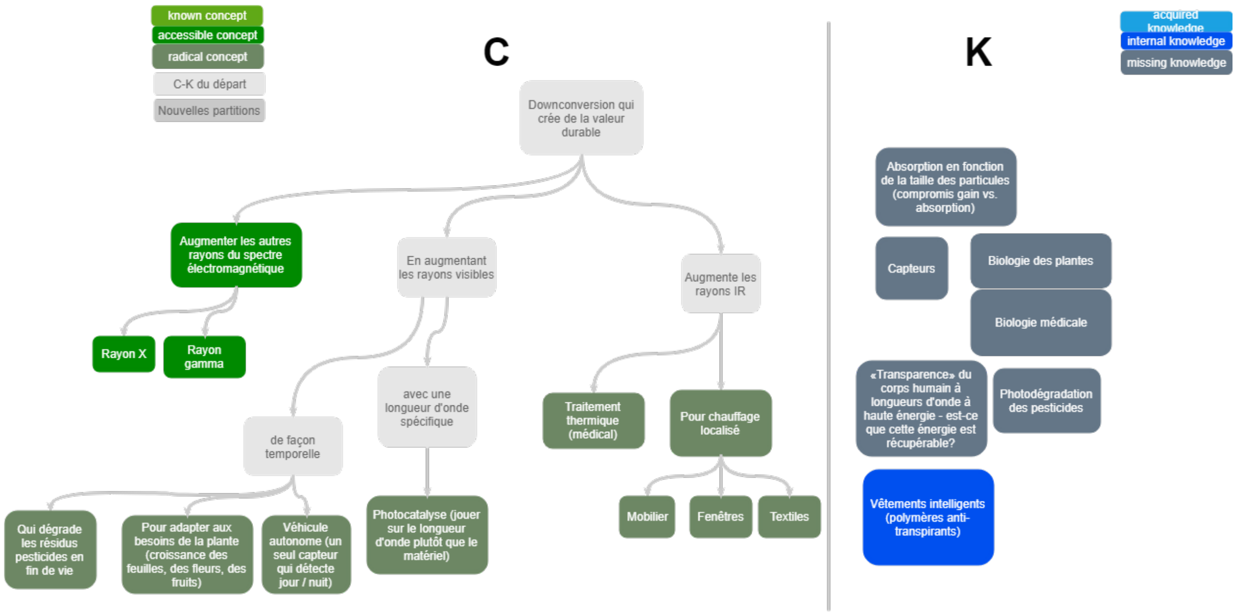

Figure B.11 – Results of Team 5 Workshop 2 with C-K coding

Table B. 5 - V2OR analysis of results from team 5 in workshop 2

Variety	High.
Originality	Very high. went further than other teams on the IR branch (where most others stopped at heat management, they had the "localized heat" idea and medical industry)
Value	High. new value spaces: chemistry, furniture, car manufacturers, agriculture, medical
Robustness	High.

B.2 SONIC

B.2.1 LCA-driven workshop

B.2.1.1 Workshop design with Sustainability-by-Design

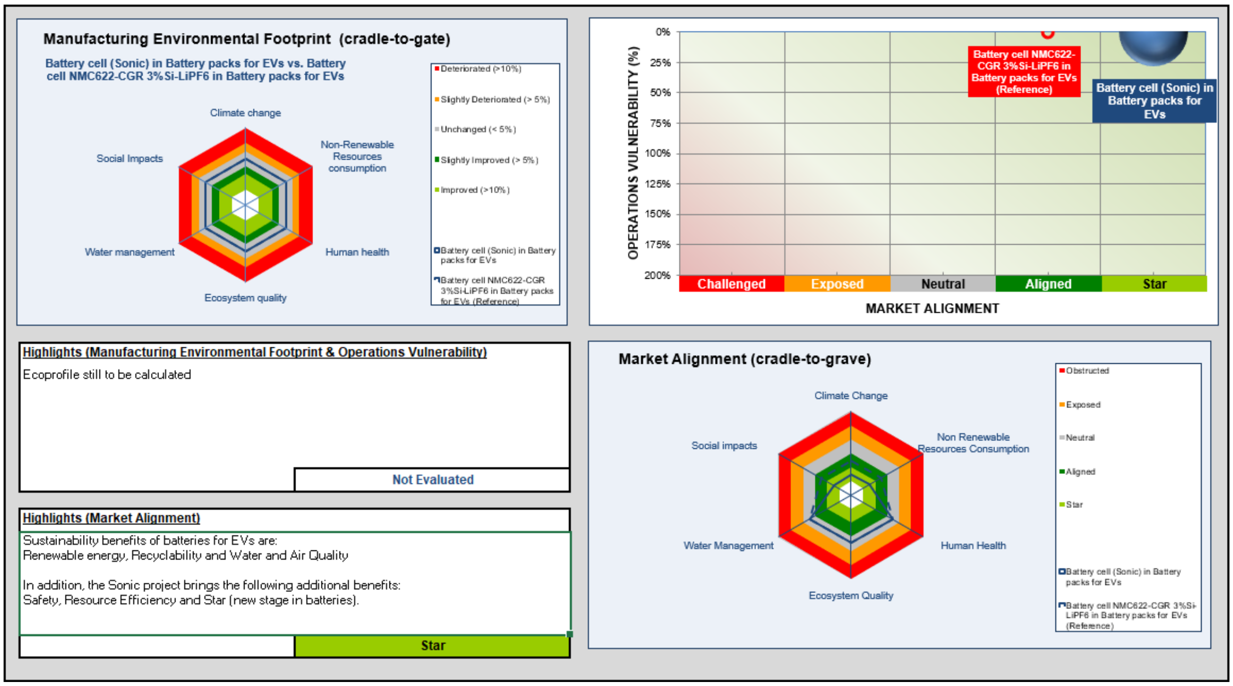

Figure B.12 - Sonic SPM results used as a starting point for LCA-driven eco-design workshop (Solvay, personal communication, June 2018)

The SPM positioning of Sonic shows that with the addition of the solid electrolyte, the battery's market alignment increases from the "Aligned" category to "Star" category. This is because the energy efficiency of the battery is said to increase, which has the potential to increase the amount of renewable energy stored on the grid.

The **reference product** chosen by the team was a state-of-the-art Lithium-ion battery cell, whereas the target product was the Li-ion cell including the solid electrolyte. The battery design changes with the addition of the solid electrolyte, so other aspects of the inventory were also modified to account for the addition of the Sonic product. The smallest system boundary that could compare the reference with the target was therefore the overall battery cell.

Two different **functional units** were chosen: “producing 1kg of battery cell”, and “storing / delivering 1 kWh”. The relationship between these two functional units is dependent on the energy density of the cell, (ie. how many MWh of energy can be produced with 1 kg of battery cell?) and is represented in MWh/kg. This parameter is not yet known and a hypothesis was made using technical assumptions from the Sonic team.

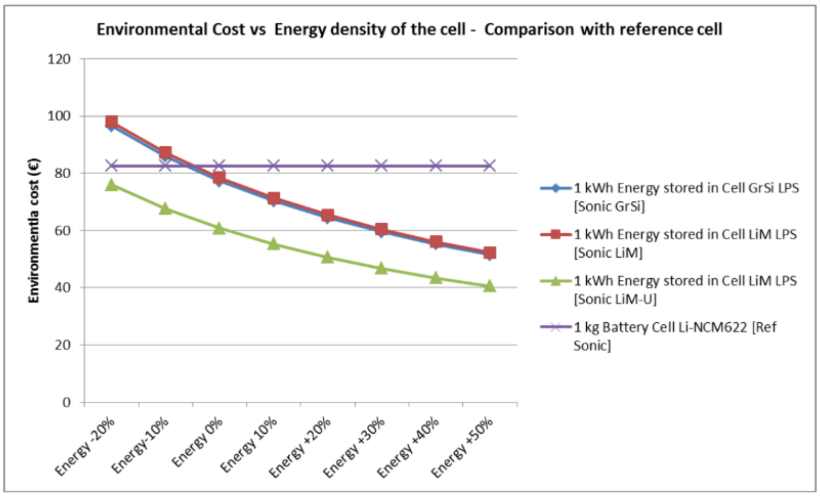

Figure B. 13 - Sonic LCA results used as a basis for LCA-driven eco-design workshop (Solvay, personal communication, June 2018)

The LCA results show that the overall contribution of the solid electrolyte relative to the battery cell is quite minimal, and dependent on the energy density of the cell. In Figure B. , a sensitivity analysis varying the energy density shows that the bigger the energy density (due to the addition of the Sonic solid electrolyte), the lower the single-score environmental profile of the entire battery, when compared to its reference.

B.2.1.2 Workshop results

During the two-hour discussion prior to brainstorming, two major themes were discussed by the group: difficulty with uncertainty in the LCA, unclear focus on life cycle approach and political pressure that created an urge to re-center on the chemical process.

Step 1 : With a group brainstorm and based on the chemical process flow diagram (ie. only the manufacturing phase of Sonic), the group identified the environmental problems associated with six sustainability indicators on the SPM hexagon. The SPM diagram was drawn on a flip board.

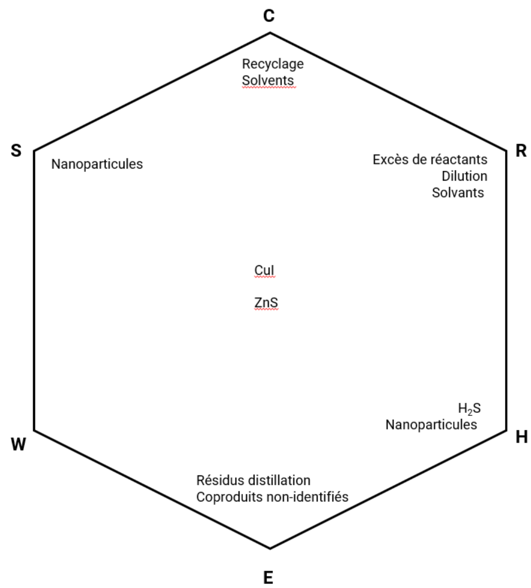

Figure B. 14 – Qualitative SPM assessment of Sonic during the LCA-driven workshop

Step 2: The group was then encouraged to spend 10 minutes brainwriting (individual brainstorming) to find potential solutions to address the problems identified in Step 1. Each participant placed their proposed solution on the environmental problem they were addressing, ie. on a corner of the hexagon on the flip board.

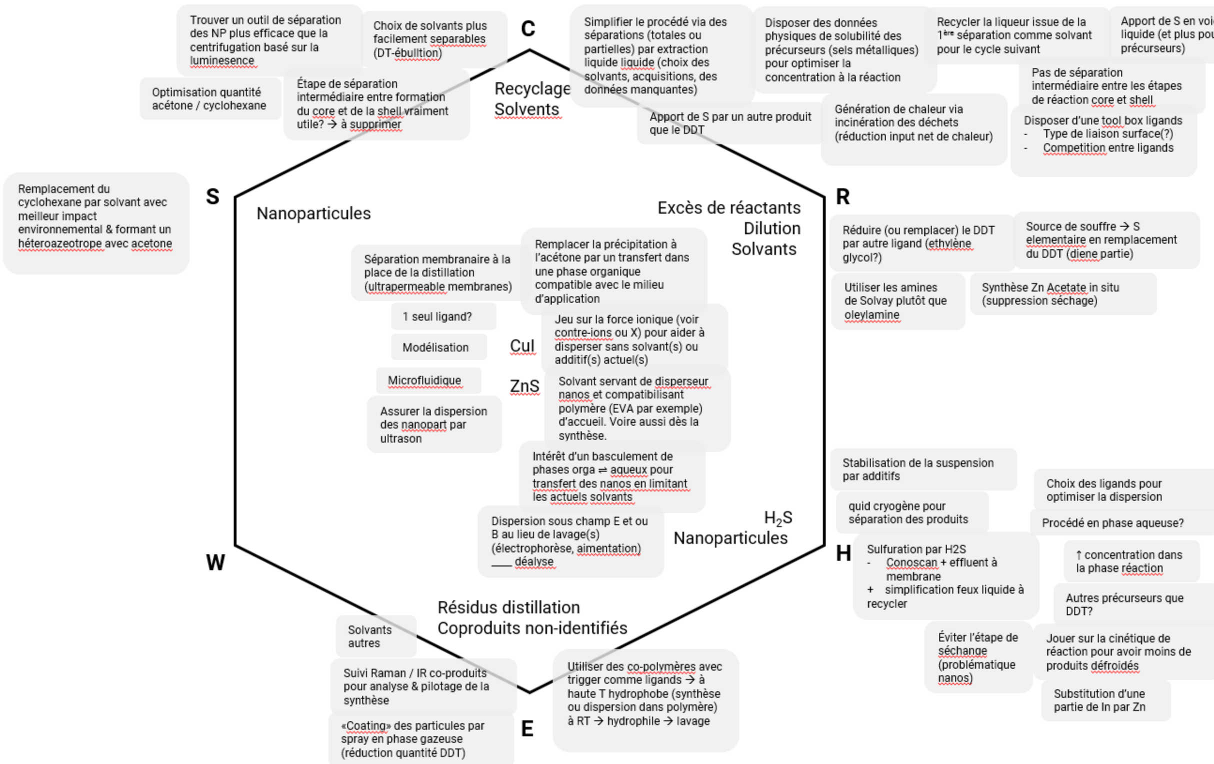

Figure B.15 – Brainstorming on the SPM hexagon during the Sonic LCA-driven workshop

Step 3: The facilitator of the group then categorized the ideas and placed them on a graph indicating their perceived attractivity level and feasibility level for Solvay.

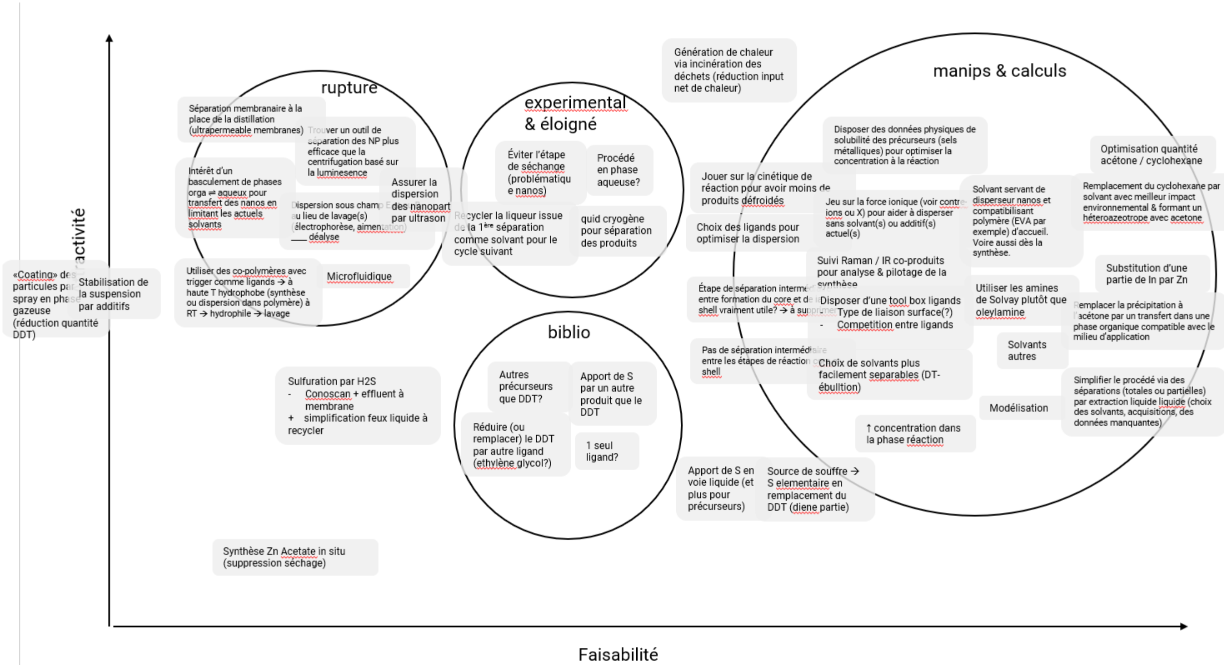

Figure B.16 – Ideas classified based on their feasibility and attractivity ratings during the Sonic LCA-driven workshop

Table B. 6 - V2OR analysis of results from Sonic LCA-driven workshop

Variety	Mediocre
Originality	Low
Value	Low
Robustness	Low

B.2.2 Creativity-driven workshop

B.2.2.1 Workshop design using Prospective Innovation

For the creativity-driven workshop on the Sonic project, we used the prospective innovation method. We began the workshop with presentations to contextualize the two foresight scenarios with which the group would be working with. The first presentation was on the importance of context when modeling the environmental impacts of electric vehicles. We also presented on circular economy and the trends in resource issues for batteries. After this contextualizing introduction, we introduced two foresight scenarios designed to project the teams in the year 2030. In Figure B.17 we show the scenarios that were presented for each group to work with.

The purpose of prospective innovation is to remove the group from their day-to-day issues and encourage exploration in a futuristic but realistic context. This method encourages a reflexion on what *could be* and what *should be* in the future, rather than only focusing on improving what *is*. Through foresight innovation, Solvay is empowered to imagine their desired future and are then encouraged to work towards this common vision by letting the foresight scenario dictate their strategic planning.

Figure B.17 - Sonic prospective innovation scenarios used as a starting point for creativity-driven eco-design workshop

We presented the scenarios as if they were excerpts from a newspaper in the year 2030, announcing a imagined achievement that Solvay might have made.

The first scenario is on circular economy, which we titled: "June 26, 2030: Solvay leads the first circularity loop of value creation for the solid electrolyte".

The second scenario is on smart mobility, which we titled: "June 26, 2030: Solvay, driving force behind new urban mobility thanks to its solid electrolyte".

The group divided into two working groups. The instructions were to begin with a divergence phase where they discussed the scenario, followed by a brainstorming session to imagine what new value spaces could arise from new technical specifications of the solid electrolyte in this scenario. We also asked them to reflect on potential business models. The divergence phase was followed by a convergence phase, where we asked the teams to use *backcasting* to specify the new design criteria they would need to develop today, as well as a new prioritisation of design criteria. They were also asked to identify new ecosystem actors that they would need to work together with to make their vision a reality, and the environmental benefits they foresaw with their proposition.

At the end of the session we asked each group to share their work, and allowed anyone to give feedback and build on their ideas.

B.2.2.2 Workshop results

B.2.2.2.1 Team 1 – Circular economy

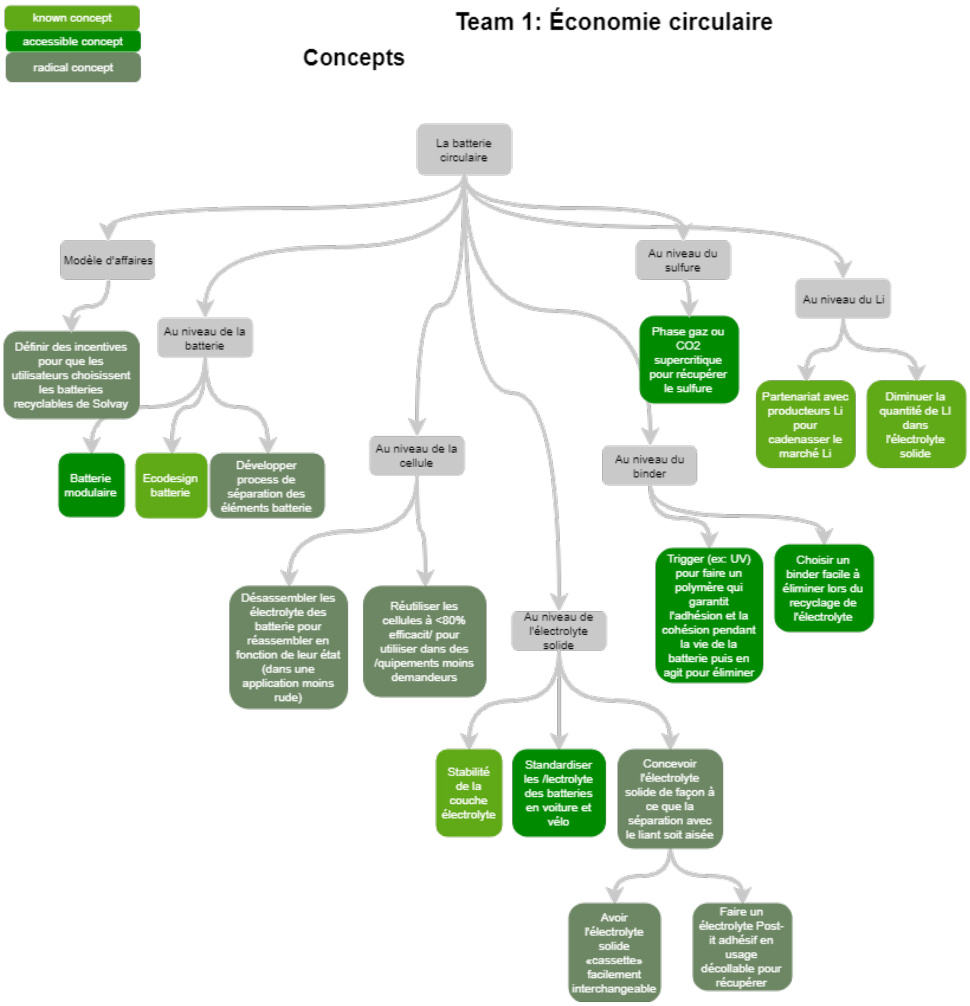

Figure B.18 - Results of Team 1 Workshop 2 with C-K coding

Table B. 7 - V2OR analysis of results from team 1 in workshop 2

Variety	High. An exhaustive exploration of the possible circularity loops of the battery.
Originality	High. Half the ideas were radical whereas the other half remained accessible and in the dominant design.
Value	Low. Did not explore potential **new** partnerships or new knowledge necessary to realize their concepts. Remained essentially in the concept space (also because the exercise did not ask them to access missing knowledge). Identified internal knowledge to activate (Novecare business unit) and Lithium producers as being important, but this is an obvious choice for a partnership – there was no element of "surprise" in the value spaces they explored.
Robustness	Low. Very specific exploration of the solid electrolyte.

B.2.2.2.2 Team 2 – Smart mobility

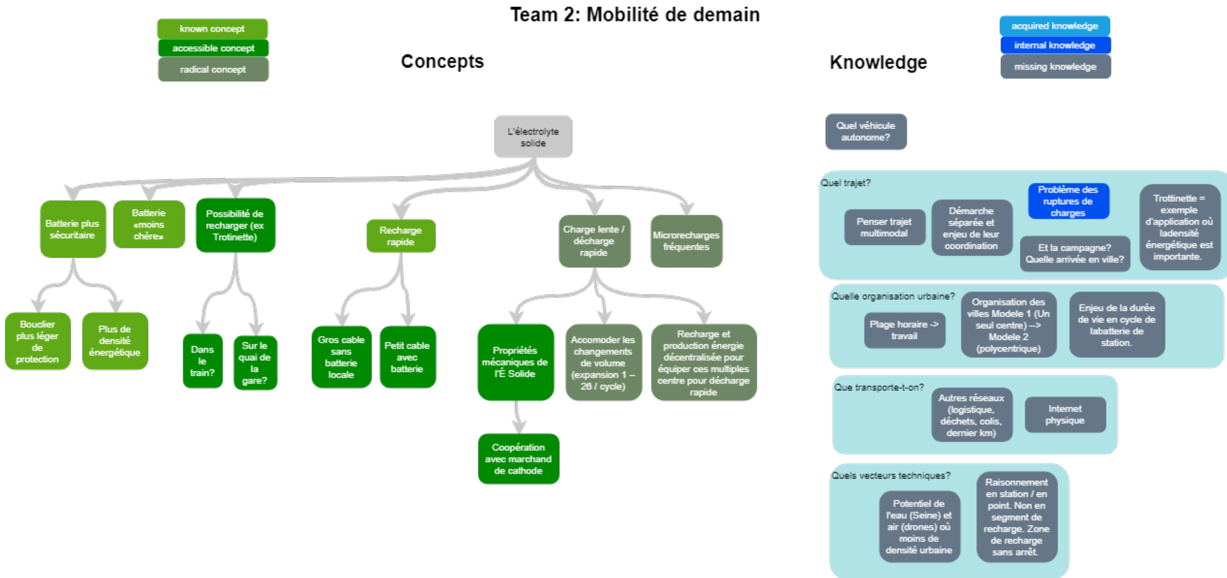

Figure B. 19 - Results of Team 2 Workshop 2 with C-K coding

Table B. 8 - V2OR analysis of results from team 2 in workshop 2

Variety	High.
Originality	Mediocre. Only radically challenged one aspect of the dominant design : reversing the paradigm of fast-charging to slow-charging stationary batteries with quick de-charging (in a world where cars have fast micro-recharges)
Value	High. High exploration of knowledge space.
Robustness	Low.

APPENDIX C – SEMI-STRUCTURED INTERVIEW QUESTIONNAIRES

PRE-INTERVIEW QUESTIONS:

1) Role in company and professional background
   a) How many years in the company?
   b) What type of projects do you work on?
   c) How did you come about joining this team at X company?
   d) Career path until today
   e) What do you find motivating in your job? What do you find to be un-motivating?
2) Familiarity with creativity and innovation
   a) Do you think you are creative in your job?
   b) Would you say you have a lot of freedom to come up with new ideas or are you constrained to doing your day to day job?
   c) Have you ever had any formal creativity and innovation training? (learning to brainstorm, learning to bisociate, use of heuristics, etc.) What was your experience like?
   d) How does company X encourage creativity?
   e) Any experience with innovation projects?
   f) How is the manager there for their team? How are they supportive of creativity?
3) Sustainability
   a) What does sustainability mean to company X?
   b) What does sustainability mean to you personally?
   c) What is your experience with the environment team at X company?
   d) How often do you encounter environmental issues in your day to day job?

POST-INTERVIEW QUESTIONS

1) Describe your experience in the two workshops
   a) Which workshop did you prefer and why?
   b) In which workshop did you feel more creative and why?
   c) What did you enjoy the most? What frustrated you the most?
2) Creativity
   a) Did you feel like you were able to de-fix in the workshops?
   b) What did you learn about your own creativity?
3) Team dynamic
   a) How do you feel you participated compared to the other sin the group?
   b) Did you feel at ease to participate and share your ideas?
   c) How was the team dynamic in general?
4) Continuity

a) Do you think you can use these methods elsewhere in your day-to-day job? In your team? Elsewhere in the company?