Processus et méthodes pour la résolution de problèmes interdisciplinaires et pour l'intégration de technologies dans des Domaines fortement Basés sur la Connaissance

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Processes and Methods for Interdisciplinary Problem Solving and Technology Integration in Knowledge-Intensive Domains

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T H È S E

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Synopsis

The present economy has been described as being essentially knowledge-based. In fact, most of the major technological challenges of the 21st century like e.g., reduction of greenhouse gas emission and sustainable energy supply, but also the bio- and nano-technological revolutions require intensified collaboration between different disciplines of engineering design as well as of natural science. Unfortunately, today, there is a lack of approaches which are appropriate to help interdisciplinary groups tackle problems which result from an increased technology convergence.
The present Ph.D. research tries to provide some insight into the questions of

- How to provide methodological support for creative problem solving in interdisciplinary groups composed of engineers and natural scientists?
- How to support the process of the integration of a technology originating from a knowledge-intensive domain in order to solve a given design problem?

In order to answer those questions, an extensive literature review was carried out. It analyzed relevant aspects on several systemic levels (global, institutional, team-, individual and problem-perspective) covering the scientific fields of (engineering) design science, psychology and cognitive science as well as organization science.
The literature review shed light on several aspects which are important for creative ideation in multidisciplinary teams, like e.g. shared mental models, some kinds of dialectical reasoning as well as the introduction and management of conflicts. Further, the review also allowed highlighting problems related to both the activity as such as well as to the methods which seem a priori appropriate to support it. In this regard, incoherent interpretive schemes and majority influence are examples for the former and performance drawbacks as well as learning difficulties associated to hierarchical methodologies are instances of the latter.
Based on the results of previous research activities, three hypotheses were developed and subsequently tested in an experiment and an industrial case study.

Experiment:

The performed experiment inquired into the impact of disciplinary group composition (H1) as well as of the applied methodology (H2) on the creative group problem solving process and its outcomes.
In a laboratory experiment 60 participants, 45 with a life science background and 15 with a mechanical engineering background were trained either in instances of intuitive approaches (Brainstorming, Mind Mapping) or in analytical, hierarchical methodology (TRIZ/USIT). Then, they had to solve an ill-defined medical problem in either mono- or multidisciplinary teams. The creative process as well as the output was documented using questionnaires and documentation sheets. Further the output was evaluated quantitatively by two domain experts before it was categorized qualitatively.
Statistical analyses (ANOVA, Correlation parameters and Attraction rates), to a certain extent, support H1 and H2. More importantly however, the experiment shows differences related to method performance in general and as a function of disciplinary group composition in particular.

Industrial case study:

In the industrial case study it was investigated whether concepts of TRIZ and its derivatives ((A/U)SIT) are appropriate to provide support for the process of technology integration before the background of an industrial NCD/NPPD process (H3).
In order to test this hypothesis, based on the findings of the previously performed experiment, a meta-model was developed which allows the identification and resolution of problems which

typically appear during the integration of a specific technology into a given application. The meta-model incorporates two of the most important concepts of TRIZ, and is sought to facilitate creative problem solving attempts in both mono- and multidisciplinary teams. However, it is sufficiently open to allow pragmatic problem solving strategies or the integration of well-established methods of several domains.

The mentioned meta-model was tested during an industrial NCD study in the roller bearing industry at which a specific customer value should be satisfied using one or several knowledge-intensive technologies. After the case study, the involved engineers were asked to compare the applied model and the associated technology integration process with existing approaches used in the company.

The results of the experiment point toward somewhat superior performance of the presented meta-model in terms of knowledge transfer-related and idea quality-related criteria. However, required resources for process conduction and necessary effort for the learning of the approach were considered comparable to existing approaches. Unfortunately, the limited number of participants of the industrial application does not all allow to draw statistically valid conclusions with regard to H3.

The present Ph.D. work contributes to the understanding of creative problem solving in interdisciplinary groups in general and related to technology integration in particular. Especially the comparison of more pragmatic intuitive methods with more hierarchical analytical approaches depending on disciplinary group composition provided relevant insight for R&D processes. The developed meta-model for the identification and resolution of technology integration problems will be further tested in industrial settings like pharmaceutical industry and in academic approaches like bio-inspired design.

1 Context of Presented Work

The present subsection of this report puts the presented Ph.D. research into an academic context. Based on that context, a research question is identified, which is subsequently positioned within three fields of research as well as against research work of the CPI Laboratory. The subsection concludes by outlining the structure of the remaining document.

1.1 Introduction

The Ph.D. research which is presented in this dissertation relates to collaborative technology-related problem solving in the context of New Concept Development (NCD) as well as New Product or Process Development (NPPD). Contrary to already existing investigations (cf. also Chapter 1.3.3), the focus is set on collaboration between subjects or groups with a natural science background and others who come from 'classical' design-related disciplines. As will be highlighted in the following chapters, the need to solve interdisciplinary problems is of utmost importance for the generation of innovations in both industrial and scientific fields. Furthermore, it will be shown that existing methodological approaches do not tackle important issues related to this kind of interdisciplinary problem solving or that their performance in this respect has not been investigated yet.

After an extensive literature review covering the fields of (engineering) design science, psychology and cognitive science, as well as organization science on five systemic levels, two opposing methodological approaches were chosen. The value of these techniques was then tested by one laboratory experiment in the context of an open ill-structured problem originating from a science-related knowledge-intensive domain (cf. Chapter 2.2.2 for a definition and classification of knowledge). The conclusions of that experiment affected the design of a descriptive and somewhat prescriptive meta-model structuring the integration of knowledge-intensive science-related technologies into a given application. The performance of the mentioned meta-model, which is sought to integrate concepts of both previously mentioned methodological approaches, was finally tested during an industrial case study. The results of both tests as well as of relevant industrial activities of the author provide some answers to the question of how to support interdisciplinary problem solving and technology integration in NCD and NPPD processes. Furthermore, those results open several perspectives for further research.

1.2 Industrial Context

The research presented in this report has been funded by a *Convention Industrielle de Formation par la Recherche* (English: Industrial Convention on Formation by Research) *(CIFRE)* and has been carried out in collaboration with *Active Innovation Management (AIM) SARL*. AIM, and its activities are briefly presented below.

1.2.1 Active Innovation Management SARL

AIM was founded in 2007 by *Giacomo Bersano*, who holds Master's Degrees in electric engineering and in management. Besides other activities, he has worked for 12 years as consultant for *Altran*, the last seven years of which as coordinator of senior consultants.

As a small consultancy company, AIM currently has a staff of four employees, three of which are working as consultants for New Concept Development, New Product Development, Project Management, Innovation Management and Knowledge/Technology Transfer. Two of those

consultants, among them the author of this report, are Ph.D students in mechanical engineering and more specifically in the field of design theory and methodology.
The whole of AIM's activities follow an approach which is characterized by (Figure 1):

- Strategic thinking, which is necessary in order to ascertain that customer companies and the projects of the latter address the right issues;
- Development of synergy effects among project stake holders and project participants, in order to benefit from various knowledge backgrounds and perspectives on problems;
- Well-structured problem solving processes in order to assure higher project effectiveness and efficiency as well as;
- Tools, i.e. methods and software which allow the implementation of the strategy as well as the synergy of perspectives and knowledge into the process in order to achieve maximally creative and thus innovative project outcomes.

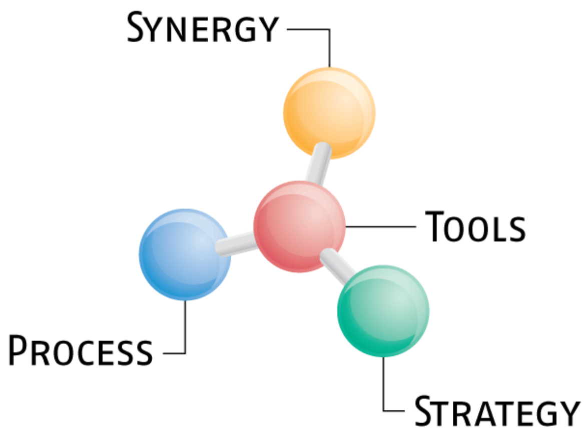


Figure 1: Strategy, synergy, process and tools as aspects of AIM's approach

1.2.2 Activities and Customers

AIM advises and supports industrial and academic R&D institutions of different size and fields of activity such as automotive industry, transportation, energy, biotechnology, pharmacology, and microbiology. Some of those partners as well as projects which have been conducted in cooperation between AIM and its customers are introduced briefly below.

1.2.2.1 Svenska Kullagerfabriken (SKF) AB

Svenska Kullagerfabriken (SKF) AB is Swedish manufacturer of roller bearing solutions for the premium market segment. It provides systems for different applications in the automotive industry along with other industrial sectors such as electric motors, hydraulic pumps, conveyor systems, etc.
As premium manufacturer, SKF seeks to develop product and service innovations in a very competitive and saturated market which is characterized by low price competition. In order to do so, SKF has adopted a knowledge oriented strategy, which reflects in its slogan 'The Knowledge Engineering Company'.
The collaboration between AIM and SKF includes several New Concept Development (NCD) projects, some of which are briefly described in Chapters 4 and 5, as well as training in design and innovation management theory and methodology.

1.2.2.2 *Other Activities*

Table 1 provides a non-exhaustive overview of other AIM activities in industry and science.

Table 1: Instances of AIM customers and activities

Domain	Field of activity	AIM activity	Topic
Industry	Energy technology	• Facilitation of technology-related problem solving sessions • Idea management	Concentrated solar power plant
Industry	Electric utility	• Technology forecasting • Technology-related problem solving	Electric mobility infrastructure
Industry	Petrochemical facilities	• Intellectual property management • Facilitation of technology-related problem solving sessions	• Ethylene processing facility • Floating liquefied natural gas facility
Industry	Mailroom technology	• Technology forecasting • New Concept Development study	Mailroom equipment
Industry	Transportation	• Training in design problem solving and innovation management methodology • Coaching in New Product Development	Signaling and train control technology
Industry	Biotechnology	• Facilitation of interdisciplinary problem solving sessions • Idea management	Biological marker technology
Public science	Virology	• Training in creative problem solving methodology • Coaching in science-related problem solving	Adenovirus-related research

1.3 Research Context

A considerable part of the above mentioned activities is related to R&D processes in highly knowledge-intensive domains. Further, the technical or biological systems, which are the topic of these processes, are often very complex and integrate knowledge issued from several industrial and scientific backgrounds. Finally, the actors in the above mentioned institutions are obliged to either find creative and innovative solutions to new problems or they must find differentiating and better solutions to previously solved problems in order to reduce costs, to access new markets, to tackle competitors or ‘simply’ to provide insight.

The research presented in this report thus relates to the question of how to provide methodological support for interdisciplinary problem solving and technology integration in knowledge-intensive domains.

In this report, the terms *interdisciplinary* as well as *knowledge-intensive domain*, point towards domains at which knowledge originating from *natural science* plays an essential role for the creation of value and which are considered crucial for industrial growth and human welfare in the present century (cf. Paragraph 1.3.1). Prominent examples for these domains are *nano-* and *biotechnology*. But, as will be discussed in Subsections 2.1 and 2.5, natural science-related knowledge has been becoming increasingly important also for classical *engineering design* products. Again, it shall be noted that in this report both terms, knowledge-intensive and interdisciplinary, within this report, refer to natural science and, in the latter case, to activities at the interface between natural science and engineering.

The following paragraphs will stress the need for the presented research and will introduce related work in general and that of CPI Laboratory (LCPI) in particular. Finally, this Ph.D. research will be set into the context of LCPI's research.

1.3.1 Need

In 1996, the Organization for Economic Co-operation and Development [OECD, 1996], described the economy of its member countries as being essentially knowledge based. This statement was explained by estimations that more than 50 per cent of the Gross Domestic Product of major OECD economies is heavily based on knowledge. Also more recent literature [OECD, 2004; Luintel and Khan, 2011] provides evidence for a strong relationship between stocks of basic (as well as applied and experimental) knowledge and the domestics' output and productivity of industrialized economies.

After the analysis of six major technological challenges of the 21st century [Bourgeois and Grou, 2007], which are introduced in Table 2, one can conclude that basic and applied knowledge originating from natural as well as life science will be continuing to play an increasing role on ever more important technological markets.

The increasing integration of more distant knowledge domains into new product and process designs leads to new and higher levels of system complexity [Tomiyama, 2006] and to increasingly interdisciplinary research and development (R&D) teams [Paletz and Schunn, 2010]. Before this background and taking into account still existing collaboration problems between more closely related disciplines [Tomiyama *et al.*, 2009], it is astonishing that inter- and transdisciplinarity as well as collaboration between disciplines have only been discussed quite recently in the literature [Gericke and Blessing, 2011; Chulvi *et al.*, 2013].

From this, a need for insight into the process of multidisciplinary creative problem solving and influencing factors such as disciplinary group composition and methodological support can be identified. Further, the problem of how to modify and adapt existing methodological approaches in order to adapt them to that purpose arises. Finally, even though there are several approaches for the search of distant domain knowledge and technologies which are a priori suitable for the resolution of a given problem, there is a lack of models and methods which effectively support the process of technology integration. Those issues shall be, to some extent, addressed in this research.

In conclusion, the following research question, which is detailed in Subsection 3, has been formulated:

> How to support methodologically the search for and evaluation and integration of knowledge and technologies originating from knowledge-intensive and natural science-related domains in product- and process design processes?

Table 2: Major technological challenges of the 21st century as identified in [Bourgeois and Grou, 2007] and related scientific disciplines

Technological field	Challenge	Reference	Related non-engineering disciplines
Environmental problems	• Improvement of food production efficiency • Reduction of greenhouse effect • Reduction of water-, soil- and air pollution • Reduction of raw material consumption • Waste reduction	[Bourgeois, 2007a]	• Biology • Veterinary medicine • Chemistry • Physics
Information and communication technology	• Increasing device miniaturization • Development of spin electronics • Development of molecular electronics	[Bourgeois, 2007b]	• Physics • Chemistry • Biology
Transportation technology	• Storage of electric energy • Improvement and implementation of hydrogen combustion and fuel cell technology	[Haouat, 2007]	• Chemistry • Physics
Energy technology	• Realization of energy mix integrating wind-, solar, geothermal and biomass energy • Development of nuclear fusion technology	[Boudin, 2007]	• Physics • Chemistry • Biology
Health and healthcare technology	• Treatment of cardiovascular and neuro-degenerative diseases • Development of new surgery methods • Improvement of targeted drug delivery • Improvement of 'intelligent' prostheses	[Deregnaucout and Haouat, 2007]	• Medicine • Biology • Nanosciences[1] • Biosciences
Water purification technology	• Improvement of distillation technology • Improvement of reverse osmosis technology	[Bourgeois, 2007a]	• Chemistry

1.3.2 Related Research

The work which is reported in this dissertation essentially relates to three fields of research: Engineering design, psychology and cognitive science, as well as organization science, which covers aspects of specialties like e.g. sociology (Figure 2). As each of these fields is discussed in more detail in Subsection 2, only some brief introductory remarks will be given here.

[1] Nanotechnology is defined as '[…] the production and application of physical, chemical, and biological systems at scales ranging from individual atoms or molecules to submicron dimensions, as well as the integration of the resulting nanostructures into larger systems' [Bhushan, 2010]. See [Meyer, 2000] for a discussion of the distinction between nanosciences and nanotechnology. The distinction is extrapolated for biosciences and biotechnology in this report.

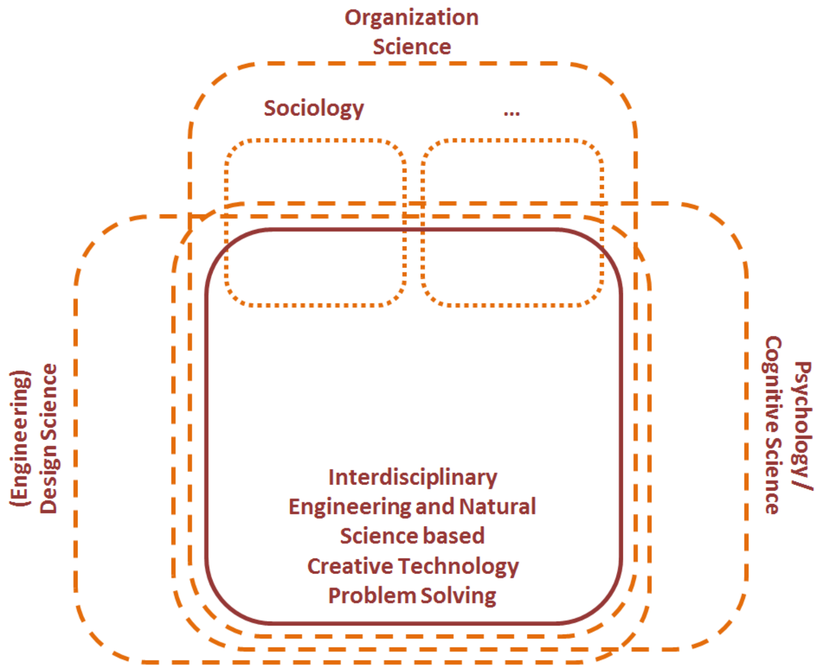


Figure 2 : Research related to the work presented in this dissertation

1.3.2.1 (Engineering) Design Science

Engineering Design is an activity consisting in applying scientific and engineering knowledge in order to solve technical problems and to optimize the obtained solutions with regard to previously set requirements and constraints [Pahl *et al.*, 2007]. Design science, which is considered a synonym for design research in this report, is defined as 'a system of logically related knowledge, which should contain and organize the complete knowledge about and for designing' [Hubka and Eder, 1996, p. 73].
For the present research, three aspects of design science are of particular interest:

- Descriptive (and partly prescriptive) models of the overall design process as presented e.g. by Pahl *et al.* [2007] and Suh [2001];
- Prescriptive methodology, methods and tools for specific design stages and problem solving in design [e.g. Cross, 2008; Altshuller and Seljuzski; 1983] and;
- Problems and theoretical aspects related to interdisciplinarity in design [e.g. Tomiyama, 2003, 2006].

1.3.2.2 Psychology and Cognitive Science

Psychology is concerned with the 'study of mind and behavior' [APA, 2014] and covers 'all aspects of the human experience.' Cognitive science has been defined as 'empirically based effort to answer […] epistemological questions […] related to the nature of knowledge, its components, its sources, its development, and its deployment' [Gardner, 1985, p. 6]. According to Gardner, the concepts of mental representation as well as electronic computers are essential to describe the activity of the human mind in cognitive science. As an interdisciplinary research field, it covers subjects like philosophy, psychology, artificial intelligence, linguistics and neuroscience.
Against the background of the present research the following aspects of psychology and cognitive science are important:

- The theory of creativity including conditions favoring creative achievement [e.g. Collins and Amabile, 1999] and models of creative reasoning [e.g. Finke *et al.*, 1992];
- The description of the human mind as information processor [e.g. Simon, 1978] and the modeling of creative reasoning as some sort of problem solving [Simon, 1985] and
- The impact of an individual's disciplinary background on his or her cognitive preferences [e.g. Kozhevnikov, 2007] and employed problem solving strategies [Lawson, 1979]

1.3.2.3 Organization Science

Organization theory, organizational theory or organization science is referred to as 'the study of how organizations function and how they affect and are affected by [their] environment' [Jones, 2003, p. 8]. According to Shenhav [2003] this 'intellectual field' (p. 183) covers aspects of such diverse disciplines like sociology, political science, psychology, engineering, management science, and economy.

The presented research takes into account several aspects of organizational theory like:

- The theory and management of innovation in an industrial context [e.g. Popadiuk and Choo, 2006; Chesbrough, 2003];
- The theory of knowledge creation [e.g. Nonaka, 1991] as well as aspects of knowledge management [e.g. von Krogh, 1998] and transfer [e.g. Argote and Ingram, 2000] and;
- The categorization of scientific disciplines from a socio-cognitive perspective [e.g. Becher and Trowler, 2001].

1.3.3 Related Research in CPI Laboratory

The research presented in this report has been undertaken in the Product Design and Innovation Laboratory (French: *Laboratoire Conception de Produits et Innovation*; *LCPI*) of *Arts et Métiers ParisTech (ENSAM).*

The research of the LCPI focuses on the improvement of design and innovation processes. Here, emphasis is put on three aspects [LCPI, 2014]:

- The integration of a set of primarily design related professions like engineers, industrial designers and ergonomists into design and innovation processes by extraction and formalization of profession-specific rules, knowledge, and tools (discipline related research);
- The control and optimization of different divergent and convergent sub processes in the design and innovation processes by fostering collaboration between all participating actors (process related research);
- The facilitation of both previous aspects by state-of-the-art design support technologies (design technology related research).

Some instances of research carried out by former and current researchers of LCPI are presented in the following (cf. also Figure 3).

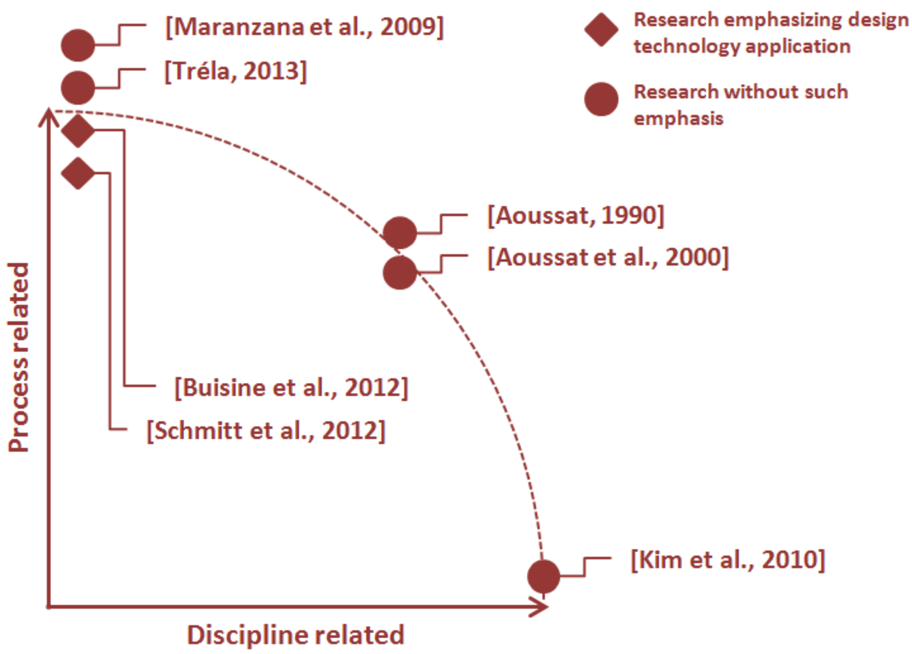


Figure 3: Overview of research carried out by members of LCPI

1.3.3.1 Discipline Related Research

One example for research of the discipline related type is the study of *Kim et al.* [2010]. They investigated how design students and professionals mentally categorize design information during the generation of product representations at divergent design phases. The result of this research is a cognitive model which contains several hierarchical levels of design information like forms, functions, and contexts as well as sets of cognitive operations [Finke *et al.*, 1992] which the designers perform during their reasoning process.

1.3.3.2 Process Related Research

Instances of process related research are the work of Maranzana *et al.* [2009], Buisine *et al.* [Buisine *et al.*, 2012; Schmitt *et al.*, 2012], as well as Tréla [2013].

Maranzana *et al.*, [2009] focused on ways to measure and – to some extent – influence the quality of problem solving processes in design. Based on the work of Gibert [1980] (cited in [Maranzana *et al.*, 2009]) and Gartiser *et al.*, [2004], they proposed ways to measure the relevance, efficacy and efficiency of problem solving activities. Further, Maranzana and colleagues identified a set of process parameters which are important for the satisfaction of the mentioned performance criteria and pointed to conflicts among these process parameters.

Tréla [2013], in his Ph.D. research, was interested in the impact of a methodology on a company's innovation performance. After having tested methods originating from *TRIZ* (cf. e.g. Chapter 2.5.3.1) and *Blue Ocean Strategy* [Kim and Mauborgne, 2005], Tréla concluded that both methodological approaches exert somewhat complementary impact on industrial performance criteria like strategy development, idea management, data integration, etc.

Buisine *et al.* analyzed the impact of the use of interactive tabletop hard- and software on performance and collaboration during *Brainstorming* (cf. Paragraph 2.5.3.2.1) sessions [Buisine *et al.*, 2012]. Further, they inquired into the impact of time and social pressure on idea quantity and quality during *Brainwriting* [Schmitt *et al.*, 2012] sessions. The results of the first study show a positive effect of the tabletop design support technology on performance and collaboration. The second experiment provides evidence for a positive relationship between time pressure and solution quantity and originality. Social pressure, however, though increasing idea quantity and motivation, was found to reduce collaboration between group members.

1.3.3.3 Research at the Interface of Both Fields

Various studies which have been undertaken in the LCPI cover both the field of design processes in general and the innovation process in particular, as well as problems regarding the integration of design-related disciplines into these processes.

Aoussat *et al.* [Aoussat, 1990; Aoussat *et al.*, 2000], for example, postulated that a systematical process for innovative New Product Development has to structure the interactions of at least the following disciplines: Ergonomics, Design, Quality Management, Marketing, and Reliability Management. Moreover, they proposed a process model which is capable of this structuring. The process essentially consists of four phases: Requirement Translation (covering the identification of customer needs and their translation into functional specifications), Requirement Interpretation (covering the search for concepts), Requirement Definition (covering the definition of the product), and Requirement Validation (covering prototype building and testing).

1.4 Positioning of Presented Research

The research presented in this report is somewhat complementary to other research carried out in the Product Design and Innovation Laboratory. The presented research matches well the major research directions of LCPI as it investigates the integration of knowledge and technologies originating from several domains into a system against the background of a New Product/Process Design Process. In addition, this dissertation extends the research field of LCPI in so far as it focuses on collaboration between design related disciplines like engineering, industrial design, ergonomics etc. and, in cognitive terms, more distant disciplines, like biology, chemistry, and so on. Figure 4 schematically positions this Ph.D. research within the context of LCPI studies.

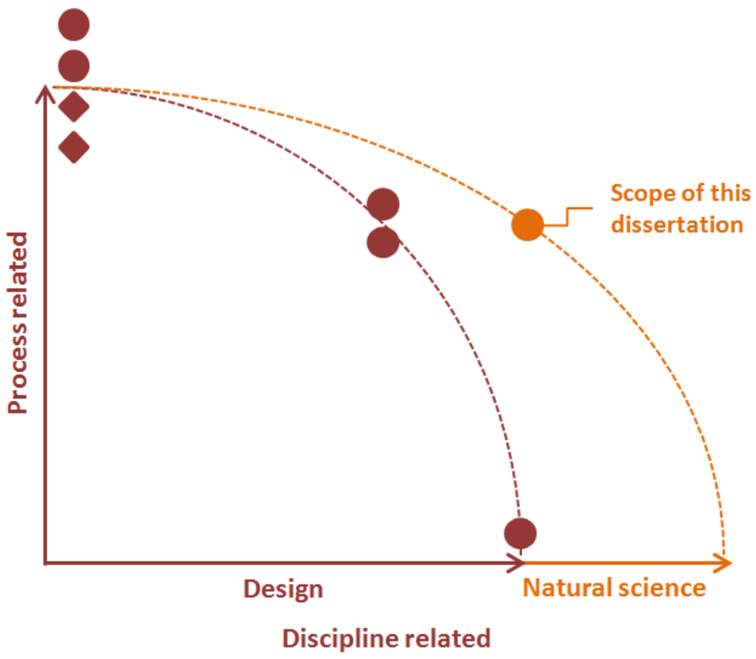


Figure 4: Positioning of this dissertation within the framework of research undertaken in the LCPI

1.5 Summary and Conclusion of the Presented Work Context

The work which is presented in this report is motivated by the industrial trend of value generation using knowledge and technologies originating from natural science related domains. Problems concerning interdisciplinary problem solving even among members of design related disciplines and a – except for some recent work – lack of approaches discussing inter- and transdisciplinary collaboration in design have been stated elsewhere. Both aspects point to a serious problem: How to provide methodological support for interdisciplinary problem solving and the integration of natural science-based technology during the design process?

This dissertation research, which is somewhat complementary to previous work performed in the LCPI and which mainly relates to design science, psychology and cognitive science, as well as organization science, can be outlined as follows:

- First, an extensive literature review has been performed in order to identify relevant theory as well as important problems related to the research question on various systemic levels (cf. Chapter 2). Due to the broad scope of the literature review and the large number of analyzed publications, in some cases it was not possible to access the original sources. Throughout the whole report, in those cases both the original and the secondary source are given.
- Then, by taking into account the results of this literature review, a research question as well as three hypotheses are formulated (Chapter 3).
- Those hypotheses are tested in one experiment and one industrial case study following complementary research methods (Chapter 4).

The results of those tests and of related industrial projects, being of both academic and industrial nature, as well as their implications are then presented (Chapter 5). Chapter 6 concludes on this Ph.D. research and indicates further research- and industry-related perspectives.

2 Literature Review

Whereas the first subsection put the present research into its industrial and academic contexts, the present subsection deals with the extensive literature review which has been performed during this Ph.D. research. After an introduction of the structure of the subsection, relevant research topic related aspects are investigated on five different systemic levels. The conclusion, finally, sums up the most important findings and problems which have been identified in the literature and draws a link to the next subsection.

2.0 Structure of Literature Review

This dissertation relates to issues of interdisciplinary problem solving and integration of natural science-based technology. Against this background, the role of methodological support for these activities is of particular interest. As outlined in Chapter 1, relevant research can be located in the fields of (engineering) design science, psychology and cognitive science, as well as organization science. However, the presented literature review is not structured according to these research fields. The structure of the chapter rather follows a systemic logic (Figure 5).

In order to investigate interdisciplinary creative problem solving (Chapter 2.5), one has to understand the theory and mechanisms of individual (Chapter 2.4) as well as team (Chapter 2.3) creativity and problem solving. Further, aspects of knowledge creation and knowledge transfer within and beyond institutional boundaries (Chapter 2.2) have to be understood. Finally, i.e. at the beginning, some basic definitions about innovation – one major motivation for interdisciplinary problem solving –, some information on the impact of interdisciplinary knowledge on industrial value creation, as well as a definition of the term *discipline* shall be given (Chapter 2.1). Chapter 2.6 sums up the most important aspects and identified problems, the latter of which finally lead to the formulation of the research question and the hypotheses as stated in Chapter 3.

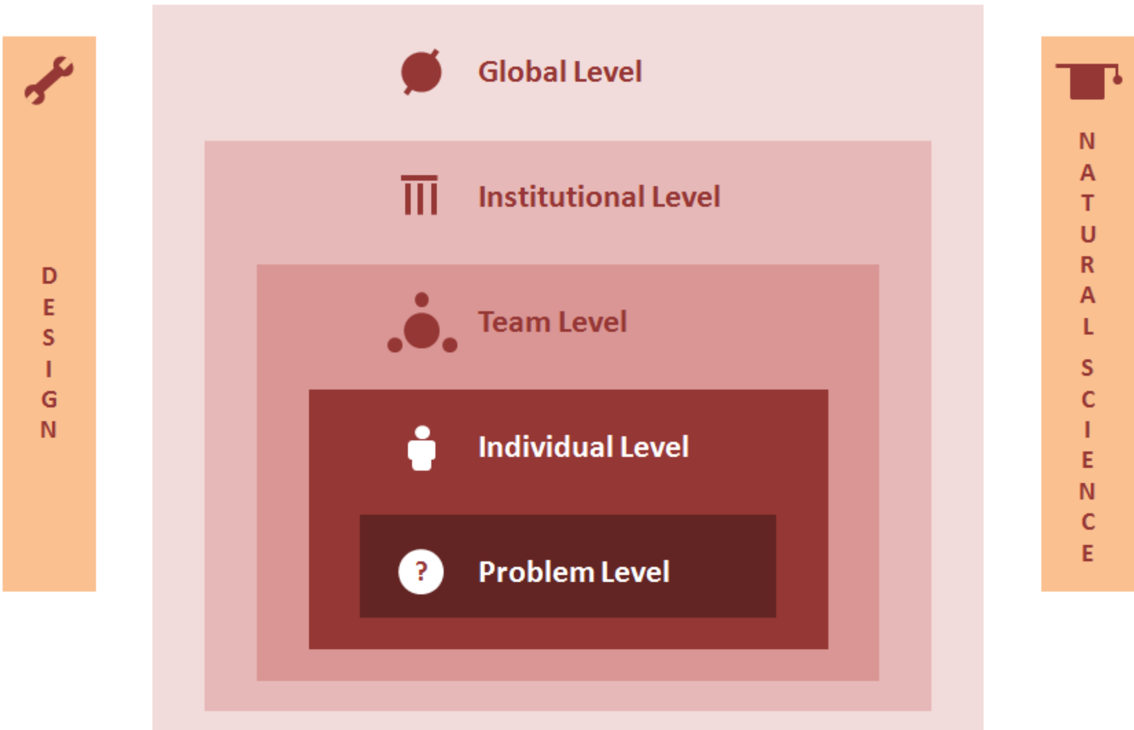


Figure 5: Structure of literature review

2.1 Global Level

2.1.0 Introduction

One of the most important motivations for creative interdisciplinary problem solving is innovation. Depending on the type of innovation, technological inventions play different roles [e.g. Popadiuk and Choo, 2006]. Scientific knowledge, mostly originating from natural science, has been found to be an important factor for the quality of inventions [e.g. Harhoff *et al.*, 1999]. Over time, the way in which scientific and industrial institutions interact in order to produce innovative products has evolved. However, disciplinary boundaries remain rather distinct, in social but also in cognitive terms [e.g. Becher and Trowler, 2001].

In the present subsection, the concept of innovation will be introduced. Further, the role of scientific knowledge, i.e., knowledge originating from natural science, for the production of innovation will be highlighted. It follows a brief overview of the history of innovation models in the historical context. Finally, the concept of discipline is introduced and the sociological and cognitive categorization of disciplines is discussed.

2.1.1 Innovation

2.1.1.0 Definition of Innovation

The terms *innovation* and *invention* have to be clearly distinguished. The Merriam-Webster Dictionary [2014] lists under the term invention ‘a device, contrivance, or process originated after study and experiment’ and gives as example the light bulb as one of the most important inventions of the 19th century. Schumpeter [1939], however, defines innovation as ‘[…] the setting up of a new production function’ which, in an economical sense, ‘combines factors in a new way.’ (p. 84). According to Schumpeter, invention is neither a necessary condition for innovation, nor is it a sufficient one even though both very often occur jointly. Weitzman [1996], who does not explicitly distinguish between innovation and invention, refers to the former of being a sort of combination of elements. Weitzman further states that combinations of initially distant elements lead to the most fruitful inventions and thus to innovations.

2.1.1.1 Types of Innovation

There exist several categories of innovations. Most often, these categories differ with respect to technological or economic value. Popadiuk and Choo [2006] give an overview of some innovation categories (Table 3) and frame them from a knowledge creation perspective [Nonaka, 1991 (cf. Chapter 2.2.2.4; Table 4).

Table 3 : Overview of innovation categories [Popadiuk and Choo, 2006]

Abernathy and Clark [1985] (cited in Popadiuk and Choo, 2006)		
Market knowledge	**Technical capabilities**	
	Preserved	Destroyed
Preserved	***Regular innovation***	***Revolutionary innovation***
Destroyed	***Niche innovation***	***Architectural innovation***

Henderson and Clark [1990]		
Component knowledge	**Architectural knowledge**	
	Enhanced	Destroyed
Enhanced	***Incremental innovation***	***Architectural innovation***
Destroyed	***Modular innovation***	***Radical innovation***

Tushman *et al.* [1997]		
Market	**Technology – (R&D)**	
	Incremental	Radical
New	***Architectural innovation***	***Major product, service innovation***
Existing	***Incremental product, service, process***	***Major process innovation***

Chandy and Tellis [1998] (cited in Popadiuk and Choo, 2006)		
Newness of technology	**Customer need fulfillment / $**	
	Low	High
Low	***Incremental innovation***	***Market breakthrough***
High	***Technological breakthrough***	***Radical innovation***

Table 4 : Innovation classification from a knowledge perspective [Popadiuk and Choo, 2006]; [a]:Abernathy and Clark, 1985 ; [b]: Henderson and Clark, 1990; [c]:Tushman *et al.*, 1997, [d]:Chandy and Tellis, 1998

	Knowledge creation	
Market knowledge	Tacit knowledge Socialization and externalization (Exploration)	Explicit knowledge Combination and internalization (Exploitation)
New market knowledge	***Architectural innovation*** [a] ***Radical innovation*** [b] ***Major product/service innovation*** [c] ***Radical innovation*** [d]	***Niche innovation*** [a] ***Modular innovation*** [b] ***Architectural innovation*** [c] ***Market breakthrough*** [d]
Existing market knowledge	***Revolutionary innovation*** [a] ***Architectural innovation*** [b] ***Major process innovation*** [c] ***Technological breakthrough*** [d]	***Regular innovation*** [a] ***Incremental innovation*** [b] ***Incremental product, service, process innovation*** [c] ***Incremental innovation*** [d]

According to von Stamm [2003], the business conditions as well as skills, structures and processes for e.g. idea generation and implementation differ significantly e.g. in the cases of incremental and radical innovation. Henderson and Clark [1990] distinguish modular and radical innovations which imply changes in their component's core design on the one hand and incremental and architectural innovations on the other hand which keep the core design component unaltered. In the former cases, underlying scientific and engineering knowledge plays a major role whereas in the latter cases, it does not.

2.1.2 Economic Importance of Science and Scientific Knowledge Production

Several literature studies, [Macho-Stadler *et al.*,2007; Fleming and Sorenson, 2004] identify both theoretical and empirical proof for the positive impact of scientific knowledge on innovation performance, a key point here being the setting up and the maintenance of 'good industry-science relations' [Macho-Stadler *et al.*, 2007 p. 484]. The impact is reported to be particularly important for sectors like biotechnology, information technology and material industry.

2.1.2.1 *Quantitative Economic Impact of Scientific Knowledge*

In a survey, Beise and Stahl [1999] asked manufacturing companies about the share of product and process innovations between 1993 and 1996 which would have been impossible without the support of research institutions. The results of this study are shown in Table 5.

Table 5: Share of companies with innovations which could not have been developed without recent public research [Beise and Stahl, 1999]

	Firms with public research-based innovations to all product- or process innovations [%]	**Firms with public research-based product innovations to all product innovations [%]**	**Firms with public research-based process innovations to all process innovations [%]**
In general	***8.5***	***7.9***	***3.4***
R&D intensive industries	***15.9***	***14.0***	***5.2***
Non-R&D intensive industries	***6.2***	***5.7***	***2.9***

Probably the most well-known example for knowledge transfer from one given scientific discipline to industry which can lead to innovation is bio-inspiration. The term covers activities and disciplines like *biomimetics* as well as *biomimicry* and *bionics* [see Fayemi *et al.*, 2014 for any further discussion].

Empirical support for the use of bio-inspiration comes from Bonser [2006]. After having performed a patent analysis on the database of the United States Patent and Trademark Office (USPTO), he identifies a considerable increase in the percentage of patents which refer to either one of the terms 'biomimetic', 'bionic' or 'biologically inspired'.

2.1.2.2 *Qualitative Impact of Scientific Knowledge*

There is also evidence for the impact of scientific knowledge on the quality of inventions. Fleming and Sorenson [2004] investigated the relationship between the citation of scientific papers in patents and the number of citations of these patens by other inventors, the latter being considered as an indicator of the usefulness of a given patent [Harhoff *et al.*, 1999]. Fleming and Sorenson show that the impact of scientific citations in patents increases with the coupling of the components of the featured invention (Figure 6). In the study, coupling is referred to as the degree to which 'a change made to one module requires a change to the other module(s) in order for the overall invention to work correctly' (p. 917). The authors of the study interpret this result as strong evidence for usefulness of scientific knowledge for the solving of difficult inventive problems.

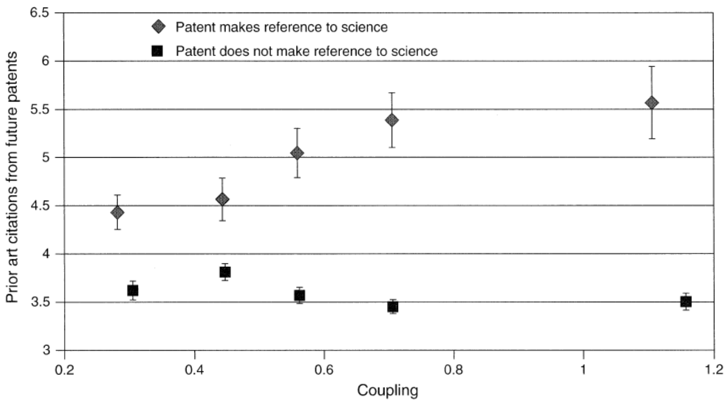


Figure 6: Mean citations across quintiles of the coupling variable [Fleming and Sorenson, 2004]

Another study [Jaffe and Trajtenberg, 1996] has investigated the relationship between the type of institutions – corporations, universities or governments – which are at the source of patents and the degree to which those patents are cited by other inventors. The results show that university patents are relatively more cited than both corporate and governmental patents, which makes the authors of the study argue for a higher 'fertility' (p. 12677) of those patents.

2.1.3 Innovation Models: Historical Perspective

The interplay of public research institutions and industrial companies in the process of innovation generation has evolved to some degree over the past. This evolution also reflects, to a certain extent, the evolution of models describing the production of innovation.

2.1.3.1 Development of Knowledge Production in Scientific and Industrial Organizations

The development of the production of scientific knowledge has been influenced by several factors [Whitley, 2000]. First, since the end of the Cold War and the changing geopolitical climate, fundamental research has lost one of its main driving forces, military related R&D activities. As a consequence, science and technology funding policies have far more focused on more directly identifiable societal returns. Second, with the recognition of the importance of formal knowledge for the generation of industrial value and the reduced costs for skilled academic work force, an increase of systematic research in a large variety of subjects has been observed. These changes [Whitley, 2000], among others [e.g. Becher and Trowler, 2001] have induced a transition of scientific knowledge production from 'Mode 1' to 'Mode 2' [Gibbons *et al.*, 1994, Gibbons, 1994]. The former is characterized by scientific 'problem solving which is carried out following the codes of practice relevant to a particular discipline and problem solving which is organized around a particular application' [Gibbons *et al.*, 1994, p. 3]. The latter refers to the production of knowledge 'in the context of application' (p. 3) which results from a 'broader range of considerations' (p. 4). This knowledge is sought from the beginning to be applicable in industry, society and so on, and is organizationally more heterarchical and transient [Gibbons, 1994].

Knowledge production by industrial organizations has been influenced as well by several factors [Whitley, 2000]. Increased competition from low cost work force areas such as East Asia, saturation of markets and ever more demanding customers have led to the decline of the *Fordist* model of mass production and mass marketing and have caused segmented markets and ever shorter product life cycles. On the one hand, the resulting uncertainty and the demand to become more responsive to a changing environment in combination with the importance of formal knowledge to obtain competitive advantage resulted in a decrease of internally conducted fundamental research by industrial companies. On the other hand, this has led to more intensive collaboration with external research organizations including universities.

The above mentioned changes in scientific and industrial organizations paralleled with the emergence of so called 'transfer sciences' [Gibbons, 1994, p. 259] like e.g. biotechnology. Those are characterized by unclear distinctions between research and professional practice, increased trans-disciplinary activity as well as a higher degree of task uncertainty.

2.1.3.2 Innovation Models

The initial states of scientific and industrial knowledge production and the resulting industrial value production is probably best reflected by the first generation of the Linear Model of Innovation [Godin, 2006], the 'Technology Push Concept of Innovation' [Rothwell, 1994, p. 8]. According to this model, an innovation is developed in a linear process consisting of the stages of basic research, applied research, development and, finally, (production and) diffusion.

The latter states or ‘modes’ of knowledge production are better modeled by nonlinear models of innovation like e.g. the Triple Helix Model [Leydesdorff and Etzkowitz, 1998]. As a matter of fact, ‘Mode 2 of Knowledge Production’ can also be seen as a nonlinear model [Etzkowitz and Leydesdorff, 2000]. According to the Triple Helix Model III [Etzkowitz and Leydesdorff, 2000] (Figure 7), the three spheres of the helix are defined as universities, industry organizations and the government. Where their organizational spheres overlap, these institutions generate knowledge infrastructures, mutually take each other’s role and build hybrid organizations

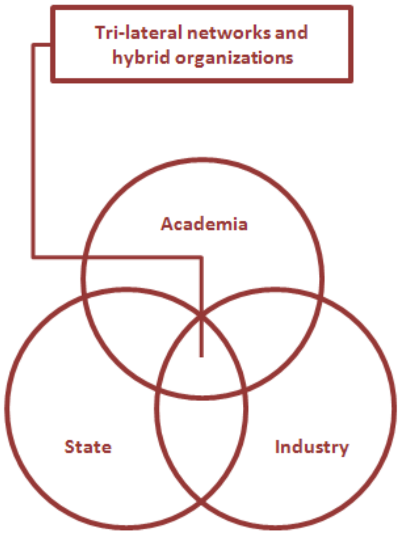


Figure 7: Triple Helix Model of innovation [Etzkowitz and Leydesdorff, 2000]

The Open Innovation Model [Chesbrough, 2003] (Figure 8) further develops the application-centered aspect of ‘Mode 2’ knowledge production. The main difference to the previous model is that (essentially) the company is required to be able to identify so called ‘false negatives’ (p. 37), i.e. to further develop projects which initially seemed to lack potential but turn out to be of value. In order to do so, the company should not only search for appropriate input, e.g. knowledge and technologies, and buy and license Intellectual Property from other actors. It should also seek to create value out of internal knowledge and technologies by applying them to new markets. The model further emphasizes that funding, generation, and commercialization of innovation should be done jointly with external entities.

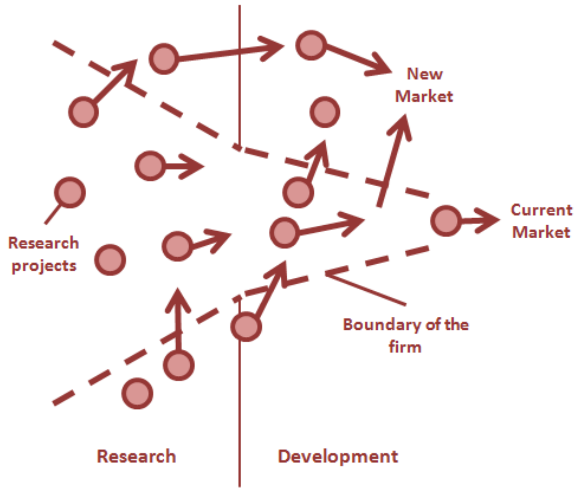


Figure 8: Open Innovation Model [Chesbrough, 2003]

2.1.4 Importance of Disciplines and Culture

The growing emphasis on the necessary interaction of different academic, industrial and governmental actors in order to create value leads to the consideration of disciplines. An important aspect of innovation is the transfer of information which originates in either one or several disciplines to other – often very disparate – disciplines [Kostoff, 1999, 2006]. The diversity of perspectives, backgrounds and trainings can facilitate the generation of new ideas and knowledge [Dougherty, 1992; Cardinal, 2001; Alves *et al.*, 2007]. However, the organization of this transfer requires considerable effort [Kostoff, 1999], a reason among others being cultural differences between the scientific and industrial communities or disciplines [EU-Commission, 2007].

2.1.4.0 Definition of Discipline

It is not easy to set the definition of an academic discipline. It often depends on such factors as the establishment of organizational structures like e.g. departments, 'a generally defined set of notions of academic credibility' or 'intellectual substance' [Becher and Trowler, 2001, p 41]. Another important aspect of academic disciplines is their ongoing fragmentation into sub-disciplines and specialist fields, the latter being considered as 'basic unit of intellectual organization' [Becher and Trowler, 2001, p. 64], [Campbell, 1969; Wax, 1969 (cited in [Becher and Trowler, 2001]); Clark, 1996; Becher and Trowler, 2001]. Becher and Trowler [2001] compare actors in academic disciplines and specialist fields to 'tribes' which 'defend their own patches of intellectual ground by employing […] devices geared to the exclusion of illegal immigrants' (p. 47) and which can resist to the adoption of values and practices stemming from different disciplines or fields. Weingart and Stehr [2000] define disciplines as 'not only intellectual but also social structures, organizations made up of human beings with vested interests based on time investments, acquired reputations, and established social networks that shape and bias their views on the relative importance of their knowledge' (p. xi). Bauer [1990], in concordance with previous statements, concludes that 'each discipline can be aptly viewed as a culture' (p. 110).

2.1.4.1 Cognitive and Social Categorization of Scientific Disciplines

Becher and Trowler [2001], have investigated the degree to which disciplines differ in terms of cognitive and social aspects like collaboration, competition, learning style, and migration among specialist areas. Based on the work of Biglan [1973 (cited in [Becher and Towler, 2001])], they categorize twelve scientific disciplines (biology, chemistry, economics, geography, history, law, mathematics, mechanical engineering, modern languages, physics, and sociology) according to four dimensions in order to highlight differences with respect to the above mentioned aspects (Figure 9). In the cognitive realm, 'hard' versus 'soft' describes whether there exist strong paradigms, whereas 'pure' versus 'applied' is an indicator for the relative concern of application in the discipline. In the social realm, 'divergent vs. convergent' refers to the degree of commonality among the members and of agreement on e.g. notions and methods. At last, by using a map analogy, 'urban' versus 'rural' describes characteristics like collaboration types, competition and sharing of knowledge.

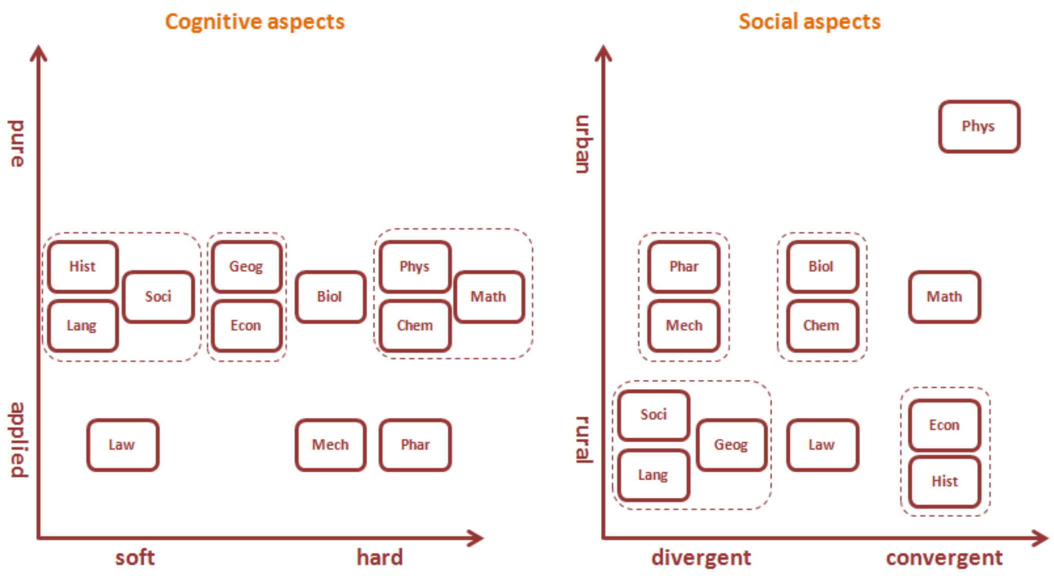


Figure 9: Cognitive and social differences between disciplines [Becher and Trowler, 2001 (based on [Biglan, 1973])]

2.1.5 Conclusion

The innovation process can be seen as a recombination process. Whether the innovation recombines new technological and/or market aspects is critical to the categorization of innovation. Scientific knowledge has important quantitative and qualitative impact on the generation of industrial value. Especially linkage of knowledge originating in distant (scientific) disciplines can affect innovative projects. The models which describe the development of innovations in the context of academic and industrial collaboration have changed along with changes in the production of knowledge. The generation of knowledge for innovation is characterized by higher uncertainty, shorter collaboration times and the need to apply an institution's capabilities to new and diverse applications and markets. However, science-industry knowledge transfer still suffers from problems due to cultural differences between the partners.

The following subsection will highlight different categorizations of knowledge and the act of knowledge creation as a social process [Nonaka and Takeuchi, 1995]. Further, knowledge transfer between scientific and industrial institutions and problems concerning this transfer will be discussed. Finally, approaches aiming at the improvement of an institution's capacity to absorb knowledge [Cohen and Levinthal, 1990] will be addressed.

In the following subsection, institutional aspects like knowledge creation, knowledge and technology transfer as well as related problems are discussed.

2.2 Institutional Level

2.2.0 Introduction

According to Grant [1996], under conditions of intensive and dynamic competition (cf. Paragraph 2.1.3.1), the profitability of an organization depends more on resource- and capability-based advantages than on advantages regarding 'generic strategy' (p. 376) or market selection. These advantages are the result of the acquisition and integration of specialized knowledge (cf. Paragraph 2.2.2.1). Kogut and Zander [1992] introduce the term 'combinative capabilities' while referring to the firm's capacity (1) to create new knowledge through the combination of existing knowledge and (2) and to exploit the previously unexplored potential of the resulting technology. For research organizations, similar conditions for value creation have been identified. Leitner and Warden [2004] assume that an alignment of the organization's 'intellectual capital' (p. 39), i.e. of its technological, human and organizational resources, to create, share and exploit knowledge within R&D projects is a necessary condition for value creation. Even though the authors cited here focus on the internal knowledge of an organization, there is strong evidence for the importance of external knowledge for this combination process [e.g. Laursen and Salter, 2006].

In this subsection, the focus will be set on the creation of different types of knowledge as well as on knowledge transfer within and between organizations. Further, emerging problems related to these processes are discussed.

2.2.1 The Organization's Activities of Exploration and Exploitation

The creation of innovation is part of a circle of exploration and exploitation [March, 1991; Nooteboom, 2000 (cited in [Gilsing and Nooteboom 2006])]. The former includes activities like 'search, variation, risk taking, experimentation, play, […] innovation' [March 1991, p. 71] and essentially refers to experimentation with new alternatives, the returns of which are uncertain and sometimes even negative. The latter is associated with concepts such as 'refinement, choice, […] efficiency, selection, implementation […]' (p.71) and describes the improvement and application of existing competences and technologies in order to create direct returns. At first glance exploitation seems to be more attractive because it yields more immediate returns. However, a balanced long term organizational strategy which integrates both cartesian [Stark, 2001] exploitation and stochastic exploration is esteemed to be more advantageous [March 1991; Gilsing and Nooteboom, 2006]. Before this background, the importance of a company's ability to create and maintain weak ties and flexible interaction with a variety of diverse knowledge sources has been stressed [Kaufmann and Toedtling, 2001]. Whether organizations actually pursue either predominantly explorative or exploitative activities reflects in changes on levels as diverse as competence, governance, network and process [Gilsing and Nooteboom, 2006] (Table 6).

Table 6: Key characteristics of exploration and exploitation [Gilsing and Nooteboom, 2006]

	Competence	Governance	Networks	Strength of ties	Transitional process
Exploration	• Radical innovation • Technology oriented • Experimentation with novel combinations • Tacit knowledge	• Spin-off, new entrants • Loose alliances • Limited use of contracts • Relation-based trust	• Dense, open networks • Informal, flexible ties • Limited size, high entry and exit • Locally embedded	• High frequency of interaction • Short duration • High(er) openness	• Divergence in knowledge and organization • Variety through break-up of existing networks and new relations to outsiders
Exploitation	• Incremental innovation • Product and process oriented • Experimentation in organization • Codified knowledge	• Entrance by incumbents • Formal alliances, acquisitions • Contracts • Intuition-based trust	• Non-dense, more exclusive networks • Formalization • Stabilization • Delocated	• Low frequency of interaction • Long duration • Limited openness	• Convergence in knowledge and organization • Selection by the institutional environment

2.2.2 Knowledge

The above mentioned modes of exploration and exploitation are linked with different types of knowledge and knowledge creation [Nonaka, 1994; Popadiuk and Choo, 2006]. The basic concepts with respect to knowledge, knowledge transfer and issues related to them are highlighted hereafter.

2.2.2.1 Distinction between Data, Information, and Knowledge

Data is defined as ‘objective facts about events’ [Davenport and Prusak, 2000, p.2]. It does not convey any judgment or interpretation nor does it tell anything about its own relevance. Data, however, is considered a sort of message. As such its role is to communicate a meaning from a sender to a receiver. The receiver has to decide whether the information he or she receives makes some difference ‘in his outlook or insight’ (p.3).

For data to become information, it must be contextualized, categorized, calculated, corrected and/or condensed. Information technology can often be helpful for those processes, an exception being contextualization where the value of such technology is rare.

Finally knowledge is referred to as ‘a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information’ (p. 5). The transformation of information into knowledge occurs through such processes as comparison, deduction of consequences, drawing of connections and conversation with other people. The value of information technology for those transformation processes is either very limited or equal to zero [Davenport and Prusak, 2000]. Another important aspect of knowledge is its ‘ability to apply information – consciously or otherwise – to solve a problem’ [Pike and Gahegan, 2007, p. 662]. However, the human acquisition of knowledge is subject to cognitive limitations of the human brain. A consequence of this is that increase in depth of knowledge is directly coupled to decrease in breadth of knowledge. The knowledge which features such characteristics is called *specialized knowledge* [Grant, 1996].

2.2.2.2 *Different Views on Knowledge*

There exist two essentially different views on knowledge. Whereas von Krogh [1998] refers to them as *cognitivist* and *constructionist* perspectives, Sveiby [2007 (cited in [Paulin and Suneson, 2012])] calls the former *knowledge as an object* (K-O) and the latter *knowledge as a subjective contextual construction* (K-SCC).

The cognitivist view on knowledge is rooted in research in computer science and the consequential modeling of the human mind as an information processor (cf. Paragraph 2.4.5.1). From this perspective, knowledge is considered to be universal and independent of personal perspective, a consequence being that it can be easily encoded (cf. Paragraph 2.2.5), stored, and transmitted to others [von Krogh, 1998].

From a constructivist perspective, which is based in neurobiology, cognitive science, and philosophy, knowledge is created in individuals. The process of this creation or construction is closely linked to e.g. previous experience. Hence, knowledge cannot be seen as universal. In this view, there also exist forms of knowledge which are difficult to express and thus to share [von Krogh, 1998] (cf. Paragraph 2.2.4.2.1).

2.2.2.3 *Knowledge Categories*

2.2.2.3.1 Explicit versus Implicit or Tacit Knowledge

The most well-known dichotomy related to knowledge is the distinction between *explicit* and *implicit* or *tacit knowledge*. While the former can be easily expressed in symbols, e.g. it can be written down [Grant 1996], the latter, which is closely associated with '"know how", skills and "practical knowledge"' (p. 377), is difficult if not impossible to codify. Polanyi [1983] refers to tacit knowledge as key ingredient for the solution of the fundamental paradox in problem solving (cf. Paragraph 2.5.2.1.1): Either the problem solver knows what he or she is looking for, but then there is no problem to be solved. Or the problem solver is ignorant regarding the goal of its search. In this case, however, there is no hope to identify a solution. By the creation of the 'tacit dimension' of knowledge, Polanyi offers a solution to this issue. Tacit knowledge can be further divided into cognitive and technical elements [Nonaka, 1994]. Cognitive elements are mental models such as schemes and parameters, which provide individuals with a perspective on the world. Technical elements describe 'know-how, crafts and skills that apply to specific contexts' (p. 16). One important aspect of tacit knowledge is its *stickiness*, which makes it difficult and costly to transfer [Szulanski, 1996]. One instance of knowledge which can be also classified as tacit knowledge is *empirical knowledge*. Chen [2010] characterizes this type of knowledge (Table 7) and divides it into the four layers *Know-What*, *Know-Why*, *Know-How*, and *Know-With*.

Table 7: Empirical knowledge characterization [Chen, 2010]

Empirical Knowledge		Description
Composition Element	Problem/Cause/ Solution	As either a problem solving method or a modified action, empirical knowledge can be described by three elements of problem, cause, and solution.
Feature	Tacit	Characterized as generally having a particular context and personalization, empirical knowledge is not easily understood, learned, imitated, communicated, transferred, and shared.
Characteristic	Hierarchical	Empirical knowledge can be distinguished into different layers based on the use purpose.
	Descriptive	'Descriptive' refers to the concept, class, and structure of empirical knowledge.
	Causal	'Causal' refers to the causality and consequence of empirical knowledge.
	Procedural	'Procedural' refers to the operational activity and procedure of an event.
	Relational	'Relational' refers to how operational activities of an event are related.
Trait	Action-oriented	Empirical knowledge can be viewed as action-oriented knowledge, which is represented by conditional action.
	Skillful	Skill indicates the object-oriented expressional behavior, which is difficult to be represented by language. While empirical knowledge can be treated as action-oriented knowledge, an action represents knowledge through its skill.

2.2.2.3.2 Taxonomy According to Blackler

Based on Collins [1993 (cited in Blackler, 1995])], and adding to a literature review, Blacker [1995] suggests that knowledge can be *embrained*, *embodied*, *encultured*, *embedded* and *encoded*. *Embrained knowledge* is considered to depend on conceptual and cognitive abilities and to cover *knowledge that* and *knowledge about*. According to Blacker, the capability of double-loop learning [cf. e.g. Argyris and Schön, 1978; Argyris, 1991] (cf. Paragraph 2.4.2.2.1) is an important instance of embrained knowledge. *Embodied knowledge* is defined as being action oriented and only partly explicit. It depends on physical presence and relates to *knowledge how* and *knowledge of acquaintance*. The concept of *encultured knowledge* is associated with shared understanding. It is socially constructed and depends on language, culture and negotiation. According to Blackler, the attribute of the following type of knowledge refers to Granovetter's [1985] concept of 'embeddedness' describing the impact of social structure on human action. Accordingly, *embedded knowledge* is defined by terms as 'technologies, roles, formal procedures and emergent routines' [Blackler, 1995, p. 1024]. Finally, *encoded knowledge* can be expressed by signs and symbols and can thus be communicated rather easily by documents or information technology.
In his literature review, Blackler also identifies general trends of transformation from organizational dependence on embedded and embodied knowledge towards dependence on embrained and encultured knowledge.

2.2.2.3.3 Taxonomy according to Alavi and Leidner

Alavi and Leidner [2001], analyze knowledge from a perspective of information technology-based knowledge management (cf. Paragraph 2.2.4.1). Their taxonomies and associated examples can be found in Table 8.

Table 8: Knowledge taxonomies according to Alavi and Leidner [2001]

Knowledge Types		Definitions	Examples
Tacit		Knowledge is rooted in actions, experience, and involvement in specific context	Best means of dealing with specific customer
	Cognitive tacit	Mental models	Individual's belief on cause-effect relationships
	Technical tacit	Know-how applicable to specific work	Surgery skills
Explicit		Articulated, generalized knowledge	Knowledge of major customers in a region
Individual		Created by and inherent in the individual	Insight gained from completed project
Social		Created by and inherent in collective actions of a group	Norms for inter-group communication
Declarative		Know-about	What drug is appropriate for an illness
Procedural		Know-how	How to administer a particular drug
Causal		Know-why	Understanding why the drug works
Conditional		Know-when	Understanding when to prescribe the drug
Relational		Know-with	Understanding how the drug interacts with other drugs
Pragmatic		Useful knowledge for an organization	Best practices, business frameworks, project experiences, engineering drawings, market reports

2.2.2.4 Knowledge Creation

As one of the founders of the 'constructivist' view on knowledge, Nonaka [1991] states that knowledge creation is more than '"processing" of objective information' (p. 97). More likely it can be described as a social conversion process of either explicit or tacit knowledge into, again, explicit or tacit knowledge [Nonaka and Takeuchi, 1995]. The interchange between those two dimensions is important in order to avoid 'superficial interpretation of existing knowledge' [Nonaka, 1994, p. 20].

Socialization, the first conversion process, transforms tacit knowledge into tacit knowledge through interaction between individuals through shared experience. The process of conversion of explicit knowledge into explicit knowledge takes place when people combine different bodies of explicit knowledge during e.g. meetings. Accordingly, this type of conversion is referred to as *combination*. The processes which convert tacit knowledge into explicit knowledge and vice versa are called *externalization* and *internalization*. The former implies an articulation of tacit knowledge and is facilitated by dialogue, reflection and the concept of metaphors. The latter refers to the act of learning and the acquisition of tacit knowledge through practice and action [Nonaka, 1994; Nonaka and Toyama, 2002]. The model of organizational knowledge creation (SECI) along two dimensions – ontological and epistemological – is depicted in Figure 10.

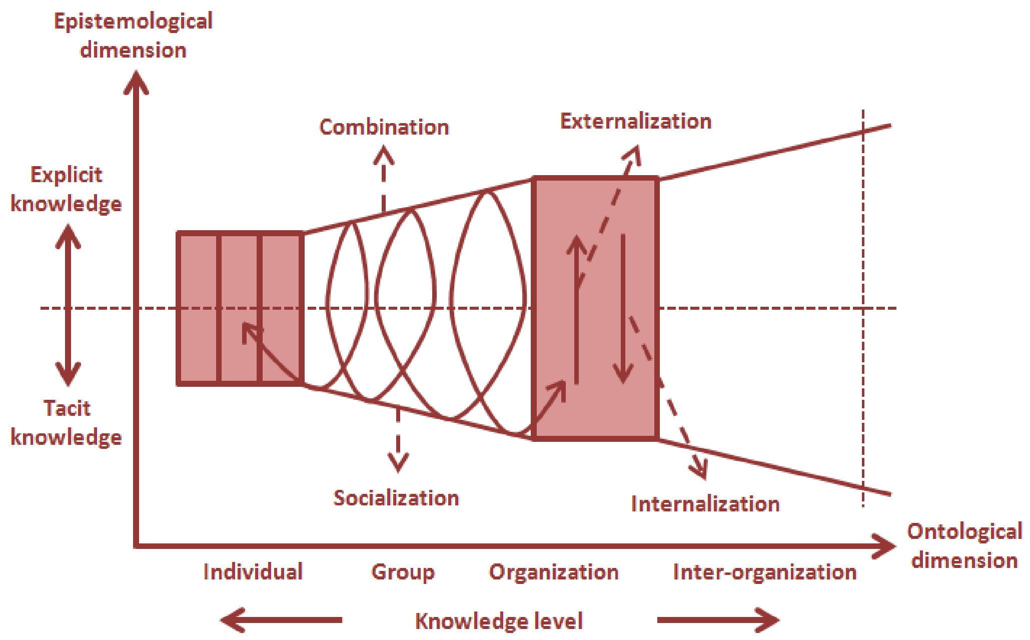


Figure 10: Model of organizational knowledge creation [Nonaka, 1994]

2.2.2.5 Codification

Codification is a conversion process of knowledge into messages which can perhaps be processed as information [Cowan and Foray, 1997]. Even though this conversion process is associated to initial costs [Cowan and Foray, 1997], it has some important advantages. It allows setting knowledge into a context of rules and relationships which allow easier communication. Further it makes knowledge to a certain extent independent from the agent who created it [Kogut and Zander, 1992].

However, knowledge codification is not without risk. As the value of a codified message depends on its interpretation by the recipient (cf. Paragraph 2.2.2.1), the latter has to be taken into account during the codification process. He or she must be able to acquire context-depending knowledge for the decodification, the interpretation and, finally, the application of the knowledge conveyed by the message [Dasgupta and David, 1994; Cohendet and Meyer-Kramer, 2001; Hall, 2006]. Roberts [2009] points out another drawback of codification, more specifically with respect to the use of information technology for that purpose. Roberts argues that such codification, by reducing often complex and rich knowledge to its perceived key components, lead to ignorance. According to Roberts, that problem emerges for every abstraction process.

2.2.2.6 Link between Types of Knowledge, Knowledge Creation and Innovation

Based on a literature review, Popadiuk and Choo [2006], show that the type of innovation which an organization can create depends on the processes of knowledge creation which take place in that organization (cf. Paragraph 2.1.1.1). If existing market knowledge is used, a firm's exploration process implying socialization and externalization of tacit knowledge can lead to revolutionary innovation and major process innovation. When a company applies tacit knowledge to new market knowledge, radical innovation and major product/service innovation can result. In the case of existing market knowledge, an exploitation process fueled by the combination and internalization of explicit knowledge, however, leads more probably to incremental product, service and process innovation. Finally, explicit knowledge applied on new market knowledge can result in niche innovation and market breakthrough.

2.2.3 Knowledge Creation and Front End of New Product and Process Development

Recently, the model of knowledge creation has been used as a framework for analyzing New *Product (and Process) Development (NP(P)D)* and its front end [Koen *et al.*, 2001] (cf. Paragraph 2.5.2.2.5). Richtnér *et al.* [2013], for example, investigated six NPD projects at two companies. They conclude that changes in the attribution of resources in terms of time and human competence often have critical impact on the knowledge creation processes in that kind of projects. Akbar and Tzokas [2013] finally focus on the front end to the NPD process and map, among other parameters, the sources and the nature of knowledge over different stages of a knowledge conceptualization process.

2.2.4 Management, Transfer, Sharing and Integration of Knowledge

Knowledge creation depends on effective access and application of information and knowledge stemming from various disciplinary and non-disciplinary sources [Hemlin *et al.*, 2008]. In this respect, knowledge management and knowledge transfer are important if not crucial activities.

2.2.4.1 Knowledge Management

Knowledge management treats the problem of the mobilization of all the knowledge resources held by individuals and groups and of the transformation of those resources into value-creating activities [von Krogh 1998]. Knowledge management activities focus on providing individuals with potentially useful information and on enhancing the assimilation of this information by the construction and management of knowledge stocks [Alavi and Leidner, 2001]. Normally, the scope of this activity is the organization [Serban and Luan, 2002; Chen, 2010].

Two strategies for knowledge management can be distinguished [Hansen *et al.*, 1999]. The first one is based on codification and focuses on the storage of codified knowledge in electronic databases in order to allow easy access to that knowledge by all members of the organization. The second strategy focuses on personalization of knowledge. I.e., knowledge stays closely related to the initial knowledge source and is distributed by person-to-person contacts. According to this strategy, information technology serves the purpose of communication rather than storage of knowledge. According to Hansen *et al.*, the former strategy better suits companies which follow a strategy based on mature products. Organizations focusing on product innovation, however, should follow the latter strategy because innovations rely on knowledge which risks getting lost when encoded.

Kazanjian and Drazin [2012] relate dominant knowledge management tasks to specific organizational activities. In their model, extending an existing product line is associated to leveraging of existing knowledge. The development of a new product platform requires a recombination and extension of existing knowledge stemming from previously unrelated disciplines. Finally, the import and development of new knowledge into an organization is seen to be crucial for the creation of a new business.

2.2.4.2 Knowledge Transfer

Knowledge transfer (KT) is defined as a 'process through which one unit […] is affected by the experience of another' [Argote and Ingram 2000, p. 151]. In the literature, with some rare exceptions [e.g. Cohendet and Meyer-Kramer, 2001], the term *technology transfer* is either used synonymously to knowledge transfer or describes a subset of it [e.g. Kingsley *et al.*, 1996; Siegel *et al.*, 2004; Bekkers and Bodas Freitas, 2008]. Throughout this chapter, the terms will be used synonymously.

Even though knowledge transfer involves the transfer and distribution of knowledge at the individual level [Argote and Ingram, 2000, Braun and Hadwiger 2011], transfer can also occur at and between different systemic levels e.g. individuals, explicit sources, groups, product lines, departments, divisions or organizations [Argote and Ingram, 2000; Alavi and Leidner, 2001]. In fact, the movement of knowledge at higher systemic levels than the individual level has been the focus of KT analysis [Wang and Noe 2010].

Szulanski [1996] stresses the importance of the term 'transfer' in order to emphasize that the movement of knowledge is a 'distinct experience' (p. 28) which depends of the characteristics of all involved parties. According to Szulanski, transfers of best practice are dyadic exchanges in which the identity of the knowledge recipient plays an important role.

The process of knowledge transfer involves several activities [Majchrzak *et al.*, 2004; Wang and Noe, 2010]: the sharing of knowledge by the knowledge source as well as the acquisition and application of knowledge by the recipient. The combination of the latter two activities, which are called *knowledge reuse* by Majchrzak *et al.* [2004], can be referred to as *knowledge integration* [Grant, 1996].

2.2.4.2.1 Knowledge Sharing

Wang and Noe [2010], by drawing on e.g. Cummings [2004], define *knowledge sharing* as the process of provision of information and know-how in order to foster problem solving, idea generation, and the implementation of procedures. Even though Cummings initially also covered the receipt of information by the term, it is often seen as a different activity. In the literature dealing with knowledge sharing, there is a lack of consensus on whether efficient and valuable knowledge sharing requires close coupling or distant and infrequent relationships between the different participants [Hansen, 1999; Dunne and Dougherty, 2012]. Closely linked to this is the – again not decisive – discussion about the value of knowledge brokering [Fleming et al., 2007], where a knowledge broker is defined as an agent who represents the only link between otherwise unrelated individuals or groups.

Wang and Noe [2010], based on a literature review, develop a framework which highlights issues of knowledge sharing research which either have been addressed or which, according to the authors, should be addressed. Among the interesting but under-investigated topics, aspects of diversity in teams and cultural aspects like group membership (cf. Subsection 2.3) are identified.

2.2.4.2.2 Knowledge Integration

Several authors identify one activity as crucial for the process of knowledge transfer. What Alavi and Leidner [2001] call knowledge application and what Majchrzak *et al.* [2004] refer to as knowledge reuse could essentially be referred to as knowledge integration, as Grant [1996] calls it. It relates to the integration or application of functional, activity-related, specialized as well as task-related capabilities in order to produce value in various forms like e.g. innovative products [Grant, 1996; Majchrzak *et al.*, 2004]. One major difficulty in knowledge integration emerges from the necessity to bring together several areas of knowledge [Grant, 1996]. Another aspect in the literature is the application of cognitive routines or ‘scripts’ [Gioia and Poole, 1984, p. 454] during problem solving. They are said to reduce the cognitive load of a problem solver but also to cause barriers for the search and application of new knowledge [Alavi, 2000 (cited in [Alavi and Leidner, 2001]); Alavi and Leidner, 2001].

2.2.4.2.3 Indirect Impact of Knowledge Transfer

Besides the direct impact of knowledge transfer on the quality and quantity of technological innovation [e.g. Fleming and Sorenson, 2004, Huggins et al., 2010], knowledge transfer, or the experimentation with new technologies can also have another more indirect impact on an organization. Experimentation with new technologies can change the mode of reasoning in organizations, e.g., the way how problems are formulated and solved. Further, it can challenge existing cognitive structures of individuals [Ahuja and Lampert, 2001].

2.2.5 Knowledge Transfer from Scientific to Industrial Organizations

Technology transfer from scientific organizations to industrial organizations plays an important economic role (cf. Chapter 2.1.2). Siegel *et al.* [2004] describe a university-industry technology transfer process based on licensing (Figure 11) as the most commonly used. However, several channels of technology transfer, like e.g. transfer of employees, hiring of students, usage of patents and scientific papers [Siegel *et al.*, 2004; Bekkers and Bodas Freitas, 2008] have been identified.

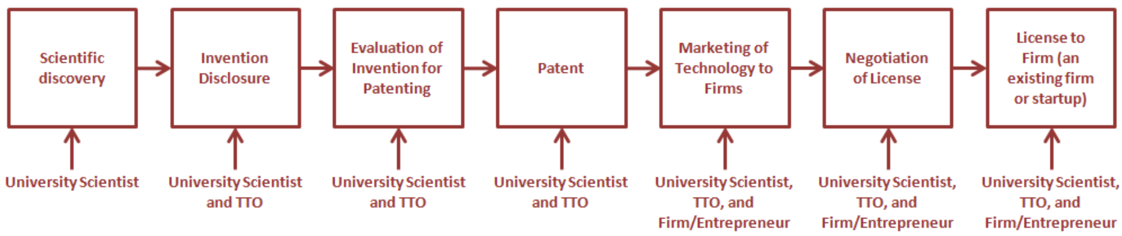


Figure 11: Technology transfer process based on licensing [Siegel *et al.*, 2004]

Bekkers and Bodas Freitas [2008] regroup 23 forms of knowledge transfer from universities to firms into six clusters: scientific output, informal contacts and students; labor mobility; collaborative and contract research; contacts via alumni or professional organizations; specific organized activities; patents and licensing. Drawing on an empirical investigation, Bekkers and Bodas Freitags show that the channels by which university-industry knowledge transfer takes place do not depend significantly on the industrial sectors in which the knowledge is applied. More likely the preferred way to transfer knowledge is related to (1) the basic characteristics (e.g. tacitness and systemicness) of the knowledge to be transferred; (2) the discipline in which the knowledge originates and; (3) (to a lesser extent) characteristics (e.g. seniority, research environment) of individuals and organizations participating in the knowledge transfer process. Interestingly, channels like *technology transfer offices*[2] and university patents are of rather low importance for knowledge transfer processes.

[2] A technology transfer office (TTO) is defined as acting as a technological intermediary to industry. It is specialized in activities such as search for partners, management of intellectual property and business development [Porcel *et al.*, 2012].

2.2.6 Factors Influencing Knowledge Transfer

Besides the influence of knowledge characteristics, disciplinary origin and individual characteristics, several other factors which influence knowledge transfer and its impact have been identified.

2.2.6.1 Personal Movement

Kane *et al.* [2005], drawing on a meta-analysis, state that personal movement, both within and between organizational boarders, is an important factor for the success of knowledge transfer. A reason for this is that knowledge transfer requires a certain trust between the donor and the recipient side [e.g. Santoro and Gopalakrishnan, 2000; Braun and Hadwiger, 2011]. Another possible cause for the importance of personal movement is the above mentioned difficulty to codify certain types of knowledge (cf. Chapter 2.2.2.3). Evidence for that difficulty has been provided by Berry and Broadbent [1987]. In their laboratory experiment, it could be shown that knowledge was successfully applied to a different task even though that very knowledge could not be expressed by the participants. A third aspect which could explain the importance of personal movement is the impact of social identity, in terms of e.g. organizational membership, on the willingness or capacity to implement new knowledge. It can be argued that only after a knowledge bearer has moved to a new organization and has spent there a certain time, other members of that organization are willing to integrate the knowledge of that knowledge bearer. Evidence for the importance of group membership to the integration of knowledge stemming from another individual has been provided experimentally [Kane *et al.*, 2005]. Kane *et al.* show that members of a given group are more likely to apply superior knowledge to a task at hand from an individual if that individual is considered to have the same social identity.

2.2.6.2 Breadth and Depth of Used Knowledge

Laursen and Salter [2006] investigated the relationship between the companies' search characteristics for external knowledge and the innovative performance of those companies, which will be interpreted here as an indicator for the effectiveness of knowledge transfer. In this empirical investigation which analyzed 2707 manufacturing firms, the impact of two characteristics of search for knowledge outside the company, its breadth and its depth, were studied. The former describes on how many different sources of knowledge or information (e.g., consultants, universities and conferences) a firm relies in order to innovate. The latter refers to the degree to which the previously mentioned knowledge sources are used intensively. The results of the study suggest an inverted U-shaped relationship between both breadth and depth of the external search for knowledge and the innovative performance of a firm (Figure 12). These results highlight both the value of knowledge stemming from different sources and the drawbacks like increased costs and decreased efficiency of too intensive and extensive external knowledge search.

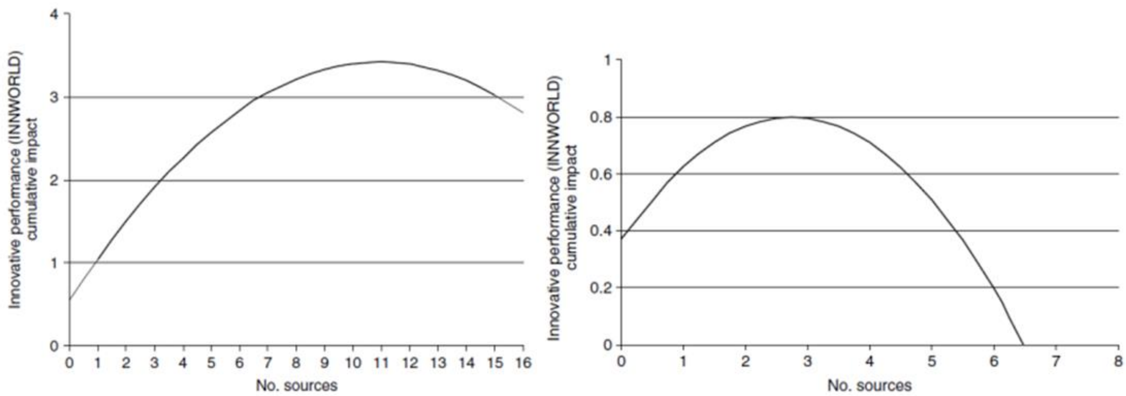


Figure 12: Relationship between breadth and depth of a firm's external knowledge search and its innovative performance [Laursen and Salter, 2007]; left: relation between search breadth and performance; right: relation between search depth and performance

2.2.6.3 *Organizational Structure and Distance*

Organizational aspects were also found to affect knowledge sharing and knowledge transfer within and between organizations.

Santoro and Gopalakrishnan [2000], having analyzed 21 research centers as well as 421 companies in a broad disciplinary context, argue that organizational structure influences knowledge transfer in its different phases. Whereas mechanistic structures are referred to as facilitating the activity of knowledge acquisition, organic organizational structures are more likely to foster the creative processes of knowledge creation (which, according to Santoro and Gopalakrishnan, is also included in knowledge transfer) and knowledge integration[3].

In this context, the work of Heinze *et al.* [2009], even though not explicitly treating knowledge transfer, is interesting. They investigated organizational conditions under which 'creative scientific achievements' occurred in scientific institutions working in the fields of nanotechnology and human genetics. The conclusion drawn by Heinze *et al.* is that large, hierarchical structures hinder the exploration mode necessary for scientific value creation. Smaller groups, which integrate different complementary scientific skills and which allow communication among the group members, are more likely provide a stimulating environment for the acquisition of new knowledge. One reason for that positive effect of small group size is that it allows efficient testing and quick discard of less promising solution paths to a problem at hand. Another interesting observation in the same work is that groups discuss topics close to their expertise more likely with groups of other organizations whereas complementary multidisciplinary knowledge and skills are acquired among groups from the same organization. From that finding, the authors of the study derive an 'inverse relationship between cognitive distance and physical distance' (p. 617) in scientific communication.

2.2.7 Knowledge and Technology Transfer Problems

Several authors investigated problems related to – or barriers for - university-industry technology transfer (UITT) (van Dierdonck and Debackare [1988 (cited in [Rohrbeck and Arnold, 2006])] and Cummings and Kiesler [2005] do not explicitly refer to UITT). Table 9 gives an overview of the

[3] Mechanistic structures are characterized by a high number of hierarchical levels, an emphasis on centralization and the differentiation of functional tasks. Organic structures are associated with a lesser degree of hierarchy, lower levels of centralization and an emphasis on integrative task solving [Santoro and Gopalakrishnan, 2000; Burns and Stalker, 1961].

results of those studies. The most noticeable issues on both the university or donor side and the industry or recipient side are the lack of mutual understanding of the partner's culture, context, constraints and goals and problems regarding the communication of knowledge between a specialist and a non-specialist. Furthermore, research organizations are considered to hinder technology transfer processes due to rigid IP and secrecy policies.
Other researchers [Gemünden and Walter, 1996 (cited in Albers *et al.*, 2014)] classify knowledge transfer barriers into four categories. Those barriers relate to problems of *not knowing*, *not wanting*, being *not capable* and being *not allowed*. Barriers of not knowing refer to missing knowledge about eventual partners or even about their existence. Barriers of not wanting include missing trust or credibility as well as corporate values which are incongruent with knowledge and technology transfer. Problems classified under 'being not capable' relate to communication difficulties and to the incapacity to adapt to a specific technology. Finally barriers of being not allowed characterize organizational and legal issues which impede e.g. the release or purchase of technologies [Lohmann, 2013; Albers *et al.*, 2014]. Three of the four types of barriers relate to essentially managerial, legal or motivational aspects. However problems of 'being not capable' concerning communication and technical problems are of special interest with regard to the present research. From a survey inquiring into the most important TT barriers, Albers *et al.* identify the difficulty to integrate the transferred technology into the product as the most important issue related to 'being not capable'. That research hence supports the more generic statements related to knowledge integration described in Paragraph 2.2.4.2.2.

Table 9 : Overview of literature addressing problems related to knowledge/technology transfer[4]

Problems/barriers for knowledge/technology transfer	Research Organization	Technology Transfer Office	Industrial Organization
Lack of mutual understanding of culture, context, constraints, goals	1, 2, 5	1	1, 2, 5
Insufficient reward system	1	1	
Bureaucracy of administrators	7	1	
Insufficient resources devoted	1	1	
Poor marketing/negotiation skills		1	
IP strategy/problems	1, 5, 7	1	5, 7
Unrealistic expectations	1,7	1	
"Public domain" mentality	1	1	
Secrecy	2, 5, 7		5
Communication problems (specialist to non-specialist)	2, 4, 5, 6		3, 4, 5, 6
Lack of face-to-face contact	2		
Lack of trust			2
Lack of dedicated structures	7		2, 3
Lack of knowledge about TT process			2
Structure and responsibility changes			5
Mutual understanding of processes and outcome	5, 7		5, 7
Pure and "long term" orientation	7		

2.2.8 Absorptive Capacity

Many of the issues related to the transfer of knowledge can be described as problems in terms of identification of potential value of information obtained from a certain source, assimilation of this information and its transformation into new knowledge. The degree to which an organization masters these three activities, recognition of information, its assimilation, and its application to

[4] 1: Siegel *et al.*, 2004 ; 2: Braun and Hadwiger, 2011 (literature review); 3: Santoro and Gopalakrishnan, 2000 ; 4: Carayannis *et al.*, 2006; 5: van Dierdonck and Debackere, 1988 (cited in Rohrbeck and Arnold, 2006); 6: Cummings and Kiesler, 2005; 7: Bruneel et al., 2010

some valuable end, defines the *absorptive capacity* of that company [Cohen and Levinthal, 1990]. In order to develop that capacity within an organization and its members, two aspects are important. The first implies that the information under question has to be processed with a certain effort in order to combine it with already possessed knowledge [Lindsay and Normann, 1977], to extract potentially valuable elements and to stock them in memory. The second important factor, according to Cohen and Levinthal, is the existence of a certain diversity of knowledge at the entity which is involved in the knowledge transfer process. This is the case because knowledge diversity increases both the probability that incoming information is related to existing knowledge and that new combinations of existing knowledge are established. The model of absorptive capacity has been applied as a framework to the analysis of knowledge transfer in several high-technology sectors [e.g. McMillan *et al.*, 2000; Pandza and Holt, 2007].

2.2.9 Conclusion

In order to innovate, organizations have to alter between processes of exploration and exploitation, which are related to different activities of knowledge creation. The latter are considered to be essentially social conversion processes of different types of knowledge. Important instances of knowledge creation are new product and process development and its front end as well as knowledge transfer and technology transfer, the latter two terms being used as synonyms in this chapter. Knowledge transfer, within an organization or across organizational boundaries, covers both sharing of knowledge by the knowledge source and integration of knowledge by the recipient (Figure 13).

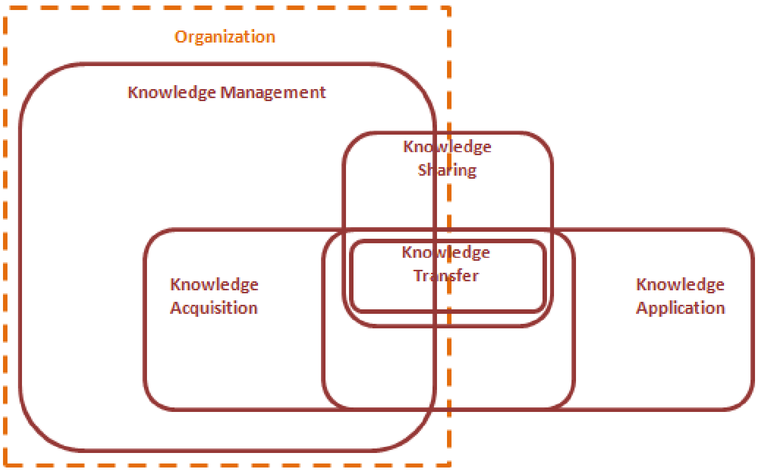


Figure 13: Schematic representation of knowledge-related activities

Codification, i.e. the transformation of knowledge into information transmitted by symbols, is one of the most important ways to transfer knowledge. However it bears the risk of excessive simplification and decontextualization thereby hindering the effective application of knowledge to new contexts. Accordingly, among the most important barriers for effective knowledge and technology transfer, the lack of mutual understanding of culture and context as well as communication problems between knowledge source and knowledge recipient have been identified in the literature. To those problems, which are suspected to impede the capacity for technology transfer, can be added technical problems related to the integration of a technology into a given product. Finally, the ability of an organization or an individual to identify potentially valuable information or knowledge, to assimilate and apply it in order to create new knowledge and thus value is called absorptive capacity. The improvement of that absorptive capacity requires intensive knowledge processing capabilities and an extensive interdisciplinary knowledge base at the receiving entity.

As stated above, face-to-face meetings and problem solving in groups are essential to most of the knowledge creation processes as well as to knowledge transfer. In the following subsection, the theory of group problem solving in general and interdisciplinary group problem solving in particular as well as problems related to these processes and solution concepts for the latter are discussed.

2.3 Team Level

2.3.0 Introduction

A team is a group of two or more individuals who interact over a certain time in order to achieve a common goal or objective. Within a team each member performs specific roles or functions [Mathieu *et al.*, 2000; Salas *et al.*, 1992 (cited in [Mathieu *et al.*, 2000])]. But for the effectiveness of a team, communication, collaboration and coordination are vital [Jackson *et al.*, 2006].
Organizational, task, and team structures; team processes; as well as team outcomes have been identified as essential mutually influencing aspects of team activity [Paletz and Schunn, 2010] (Figure 14). The first complex refers to resources which a team can access and to the composition of the team. Relevant team processes include communication among team members and the way conflicts are resolved. Finally Team Outcomes describe the productivity of a team and team member satisfaction. The present model will serve as a framework for the following subsection. First, an overview of task and team structures will be provided. It follows a brief discussion about both positive and negative outcomes of team work. Then, processes which lead to problems in team work and strategies to engage these issues will be highlighted. In the last paragraph, the information processing perspective on reasoning and its application on group processes will be briefly outlined.

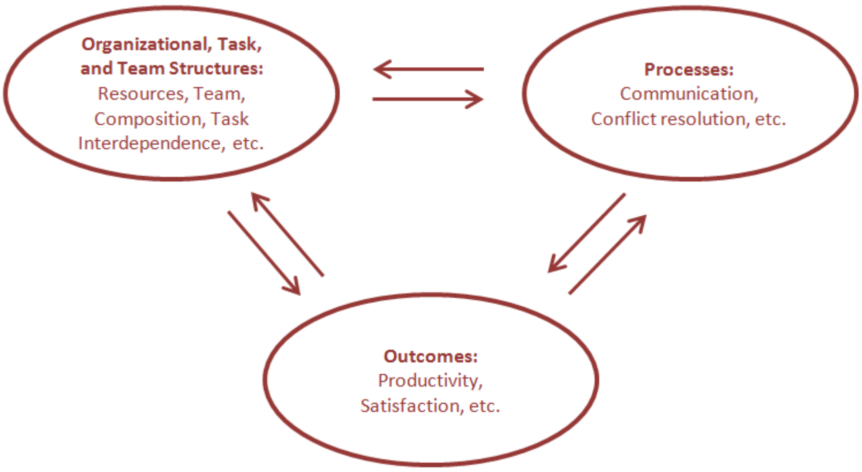


Figure 14: Mutually interacting concepts in teamwork [Paletz and Schunn, 2010 (based on [Saunders and Ahuja, 2006])]

2.3.1 Task and Team Structures

2.3.1.1 Categorization of Team Tasks

McGrath [1984], based on a literature review, provides a categorization of team or group tasks along two dichotomies. The first is a distinction between conceptual and behavioral features of the task and the second assigns either conflict or cooperation as essential task characteristic (Figure 15). Reducing the scope of analysis on conceptual group activities, four group tasks can be identified. Creative idea generation and intellective problem solving as being essentially based on cooperation and decision making and resolution of conflicts of viewpoints as conflict-based tasks.

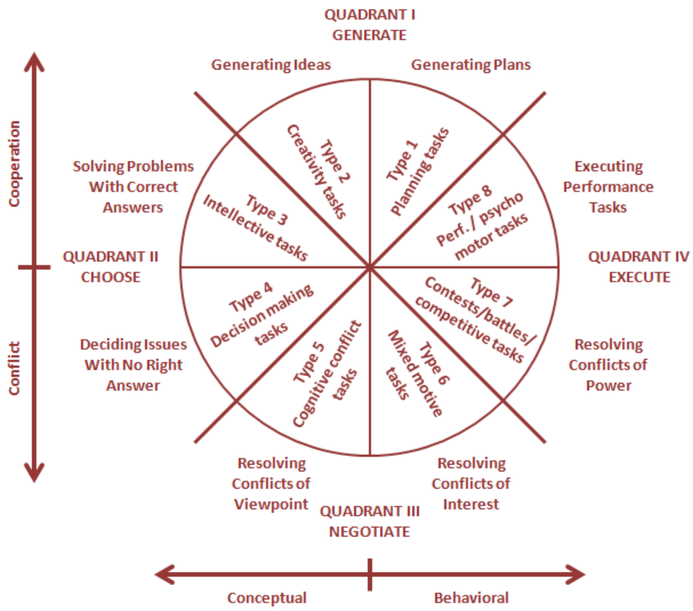


Figure 15: Categorization of group tasks according to McGrath [1984]

2.3.1.2 Diversity in Team Composition

According to Jehn *et al.* [1999], different types of diversity exist. *Informational Diversity*, which relies on differences in terms of e.g., education, experience and expertise, describes the degree to which team members differ in terms of knowledge bases and perspectives. *Social category diversity* refers to, often more explicit, aspects like ‘race’ (p. 745), gender and ethnicity. Finally, *value diversity* points to differences related to individual opinions on the goal of the task and the way these goals should be obtained.

Gebert *et al.* [2006] state that *functional diversity*, i.e. diversity in terms of the team members’ organizational occupation (e.g., marketing, research and development), can cause both informational and value diversity within a team. As academic disciplines essentially differ in terms of value [Bauer, 1990] as well as in terms of cognitive and social aspects (cf. Paragraph 2.1.4.1), disciplinary diversity will be regarded as equivalent to functional diversity here.

2.3.1.3 Interdisciplinary Teams

According to Grigg and colleagues [2003], several terms are used interchangeably in order to describe juxtapositions of and links between different disciplines. Some examples are cross-, inter-, trans-, multi-, and pluri-disciplinary. The OECD [1972 (cited in [Grigg, 1999])] has defined *interdisciplinary* to be an ‘adjective describing the interaction among two or more different disciplines’ ranging ‘from simple communication of ideas to the mutual integration of organizing concepts, methodology, procedures, epistemology, terminology, data […]’ (p.25) and an *interdisciplinary team* as a group consisting ‘of persons trained in different fields of knowledge (disciplines) with different concepts, methods, and data and terms organized into a common effort on a common problem […]’. (p. 25). In accordance with this definition, here below it will be referred to interdisciplinary teams, interdisciplinary problem solving, etc.

2.3.2 Outcomes of Collaboration and Team Work

In the following paragraphs, findings and conclusions regarding positive and negative aspects of both, collaboration in general and multidisciplinary collaboration in particular are discussed.

2.3.2.1 Positive Outcomes of Collaboration and Team Work

Based on a literature review, Lee and Bozeman [2005] identify division of labor, access to complementary and acquisition of new information and skills, time efficiency, intellectual stimulus, advantages for discussion, and access to equipment as positive aspects in collaborative research. Researchers who are involved in collaboration projects name increase of knowledge, higher scientific quality, and generation of new ideas as main benefits of collaboration [Melin, 2000].

Further, there is experimental evidence for the benefit of collaboration. Laughlin and McGlynn [1986] compared group and individual performance in solving an intellective problem solving task and found that groups outperform individuals. Communication of hypotheses and perception of evidence among the members of a group has been identified as one reason for superior problem solving performance in groups. Another explanation for benefits of collaborative intellective problem solving has been provided by Freedman [1992]. Through an experiment he could show increased aptitude of groups compared to individuals to identify a given pattern by introducing and testing multiple hypotheses. Freedman explains this finding with the difficulty of individual problem solvers to form mental representations of more than one hypothesis. In another experiment on hypothesis generation and validation, Okada and Simon [1997] could also produce evidence for superior group performance. In a discovery task essentially consisting of the generation and testing of hypotheses, Okada and Simon identified increased explanatory activities such as the discussion of ideas and the search for idea validation as main reasons for this superiority. As a further benefit of collaboration, the induction of more complex reasoning has been named [Antonio *et al.*, 2004]. In an experimental study, they showed that diverging opinions with respect to an issue within a group leads to increased differentiation and integration of different perspectives and dimensions in the reasoning of the group members. Finally, there is experimental evidence [see Hinsz *et al.*, 1997 for an overview] that groups use information processing strategies (cf. Paragraph 2.3.5) in a more reliable and consistent manner than do individuals.

Specifically the value of multidisciplinary or multifunctional team work has been pointed out in literature. In industry, cross-functional interfaces between research departments and product development units, including direct personal contact in cross-functional teams, are found to increase absorptive capacity (cf. Paragraph 2.2.8) and to reduce product development times [Cohen and Levinthal, 1990; Clark and Fujimoto, 1987 (cited by [Cohen and Levinthal, 1990])]. One main argument for the value of multidisciplinary team composition is that it entails information diversity, which has been found to be important for team performance and team effectiveness [Jehn *et al.*, 1999]. Another positive aspect of background diversity in groups is that it is supposed to bring forth a variety of ways to process information [Hinsz *et al.*, 1997]. Finally, in the field of scientific research examples have been provided for the positive relationship between interdisciplinary team composition and the quality of team output in terms of publications [Hicks, 1992].

2.3.2.2 Negative Outcomes of Collaboration and Team Work

However, some authors argue that groups fail to be effective in terms of decision making, and (creative) productivity [see Nemeth and Nemeth-Brown, 2003 for a review].

Further, disciplinary diversity is associated with integration costs [Cummings, 2004; Rafols and Meyer, 2006]. First, these costs are related to cognitive barriers [Grigg, 1999]. I.e., extra effort is required for coordination and communication in order to assure mutual understanding of the team members' knowledge [Rafols and Meyer, 2006]. Second, there exist cultural barriers [Grigg, 1999]. Diversity in disciplinary culture is often linked to value diversity, which has been found to increase group performance in the long term but to impede group effectiveness and efficiency in the short term [Jehn *et al.*, 1999]. A second example of the negative consequences of disciplinary diversity is the negative relationship between personal identification with the functional background of a group member and the individual performance of that group member in a cross-functional team [Randel and Jaussi, 2003].

2.3.3 Team Processes

In conclusion of the previous paragraph, it can be stated that collaboration and teamwork bear potential for creative problem solving and innovation whereas diversity in team composition can be a 'double-edged sword' [Simsarian Webber and Donahue, 2001, p. 142]. In the following paragraph, the processes occurring during team work which are responsible for the mixed results of teamwork will be described.

2.3.3.1 Groupthink, Majority Influence, and Knowledge Sharing

One explanation for the sometimes poor performance of teams is that errors and biases produced by individuals are often amplified in groups [Hinsz *et al.*, 1997]. Nemeth and Nemeth-Brown [2003] identify a 'strain for consensus' (p. 64) within groups as an underlying problem. They point to several group phenomena in order to explain this effect of premature convergence.

2.3.3.1.1 Groupthink

By the term *groupthink*, a reasoning mode is described 'that people engage in when they are deeply involved in a cohesive in-group, when the member's strivings for unanimity override their motivation to realistically appraise alternative courses of action' [Janis, 1972 (cited in [Aldag and Fuller, 1993])] p. 9]. In the case of groupthink, the group members try to avoid dissent, the consideration of negative points of a taken decision as well as the taking into account of alternatives [Nemeth and Nemeth-Brown, 2003]. The risk of occurrence of such thinking increases with high group member homogeneity in terms of social background and ideology, with high group cohesion, and when the group is exposed to strong and direct leadership [Aldag and Fuller, 1993; Nemeth and Nemeth-Brown, 2003].

2.3.3.1.2 Majority Influence

The normative influence of majority opinions in groups which has been shown by a lot of studies [Allen and Levine, 1969; Nemeth and Nemeth-Brown, 2003] can also be considered as a reason for deficient performance in teams. The tendency of individuals to agree with the opinion of other group members when the latter are in the majority is dangerous because it can occur when the majority is right but also when it is wrong [see Brodbeck *et al.*, 2002 for a review]. Further, facing an opposing majority leads to convergent thinking in individuals [Nemeth, 1986] and thus impacts creative thought when divergent thinking is required.

2.3.3.1.3 Information Sharing

The way in which groups share information is a third aspect which explains reduced group effectiveness in problem solving. According to Stasser and Titus [1985], group members tend to pool and to consider information with regard to the problem at hand more likely if this information was previously known by several group members. So called 'unique information' [Stasser and

Titus, 1985, p. 1477], especially when it could change a group's decision making process, risks to remain unconsidered [Stasser and Titus, 1985; Brodbeck *et al.*, 2002]. Further literature has confirmed these findings [Mohammed and Dumville, 2001].

2.3.3.2 Incoherent Interpretative Schemes

In groups composed of members having different functional and disciplinary backgrounds, there is an issue with incoherent 'interpretive schemes' [Dougherty, 1992, p. 181]. Examples for those divergent disciplinary or functional views on the same problem are languages or coding schemes [Tushman, 1978], diverging perceptions of problems and their priority [Dearborn and Simon, 1958], or even between entire 'thought styles' [Fleck, 1979, p. 99]. Insufficient alignment of these schemes can actually hinder the communication of information [Tushman, 1978] and, in the context of creative problem solving probably more important, the communication of ideas [Fleck, 1979]. The reduction of those communication barriers can lead to what Rafols and Meyer [2006], based on Grigg *et al.* [2003], call *conversiant capacity*. That concept refers to the ability to recognize and assimilate external information and knowledge and to apply it to specific goals. According to Rafols and Meyer [2006], conversiant capacity plays the same role in multidisciplinary teams as absorptive capacity (cf. Paragraph 2.2.8) in organizations.

2.3.3.3 Certain Types of Unmanaged Conflicts

Other factors which can impede group performance and which are to some extent linked to the concept of incoherent perspectives are conflicts. The subgroup of conflicts which is investigated in the following paragraph, contrary to groupthink, is a consequence of multidisciplinary group composition [Pelled, 1996; van Knippenberg and Schippers, 2007].

Functional and disciplinary diversity in teams is supposed to cause informational diversity [Jehn *et al.*, 1999] and value diversity [Jackson *et al.*, 1995] among the team members. Those kinds of diversity can lead to several types of conflicts, the most important being *relationship conflict*, *value conflict*, and *task conflict* [Gebert *et al.*, 2006].

Relationship conflicts are based on emotional tensions between group members and will not be further illustrated here. Value conflicts relate to differing or opposing perceptions regarding the outcome of the team process [Gebert *et al.*, 2006]. They have been found to reduce the effectiveness and efficiency of a team [Jehn *et al.*, 1999]. Task conflicts describe situations in which there is disagreement about which procedures and processes to choose in order to fulfill a certain task [Pelled *et al.*, 1999].

Whereas relationship conflicts and value conflicts are considered undesirable phenomena in team processes, research has provided mixed results regarding the evaluation of task conflict [see van Knippenberg and Schippers, 2007 for a discussion].

2.3.4 Improving Group Performance

In the present subsection, it has been illustrated how task and team structures as well as team processes relate to, often mixed, outcomes of team processes. In the following paragraphs, concepts which bear the potential to improve the outcome of teamwork will be outlined.

2.3.4.1 Managed Conflicts

Unmanaged conflicts have detrimental effects on group performance [Jehn, 1997; Jehn *et al.*, 1999]. They can reduce cooperation and thus induce dissipation of energy during team work [Baron, 1991]. However, carefully managed, some conflicts bear the potential to enhance group

performance [Tjosvold *et al.*, 1998; Gruenfeld *et al.*, 1996]. They may lead to reduced conformity pressure and to an increased generation of alternative solutions to a problem, thereby improving decision making performance [Schwenk and Valacich, 1994]. Further, managed conflict can help to profit from minority influence, which is, contrary to majority influence, supposed to increase the consideration of previously unshared information [Brodbeck *et al.*, 2002] and divergent thinking in groups [Paletz and Schunn, 2010; Hinsz *et al.*, 1997].
However, the benefit of conflict does not only depend on whether it is managed but also on the degree to which the group holds high levels of openness, psychological safety, and within team trust [de Dreu and Weingart, 2003]. Consistent with this view are the results of an experimental study carried out by Gruenfeld *et al.* [1996]. They showed that groups composed of members who are unfamiliar with one another outperform groups with familiar members when conflict potential is low whereas the opposite is the case of high conflict potential.

2.3.4.2 Shared Mental Models

One solution to problems induced by incoherent interpretative schemes (cf. Paragraph 2.3.3.2) and unshared frames of references [van Knippenberg and Schippers, 2007] within multifunctional and multidisciplinary teams are shared mental models [Hinsz *et al.*, 1997].
Mental models refer to 'organized knowledge structures that allow individuals to interact with their environment […] to predict and explain the behavior of the world around them [,] to recognize and remember relationships among components [and] to construct expectations for what is likely to occur next'. [Mathieu *et al.*, 2000, p. 274]. Additional functions of mental models are 'descriptions of system purpose [and] explanations of system functioning' [Rouse and Morris, 1985, p. 7].
According to Birkhofer and Jänsch [2003], different views on the contents of mental models, so called *modalities*, play an essential role in the creation of mental models. Among these modalities, dichotomies like e.g. part – whole, abstract – concrete, spatial – temporal, text – graphic, object – process can be found (p. 108).
Shared mental models in a team have several advantages. First, they help discovering conflicts which are due to divergent personal perceptions of a problem, thus making those conflicts explicit [Hinsz *et al.*, 1997]. Second, during creative problem tasks, shared mental models or problem models lead to the reduction of the required time for consensus building, facilitate the elaboration and extension of conceptual ideas, and improve the coordination of group members [Mumford *et al.*, 2001].

2.3.4.3 Methodological Approaches

2.3.4.3.1 Reducing Drawbacks of Brainstorming

Research has found evidence that performance of interactive groups, e.g. in *Brainstorming* sessions (cf. Paragraph 2.5.3.2.1) is inferior to performance of individuals working in nominal groups [e.g. Taylor *et al.*, 1958; Diehl and Stroebe, 1987], i.e. individuals generating ideas without interaction with other group members [Mumford *et al.*, 2001]. According to Taylor and colleagues, two phenomena could explain this effect. First, despite the fact that group members are instructed to suspend criticism, the implicit fear of being criticized for seemingly weak ideas could inhibit the willingness of certain participants to express all their ideas. Second, individuals could become victim of mental fixation (cf. Paragraph 2.4.3.2) on ideas expressed by others, which could interfere with their capability to follow different lines of thought. In order to deal with those problems, several methodological variations of brainstorming like e.g. *Brainwriting* and *Method 6-3-5* have been developed. Those methods are meant to reduce the above-mentioned negative phenomena by separating the processes of idea generation and idea presentation to a certain extent (cf. Chapter 2.5.3.1).

2.3.4.3.2 Stimulating and Managing Conflict

Managed conflicts can have positive impact on group performance (cf. Paragraph 2.3.4.1). Two methods or techniques which are sought to stimulate and to manage conflicts are *dialectical inquiry* and *devil's advocacy* [Mason, 1969 (cited in [Schwenk, 1990]); Schwenk, 1990].

Dialectical inquiry can be characterized as a three stage process. First, the identification of assumptions which underlie a given plan; second, the elaboration of a feasible and credible counterplan based on assumptions opposed to the ones of the initial plan; and finally, a discussion of the pros and cons of both the initial plan and the counterplan. During devil's advocacy, one or several members of the group are chosen to criticize a given plan or decision irrespective of whether the actually agree or not [Schwenk, 1990]. Alternatively, two groups develop alternative plans simultaneously but independent from each other. After mutual presentation and defense of each alternative with respect to the other group follows a session during which strategies are developed in order to best meet the opposite requirements [Barabba, 1983 (cited by [Lunenburg, 2012]); Lunenburg, 2012].

Based on a meta-analysis of 16 experiments, Schwenk [1990] argues for the value of devil's advocacy and, to a lesser degree, for the value of dialectical inquiry. However, Nemeth *et al.* [2001] found that contrary to genuine conflicts, artificial dissent which is introduced by devil's advocacy does not lead to significantly increased solution generation by groups. Furthermore, original dissent has been found to be more effective than contrived dissent in keeping group information search balanced [Schulz-Hardt *et al.*, 2002].

2.3.5 Information Processing View on Group Processes

Much like reasoning of individuals (cf. Chapter 2.4), group reasoning can also be modeled from an information processing perspective (cf. Paragraph 2.4.5.1).

One of these approaches is provided by Hinsz *et al.* [1997] (Figure 16: Generic information processing model applied on group processes [Hinsz *et al.*, 1997]). According to this model, the group obtains information embedded in a context from which the processing objective is derived. The processing workspace interacts with the information filtered by attention which is given to certain parts of the information corpus. Further, the input is structured, evaluated, interpreted and transformed into a representation which is then stored in memory. Whether group members perceive and treat information in the same or a different way is, according to Hinsz *et al.*, important for subsequent phases of the group process. After an eventual retrieval the information is schematically processed and integrated using a number of rules, strategies and procedures in order to generate a response to the processing objective. This response can be a choice, a conclusion, an insight or a solution to a problem and it generates a feedback to the initial information corpus.

Hinsz *et al.* use the information processing perspective on group processes in order to discuss some of the aspects mentioned in this subsection. In addition, they discuss differences between group and individual task fulfillment on the basis of this framework.

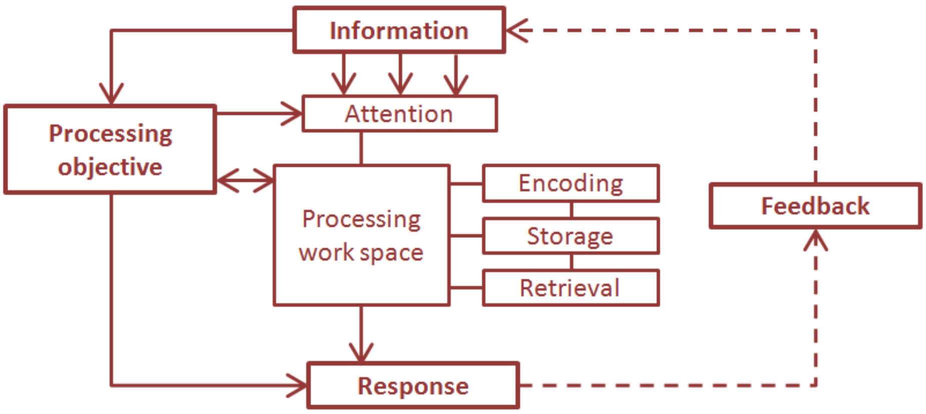


Figure 16: Generic information processing model applied on group processes [Hinsz *et al.*, 1997]

2.3.6 Conclusion

Groups are often used to engage in tasks like creative idea generation, problem solving, decision making, and conflict resolution. In order to do so, teams often use strategies in a more reliable manner than individuals. However, both homogeneous as well as heterogeneous groups – especially in terms of disciplinary and functional background – not always produce superior results. Three strategies can be identified to increase group performance. First, the identification and even introduction of conflicts can lead to improvement of group processes if these conflicts are carefully managed. Second, shared mental models, which rely on so called modalities, can lead to the communication and integration of diverse viewpoints. Finally, methodological approaches conceived to reduce mental fixation on certain concepts have proved some effectiveness. Finally, reasoning processes which occur within individuals have important influence on the way groups perform tasks.

Many of the issues of group problem solving are related to differences in individual reasoning processes. Hence, in the following subsection, theories and models regarding processes of individual creative reasoning and problem solving as well as individual differences in this respect are developed.

2.4 Individual Level

2.4.0 Introduction

The innovative capacity of an organization relies to a large extent on the creativity of its teams. The latter, in turn, depends – among other factors which have been discussed in the previous chapter – on the individual creative performance of the team members. In the present subsection, an overview of different aspects of personal creativity shall be given. First, creativity will be defined. Then, a short description of factors which have been found to foster creative performance like domain expertise and general creative thinking skills will be given and aspects which potentially hinder creative thought will be discussed. After the introduction of models which describe the overall creative process in theory, several cognitive views like the computational or the combinatorial perspective will be outlined. The chapter concludes with an overview of differences in terms of creative strategies and information processing among individuals in general and members of different disciplines in particular.

2.4.1 Definition and Categorization of Creativity

2.4.1.1 Definition of Creativity

Creativity has been described as one of the most complex human behaviors relying on several developmental, social, as well as educational experiences [Runco and Sakamoto, 1999]. The two most commonly described traits of creative work and its outcome are originality and value [e.g. Gruber and Wallace, 1999; Simonton, 2010]. Other aspects which are added to describe the creative process are purpose and duration [Gruber and Wallace, 1999]. Thus, creativity can be defined as a necessary concept for the purposeful production of output which cannot solely be explained with past knowledge [Hausman, 1975] and which can be used or applied by either the creator him or herself or by someone else to some significant goal.

In some domains like science, creative production is evaluated in terms of plausibility and originality, the former referring to conformity with previous norms and the latter requiring the opposite [Heinze *et al.*, 2009]. This is one reason why the investment in work which may lead to creativity can be seen as taking a calculated risk [Mumford *et al.*, 2002].

2.4.1.2 Categorization of Creativity

There exist different categories of creativity. Boden [Boden, 1998; Boden 1999; Boden, 2004] distinguishes two dimensions. The first categorization relates to the degree of novelty of the creative output and the second refers to the ways this output can be obtained. Whereas *H-creativity* (H for historical) refers to the generation of products which appear for the first time in history, *P-creativity* (P for psychological) produces outcome which is novel only to the creative individual him- or herself. The second categorization is rooted in the computational theory of creativity [Boden, 1999] (cf. Paragraph 2.4.5.1) and includes *combinational creativity* on the one hand and *exploratory-transformational creativity* on the other. Combinational creativity points to new and improbable combinations of known concepts such as poetic imagery but also to analogy (cf. Paragraph 2.4.4.2). Exploratory-transformational creativity comprises idea generation by

exploration of conceptual spaces[5] (exploratory creativity) and/or by change or deletion of one or more constraints of the conceptual space (transformational creativity).
A further typology of creativity is given by Heinze *et al.* [2007], who categorize scientific creativity by the type of the creative product (Table 10).

Table 10: Categorization of scientific creativity according to Heinze *et al.* [2007]

	Type of scientific research creativity	Examples
1	Formulation of new ideas (or set of new ideas) that opens up a new cognitive frame or brings theoretical claims to a new level of sophistication.	Theory of specific relativity in physics (by Einstein)
2	Discovery of new empirical phenomena that stimulates new theorizing.	Biodiversity → Theory of evolution (Biology) (by Darwin)
3	Development of a new methodology, by means of which theoretical problems can be empirically tested.	Factor analysis → Theory on mental abilities (Psychology) (by Spearman)
4	Invention of novel instruments that opens up new search perspectives and research domains.	Scanning tunneling microscopy → Nanotechnology (Physics) (by Binnig and Rohrer)
5	New synthesis of formerly dispersed existing ideas into general theoretical laws enabling analyses of diverse phenomena within a common cognitive frame.	General systems theory (Biology, Cybernetics, Sociology) (by Bertalanffy, Asbhy and Luhman)

2.4.2 Conditions Favoring Creativity

In order to be capable of creative achievement, individuals have to satisfy a certain conditions [Amabile, 1983; Amabile, 1998; Mascitelli, 2000]. According to Amabile [1983; 1998; Collins and Amabile, 1999], expertise or *domain-relevant skills*, creative thinking skills or *creativity-relevant skills*, as well as *motivation* are necessary for creativity.
Quite similar to this, based on a meta-analysis, Mascitelli [2000], though in the context of technological innovation, refers to tacit technical skills and tacit cognitive skills as being prerequisites for innovative abilities (Figure 17).
As factors which are responsible for superior problem solving performance of certain individuals, Hoover and Feldhusen [1994] list memory organization and facilitation; problem-specific knowledge and; general problem-solving skills.
Whereas questions of extrinsic and intrinsic motivation are important for creativity management, this literature review will only focus on cognitive aspects like domain-relevant skills or expertise and general creative thinking skills.

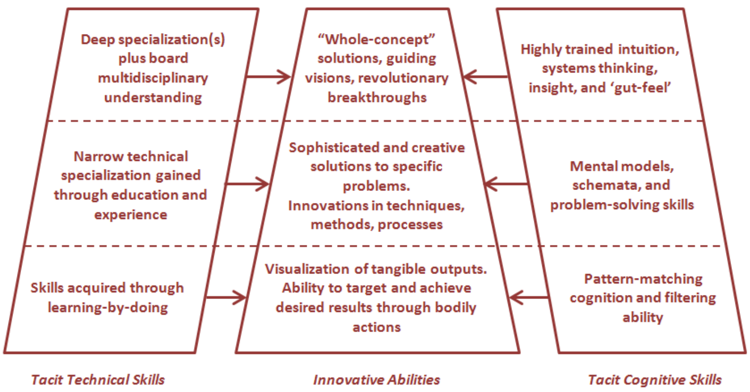


Figure 17: Technical and cognitive skills leading to innovative abilities [Mascitelli, 2000]

[5] A conceptual space is defined by Boden [1999] as 'a set of enabling constraints, which make possible the generation of structures lying within that space' (p. 352).

2.4.2.1 *Expertise*

Extensive domain knowledge is the most important prerequisite for creativity and explains to a large extent differences in creative performance between novices and experts [Weisberg, 1999]. However, naives and specialists differ not only in the quantity of knowledge [Chase and Simon, 1973] but also in terms of qualitative knowledge representation and organization [Larkin *et al.*, 1980; Casakin and Goldschmidt 1999] as well as in the level of abstractness at which the knowledge is processed [Chi *et al.*, 1982; Gobet 1998, Dogusoy-Taylan and Cagiltay, 2014]. An expert possesses a considerable number of patterns stored in long term memory. These patterns quickly lead him or her to problem-relevant parts of his or her corpus of knowledge which are organized in schemata or conceptual chunks [Chase and Simon, 1973; Egan and Schwartz 1979] of different complexity [Larkin *et al.*, 1980]. The ability of experts to recognize these patterns has been detected in such diverse domains like e.g. chess [Chase and Simon, 1973] or electronics [Egan and Schwartz, 1979]. Further, an expert's ability to represent problems in a more abstract way leads to better understanding of underlying principles, to hierarchically deeper categorizations of problems [Chi *et al.*, 1982] (Figure 18), and finally to better problem solving e.g. in design [Moss *et al.*, 2006]. The combination of declarative and procedural knowledge is another reason for superior expert problem solving [Chi *et al.*, 1982]. Declarative knowledge about a domain is used in order to generate alternative problem configurations which in turn can be processed by the large procedural knowledge in order to generate new solutions to problems.

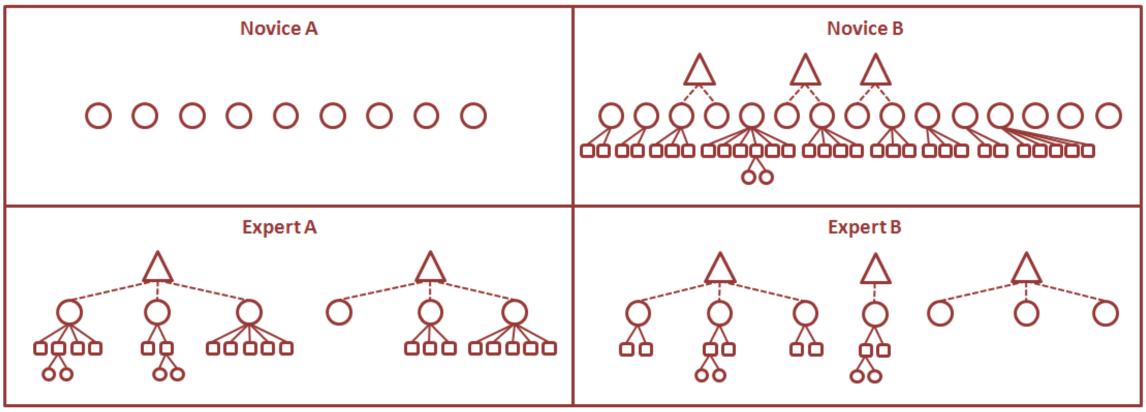


Figure 18: Comparison of expert and novice's depth of problem categorization [Chi *et al.*, 1982]

2.4.2.2 *Creative Thinking Skills*

Besides domain knowledge, also general thinking skills play a role in creative reasoning. Based on a meta-analysis of psychometric approaches to creativity, Finke *et al.* [1992] identify several cognitive styles which have been found to promote creative thinking. Some examples are creative associating, use of abstract thought, divergent thinking [Shouksmith, 1970, (cited in [Finke *et al.*, 1992])]; breaking of mental sets, keeping options open, suspending judgment, using wider rather than narrow categories, recognizing the importance of new ideas [Amabile, 1983]; metacognitive skills, evaluative skills, and the ability to generate original ideas [Runco, 1990 (cited in [Finke *et al.*, 1992])].

2.4.2.2.1 Metacognition

Metacognition comprises metacognitive knowledge and metacognitive skills [Veenman *et al.*, 2006]. The former refers to 'knowledge and cognition about cognitive phenomena' [Flavell, 1979, p. 906] and the latter to 'problem-solving skills' like 'predicting, checking, monitoring, reality testing and coordination and control of deliberate attempts to learn or solve problems' [Brown, 1977, p. 5].

According to Jaušovec [1994], superior problem solving performance of experts is also due to metacognitive knowledge which leads in the problem solver to meta-analyses of taken actions, the reasons for the choice of action, and the use of the action's outcome in further problem solving steps.

A meta-analysis of five laboratory experiments makes Jaušovec conclude that good problem solving performance is associated to an awareness of cognitive processes, to an ability to estimate the closeness to a solution while still being in the problem solving process, as well as to a sensitivity to the effectiveness of potential problem solving strategies.

In a similar realm, superior 'strategic knowledge' [Kavakli and Gero, 2003, p. 50], i.e. strategies which help organizing and structuring cognitive activity, have been found to be responsible for superior expert performance in design tasks. According to Kavakli and Gero, those metacognitive strategies lead to a reduction of concurrent cognitive actions to a number which is manageable in short term memory (cf. Paragraph 2.4.3.1).

Another capacity, which is assumed to promote creativity and which can be categorized under the term metacognitive skills is *Double Loop Learning*. Stemming from management literature (e.g. [Argyris and Schön, 1978; Argyris, 1991], this type of learning refers to the ability of individuals (groups, and organizations) not only to find good solutions to a problem but also to finally find differential problem settings, to which solutions are even more effective for the overall task at hand.

2.4.2.2.2 Janusian Thinking

Another thought process which has been found to be strongly related to creative thought is *Janusian Thinking* [Rothenberg, 1983 (cited in [Rothenberg 1987]); Rothenberg, 1987; Simonton, 2004]. It 'involves the active and intentional conception of two or more [equally operative and valid] opposites or antitheses simultaneously' [Rothenberg, 1987, p. 150] often during early phases of the creative process. These opposites are supposed to undergo frequent modifications and transformations through cognitive operations like e.g. combination and unification and often cannot be identified in the final creative product. Evidence for the relationship of this reasoning strategy has been found both in laboratory experiments [Rothenberg, 1983 (cited in [Simonton, 2004])] and historical case studies of Einstein and Bohr [Rothenberg, 1987]. Theoretical support for the theory of Janusian thinking is given by Finke *et al.* [1992] in their Geneplore Model (cf. Paragraph 2.4.5.3).

2.4.3 Factors Impeding Creativity

Research has also identified factors which have been found to limit or impede creativity. Whereas some causes are due to invariant limitations of the human mind, others are – at least partly – related to familiarity with a given problem.

2.4.3.1 Restrictions in Memory

The capability of humans to store information in short term or intermediate memory seems to be limited. Having analyzed several laboratory experiments on human capacity of absolute judgment and information retention, Miller [1956] states that human short term memory is not able to store more than 7 +/- 2 chunks[6] of information. Even though other researchers proposed slightly different amounts of chunks to be storable in short term memory [see Baddeley, 1994 for an overview], Miller's arguments have been generally approved. Ehrlenspiel [2003] lists instances of human behavior in design which, as he argues, are due to those limitations in human (working) memory (Table 11). Especially the behaviors number eight to ten can be considered behaviors which limit creativity.

Table 11: Human behavior in design which is due to restrictions of working memory [Ehrlenspiel, 2003]

1	Working in steps	6	Sub problem-oriented design
2	Iterative working	7	Corrective design
3	Swinging between the whole and the detail	8	Applying known solutions, if possible out of own experience
4	Swinging between the abstract and the concrete	9	Reduction of alternative solutions
5	Doing the essential first	10	Evaluation of solutions without analysis

2.4.3.2 Rigid Mindsets and Fixation

Similarly to groups (cf. Chapter 2.3.3.1), rigid mindsets of individuals have also been found to hinder creativity or innovation [Williams and Yang, 1999]. They can be the mere result of excessive familiarity with a given domain [Sternberg, 1997 (cited in [Williams and Yang, 1999])], of an expert's biased view on a problem, which is often the result of considerable intellectual or emotional investment [Frensch and Sternberg, 1989 (cited in [Williams and Yang, 1999])], or of vested interests in the creative outcome [Simon and Dearborn, 1958; Pelled, 1996]. Those mindsets can bias the analysis of problems [Simon and Dearborn, 1958] but they can also interfere with the generation of new solutions [Jansson and Smith, 1991; Smith and Blankenship, 1991; Purcell and Gero, 1996; Bachelard, 2004]. Whereas rigid mindsets cause the phenomenon of design fixation in design problem solving [Jansson and Smith, 1991; Purcel and Gero, 1996], they can also be interpreted as reasons for reduced contributions to revolutionary scientific insight generated by researchers who have passed a certain age [Zuckerman, 1977; Bachelard, 2004].

2.4.4 Process Models of Creative Thinking

Models of the creative thinking process have been proposed by several authors. Instances from the overview of these models given by Mumford *et al.* [1994] are depicted in Figure 19. The classic models [Dewey, 1910 (cited in [Mumford *et al.*, 1994]); Wallas, 1926 (cited in [Mumford *et al.*, 1994])] and those grounded on them [e.g. Merrifield *et al.*, 1962 (cited in [Mumford et al. 1994])] structure the process of creativity into four to five phases which roughly fit into the stages of problem analysis, solution generation, as well as solution evaluation and choice. Some models [e.g. Merrifield *et al.*, 1962 (cited in Mumford *et al.*, [1994])] add concepts of divergent and convergent and/or cyclical sub processes to these structures.

Basadur [1994], who is not considered by Mumford and colleagues, adds the stage of solution implementation in order to emphasize that creativity is only valued if it is implemented and used.

[6] Miller [1956] refers to chunks as input being grouped to familiar units.

Basadur, based on Basadur *et al.* [1982], states that the optimal ratio between ideation, which can be interpreted as divergent thinking, and evaluation, which can be thought of as convergent thinking, changes over the process. Whereas divergent sub-processes should play a more important role during the problem finding stage, activities of evaluation are considered to be dominant at the stage of solution implementation.

Other researchers [e.g. Sternberg, 1986; Mumford *et al.*, 1994] have modeled the creative processes, or parts of it from an information processing perspective (cf. Paragraph 2.4.5.1).

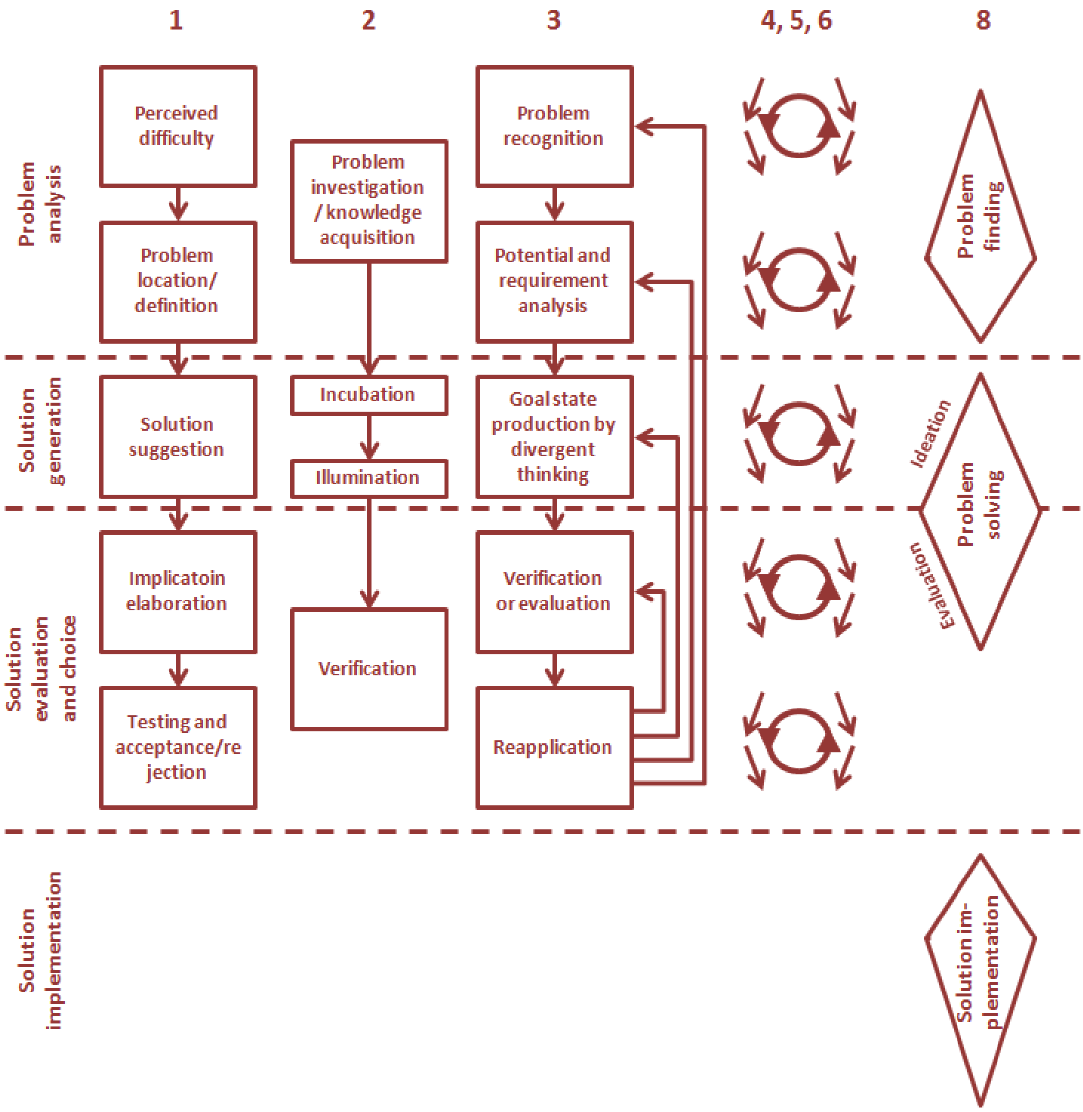


Figure 19 : Models of the creative process [based on Mumford *et al.*, 1994] (1: Dewey, 1910; 2: Wallas, 1926; 3: Merrifield *et al.*, 1962; 4: Kepner and Tregoe, 1965; 5: Guilford, 1967; 6: Parnes, 1967; (all cited in [Mumford *et al.*, 1994]) 8: Basadur, 1994)

2.4.4.1 Problem Analysis and Problem Construction

Problem solving processes are an important subset of creative activity and some researchers claim that all creative processes can be seen as instances of problem solving (cf. Paragraph 2.4.5.1). Thus both problem identification or construction and problem analysis are considered to be vital for creativity [e.g. Zuckerman, 1977; Miller, 2000; Csikszentmihalyi, 1999]. Hayes and Simon [1979], for instance, provided experimental evidence that different representations of essentially the same problem can impact problem solving and transfer performance in individuals. Further, the way in which individuals represent and categorize problems has considerable effects on the strategies which they can use for problem solving (cf. Paragraph 2.4.2.1).

Mumford *et al.* [1994] established a model which describes the process of problem construction in individuals in a number of sequential cognitive operations. According to this model, stimuli stemming from an event are filtered depending on individual knowledge structures [e.g. Fiske *et al.*, 1983] and activate several problem representations stored in memory. These problem representations, which, according to Holyoak [1984 (cited in [Mumford et al., 1994])], contain information like goals, objects, procedures, problem solving operations, and constraints, are then screened for specific elements. Finally, elements which have been selected are extracted from their embedding representation and reorganized during problem construction.

2.4.4.2 Idea and Solution Generation by Analogy

Problem construction is followed by the divergent generation of solution candidates. Solution generation is often facilitated by analogies. An analogy is defined ‘as similarity in relational structure’ and as ‘one-to-one mapping from one domain representation (the base) into another (the target)’ [Gentner *et al.*, 1993, p. 526]. The shared attribute which creates this mapping is the system of relationships among the objects of either, base and target.

Whereas it is this relational similarity which is responsible for successful analogical transfer, it can be difficult to identify this shared attribute at first glance because access to the analogical base has been found to be more likely facilitated by superficial similarity [Christensen and Schunn, 2007]. Research, however, has identified several conditions and means which facilitate analogical problem solving.

First, expertise in the target domain is considered an important factor for the promotion of analogies. Thanks to the rich and tightly structured representations of systems within the domain of expertise, access to more and more remote analogies as well as mapping of more complex structures are possible [Vosniadou, 1988]. Second, in a series of experiments, Gick and Holyoak [1983] provided evidence that the induction of schemas leads to an increased probability of analogy notification and facilitates the mapping process between target and source, thereby promoting analogical problem solving. Third, in the case of design problems, Casakin and Goldschmidt [1999] showed that the explicit instruction to use analogies to previously presented design concepts can improve performance of novices under time pressure. From this, they conclude that analogy can be regarded as one strategy to ‘mobilize’ (p. 172) knowledge from memory for quick problem solving.

However, an empirical study on New Product Design projects involving designers with diverse background indicates the limitations of analogical problem solving [Kalogerakis *et al.*, 2010]. The investigated instances of analogical transfer were either based on very general knowledge like shapes and design arrangements or the analogical source was situated rather close to the target (Figure 20). The fact that no technological solution or functional principle could be identified as a result of a non-domain analogy can be interpreted as evidence that distant rich analogies are rather an exception in (design) problem solving.

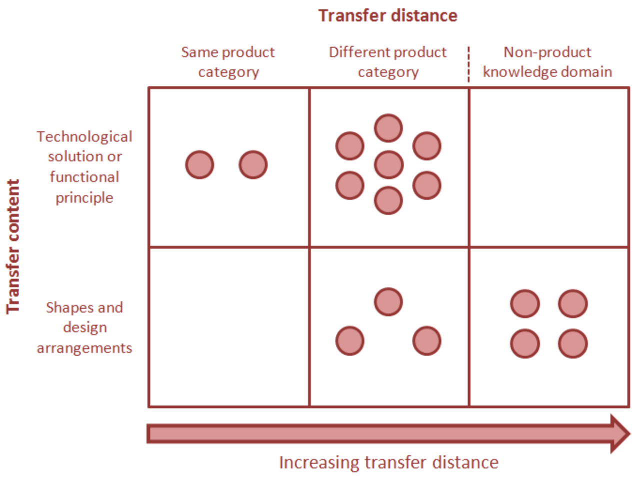


Figure 20: Number, distance and content of analogies drawn in analyzed design projects [Kalogerakis *et al.*, 2010]

2.4.5 Cognitive Perspectives on Creative Reasoning

Some of the overall process models of creative thinking outlined in Paragraph 2.4.4 rely on influential cognitive theories and models [see Shah *et al.*, 2000 for an overview]. In the following paragraphs some of these perspectives on human creativity will be described briefly.

2.4.5.1 Computational Perspective

The computational model of creativity relies on two assumptions. The first one defines creativity as a special type of problem solving [Simon, 1985] (cf. Chapter 2.5.2.1) while the second models the human mind as an information processor [Newell and Simon 1972 (cited in [Simon, 1978]); Simon, 1978].

The information processing theory describes human problem solving behavior in a framework which contains essentially three components: the task environment, the information processing system and the problem representation by the processing system in terms of a problem space. According to the theory, the task environment influences the structure of the problem space which, in turn, has essential impact on strategies which the problem solver can use [Newell and Simon, 1972 (cited in [Simon, 1978]); Simon 1978].

In the computational framework, problem solving by the human brain occurs by receiving encoded symbols from the task environment, by copying and reorganizing these symbols in memory, and by outputting symbols and symbol structures stored in memory while comparing present states with desired goal states [Langley *et al.*, 1987]. The information-processing model which Hinsz *et al.* [1997] provide for group process (cf. Paragraph 2.3.5; Figure 16) also fits to individuals.

In accordance with the information-processing view, Sternberg [1986] describes three processes which describe a reasoning task, namely selective encoding, selective comparison, and selective combination. Selective encoding, which is carried out in the working memory, refers to decisions of the problem solver with respect to whether information is worthwhile to process. Selective comparison, however, relates to the selection of information stored in long-term memory in order to compare it with previously encoded representations. Finally, selective combination is referred to as the process during which encoded and/or compared information is put together and stored in working memory in order to accomplish reasoning.

According to the literature, information can be perceived [Simon, 1962] and stored [Sternberg, 1986; Anderson, 1987] in one of two ways. Simon refers to the perception of either state descriptions or process descriptions and e.g. Sternberg postulates information storage as either declarative or procedural knowledge.

The computational perspective on creativity and the underlying theory of information processing have obtained experimental support by a large number of computer models which have been shown to produce P-creative and sometimes H-creative (cf. Paragraph 2.4.1.2) output [e.g. Lenat,1978; Langey *et al.*, 1983; see Boden, 1999 for a review]. Provided with a certain amount of information and heuristic problem solving operators (cf. Chapter 2.5.4), artificial information processors like BACON have (re)discovered e.g. Black's law of temperature equilibrium [Bradshaw *et al.*, 1983]. Further, by implementing both general and domain specific heuristics, researchers created for instance computer programs capable of generating scientific findings in chemistry which were original enough to be published in domain journals [Lenat, 1978].

The theories and models described in this paragraph are important for problem modeling and problem solving methodology as well as for problem solving heuristics which will be discussed in Subsection 2.5.

2.4.5.2 Combinatorial Perspective

The combinatorial perspective on creativity assumes that creative achievement, especially in science, is the result of rather blind combination and/or variation and selective retention of elementary concepts (i.e. phenomena, facts, variables, techniques, theories, etc.) which an individual has acquired during his or her activity in a given domain [Campbell, 1960 (cited in [Simonton, 2004]); Simonton, 2004, 2010]. The theory, which is based on historiometric analyses of personal creative production over decades [e.g. Simonton, 2002] and introspective reports of Helmoltz, Hadamard, Poincaré, and Faraday [Simonton, 2004] thus claims that creativity is essentially a chance process.

The combinatorial theory of creativity is supported by the successful application of genetic algorithms to problems like e.g. the design of jet engines or the control of gas pipeline systems [Holland, 1992]. Interestingly – by using modification and recombination operators [Koza *et al.*, 2004] – the related concept of genetic programming, has been found to be able to produce Kepler's Third Law of Planetary motion, as did one of the heuristic-based programs described in Paragraph 2.4.5.1 [Koza, 1992].

2.4.5.3 Geneplore Model

The name *Geneplore* refers to two basic processes, generation and exploration, which, according to this model, build the creative reasoning process. According to Finke *et al.* [Finke *et al.*,1992, Ward *et al.*,1999], individuals engaging in creative thought first generate or construct so called *preinventive structures*, mental representations which are assumed to facilitate creative discovery by their special properties. In the second stage of the reasoning process, the initially generated structures are explored through attempts of meaningful interpretation in order to produce a creative end product. Generation and exploration can occur in a cyclic manner when the exploration phase leads to the modification or regeneration of preinventive structures. Constraints related to the product can be considered during either the generative or the explorative phase (Figure 21).

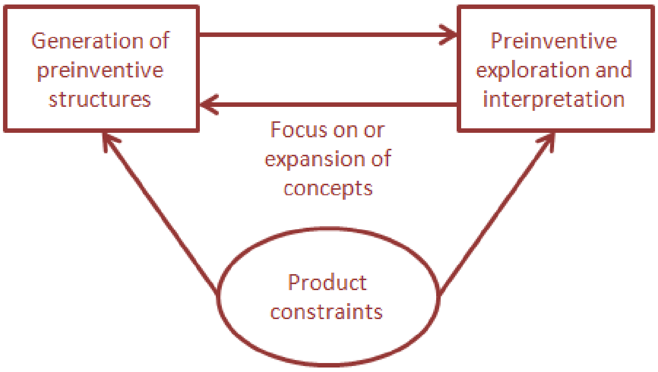


Figure 21: Generation and exploration phases of the Geneplore model [Finke *et al.*, 1992]

Among the properties responsible for the creativity stimulating capacity of preinventive structures, Finke *et al.* [1992] mention (1) novelty; (2) ambiguity, which allows interpretation in a variety of ways; (3) implicit meaningfulness, which is assumed to stimulate deeper exploration; (4) emergence, which relates to the degree to which unexpected attributes of and relations between those structures appear during their exploration and combination; (5) incongruity, which implies an underlying conflict among the concept's components; and (6) divergence, which refers to the degree to which multiple uses and meanings can be inferred from the same structure.
The authors of the Geneplore Model highlight several strategies which could lead, according to their framework, to more creative reasoning. First, they suppose that the suspension of expertise in a given domain while generating preinventive structures can lead to more creative products when these very structures are later explored by taking into account domain knowledge. Second, while mentioning Koestler's [1964] concept of *Bisociation*, they state that the conceptual combination of preinventive structures with incongruent or contrary patterns makes creative discovery more likely to occur (cf. Paragraph 2.4.2.2.2).

2.4.6 Individual and Disciplinary Differences

Several differences regarding creative thinking and the creative process have been identified. In the following paragraphs, those differences, which are due to personal cognitive style, to disciplinary background, and to employed tactics, are briefly discussed.

2.4.6.1 Individual Differences

2.4.6.1.1 Cognitive Style

Cognitive style refers to an individual's cognitive functioning e.g. regarding problem solving approaches and ways to acquire and deal with information [Field, 1971; Witkin *et al.*, 1977; Ausburn and Ausburn, 1978; Kozhevnikov, 2007]. Kozhevnikov [2007] gives an overview of several dimensions according to which individual cognitive style can be assessed. A number of cognitive dimensions are given in Table 12.

.

Table 12: Dimensions of cognitive style, based on [Kozhevnikov, 2007][7]

Dimension	Explanation	Reference
Tolerance for instability or unrealistic experience	Tolerance for compromise solutions if data conflicts with knowledge	1
Breadth of conceptualization	Extent to which differences among elements of a sample are perceived	2,3
Constricted/flexible control	Degree to which contradictory cues are taken equally into account	2
Field articulation	Extent to which discrete elements or large forms can be articulated from background patterns	4
Scanning range	Amount of information which an individual scans before interacting with an environment	2
Conceptual articulation	Degree to which elements of a concept are distinguished from one another	5,6
Conceptual complexity	Tendency to differentiate and integrate information (weak tendency: concrete; strong tendency: abstract)	7
Holist/serialist	Preferences regarding either holist or iterative problem solving strategies	8,9
Visualizing/verbalizing	Preferences for either visual or verbal information processing	10,11

The composition of work groups in terms of cognitive style has been found to impact group performance [Aggarwal and Williams Woolley, 2013]. According to Aggarwal and Williams Woolley, the presence of individuals with a certain cognitive style can significantly impact a group's process focus and thus the amount of errors committed by the group while engaging in certain tasks.

Interestingly, some cognitive traits are related to performance in specific problem solving tasks. Ansburg and Hill [2003] for example, based on the results of a laboratory experiment, suggest that the tendency to allocate attention broadly to a problem setting is a particularly helpful characteristic for creative problem solving.

2.4.6.1.2 Solution Search Strategy

An example for individual differences in terms of problem solving strategy has been provided by Fricke [1996]. Based on the results of a laboratory experiment, he distinguishes three strategies for searching solutions to design problems (Figure 22). (1) Emphasis on expansion of the search space, i.e. divergent operations like the generation of multiple variants clearly dominate convergent ones; (2) Strong restriction of search space, i.e. early focus on the concretization of one single solution without looking for alternatives; and (3) Balanced search, i.e. equilibrated alteration between divergent and convergent operations. Having compared the problem solver's strategy with the quality of the creative outcome, Fricke assumes that the strategy of balanced search leads to better results than the two extreme strategic alternatives. However, it has to be emphasized that these results are valid for the special case of design problem solving under time constraints.

[7] **1: Klein and Schlesinger, 1951; 2: Gardner *et al.*, 1959; 3: Pettigrew, 1958; 4: Messick and Fritzky, 1963; 5: Bieri, 1955; 6: Messick, 1976; 7: Harvey *et al.*, 1961; 8: Pask, 1972; 9: Pask and Scott, 1972; 10: Paivio, 1971; 11: Richardson, 1977; (all cited in [Kozhevnikov, 2007])**

Figure 22: Different types of solution generation strategies [Fricke, 1996]

2.4.6.2 Disciplinary Differences

Occupational, professional, educational, and disciplinary background seems to impact cognitive preferences [e.g. Kozhevnikov, 2007], employed problem solving strategies [Lawson, 1979], as well as performance at different problem solving tasks [Lehman *et al.*, 1988]. One example for research in this direction is the work of Field [1971], who compared cognitive styles of highly and lowly science-oriented students and pupils. Based on significant differences between the two thinking orientations, Field suggests the 'science cognitive style' (p.25) to be characterized by high scores in terms of conceptual differentiation (i.e. the ability to identify common properties among elements of a set of concept (cf. Breadth of conceptualization; Table 12)); object categorizing flexibility, preference for analytic-descriptive concepts; and originality. On the other hand, according to Field, this cognitive style lacks ideational fluency, flexibility, and preferences for psychological concepts in grouping people.

Evidence for different problem solving strategies used by scientists compared to e.g. designers has been provided by Lawson [1979]. Having compared experimentally the behavior of scientists and architects while solving conjunction, affirmation and disjunction problems, Lawson, points to significant differences. Scientists follow, as Lawson calls it, a 'problem focusing' strategy (p. 66), i.e. they engage more in the discovery of the problem structure. However, architects engage in a 'solution focusing' strategy (p. 66), i.e. they generate a higher number of solution candidates until the correct solution is found. Another important finding obtained from interviews with the subjects concerns their inability to find alternatives to their problem solving strategies. According to Lawson, both of the strategies lead to increased performance in specific but different problem solving tasks.

2.4.7 Conclusion

Humans are capable of generating a variety of creative products, some of which are the result of the deletion of some sort of constraints or barriers in the reasoning process. Especially in science, creativity can result in both theoretical products and sophistically designed technological systems. In order to be creative, it is necessary that individuals possess a certain degree of domain expertise, and particular creativity-related reasoning strategies.

Domain expertise manifests in huge amounts of chunks of structural and procedural knowledge. It leads to deeper and often more abstract problem representations which can then be solved e.g. by analogies. Still, even in case of a certain expertise in various domains, the drawing of distant analogies, which are esteemed most creative, remains rare. However, instructions to use this type of reasoning can have a positive impact on analogical problem solving. Further, too much familiarity with a given domain can also interfere with creative achievement.

Among the more general reasoning skills, meta-cognitive strategies lead to a certain organization of the thought process thereby overcoming cognitive limitations in terms of memory capacity. Further, the parallel development of opposite, conflicting concepts and their synthesis is a thought process which often produces creative outcome.

Cognitive scientists and psychologists describe the creative process as the generation and modification of elementary concepts some of which are then combined and developed further. In this view, special characteristics of these elementary concepts like ambiguity and incongruity are supposed to be responsible for the creative outcome.

Finally, it has been found that there exist differences among individuals in terms of cognitive style, i.e. the way in which individuals perceive information and deal with problems. Some of these cognitive preferences have been found to be related to disciplinary background. In accordance with this, robust differences in employed problem solving strategies have been detected between scientists and designers.

Besides differences in terms of individual cognitive styles, design and science also feature differences in terms of treated problems as well as with regard to the way these problems are modeled and finally solved. In the following subsection, the theory of as well as methods and heuristics for problem solving in general as well as in design and natural science in particular are highlighted.

2.5 Problem Level

2.5.0 Introduction

In order to understand how human problem solving during design and scientific activity in particular works, one has to understand what problem solving means in general. Further, related process models, axioms, methods and heuristics should be understood.
The present chapter discusses theoretical and practical aspects of problem solving activities in general, in design and in scientific research. It describes several models as well as methodologies and methods which have been developed in order to support the problem solving process. As this subsection gives an overview of a very large complex of theories, methods and heuristics, it should be considered as very synthesizing, i.e. the presented instances are only a subset of a far larger plethora of concepts.

2.5.1 Terminology

In this paragraph, activities in the domain of design will be distinguished from scientific research activities. Further, definitions of theory, methodology, methods, and heuristics will be given.

2.5.1.1 Design and Scientific Research Activities

It is difficult to strictly distinguish between design and research activities. Organizations, teams, and individuals involved in industrial product development often also engage, as part of their design activity, in research questions. On the other hand, scientists, in order to be able to carry out their research, frequently have to engage in the design of often very complex devices, instruments and apparatuses, from microscopes to particle accelerators. The concept of design of experiments [e.g. Atkinson and Hunter, 1968] or experimental design is another example for ‘design’ activities in the field of scientific research. Further, both design [e.g. Goel and Pirolli, 1992] as well as research [e.g. Simon *et al.*, 1981] activities have been described as some sort of problem solving, which implies a certain similarity in the underlying reasoning processes. The argument of similarity is further supported by Latour and Wooglar’s [1996] empirical observation of resemblance between the type of reasoning used by scientists during their work and the means applied in order to engage in day-to-day actions. Further complicating the distinction between the two activities is the increased necessity to take into account from the beginning potential industrial applications of the results of scientific research (cf. Paragraph 2.1.3.1).
However, even though instances of problem solving are similar, the motivation for the reasoning processes is different, at least when one considers the stereotype activities in those two domains. A practical example is given by Trotta [2011]. She describes an engineer’s task as the search for solutions to a design problem whereas she refers to the activity of a biologist as the attempt to find the problems to which the structures of organisms present a solution. Simon [1996] formulates this difference by stating that natural science is concerned with ‘how things are’ (p. xii) whereas design asks ‘how things ought to be’ (p. 4).
Design activity, in general, has been defined as a ‘refinement process […] from the abstract to the concrete, from the general to the specific’ [Lossack and Grabowski, 2000, p. 4]. On the other hand, scientific research is supposed to put emphasis on the construction of hypotheses from experimental data or accepted axioms [Miller, 2000] and on the testing of these hypotheses against empirical evidence [Langley *et al.*, 1987].

The distinction between the two domains in terms of analysis and synthesis or deduction and induction has been found to be difficult because all of these operations take place, at least to some extent, in both domains design and science [Roozenburg, 2002].
Building on these statements, design will be referred to as the domain in which actors engage in the synthesis of physical or technical artifacts and products which serve the purpose of transforming material, energy, and/or information [Pahl *et al.*, 2007]. Scientific research will be defined as the domain in which agents work on the generation and testing of hypotheses in order to model and explain structures and phenomena in our environment.

2.5.1.2 Theories, Methods, and Heuristics

The present subsection is sought to give an overview of some of the most important theories, methods, and heuristics which have been developed in order to describe and/or facilitate the creative problem solving process in general, design activity, research activity, and/or multidisciplinary activities. In this paragraph, an overview of the issues concerning the terminology of these concepts as well as working definitions will be given.
As mentioned by several authors [e.g. Vadcard, 1996; Araujo, 2001; Lahonde, 2010], there seems to be a lack of consistency in literature when it comes to the distinction e.g. between design theories and design methods [e.g. Lahonde, 2010] or between design methods and design tools [e.g. Vadcard, 1996].
In the present document, the above mentioned concepts are categorized according to the following definitions given by Vadcard, Araujo and Lahonde, which are also applied on domains other than design:

- *Theory*: Descriptive models as well as overall process descriptions of prescriptive models of reasoning processes. A theory can be the basis of methods/tools and heuristics.
- *Methodology*: A, at least partially, prescriptive or normative system of methods/tools [Araujo, 2001].
- *Method/tool*: Elementary components of a methodology leading to concrete results, which can be used as input in other steps of the methodology. Examples are modeling techniques [Araujo, 2010] or *Brainstorming* [Cross, 2008; Lahonde, 2010].

An important aspect of several theories, methodologies, and methods are heuristics. The latter are defined as follows:

- *Heuristic*: Principles or tactics, selected on the basis of experience or judgment, which have a certain probability to yield a reasonable solution after relatively short search [Newell and Simon, 1972; Silver, 2004].

The given definitions allow distinguishing several concepts which emerge in the context of others. *TRIZ* (cf. Paragraph 2.5.2.2.7), for example, refers to *Theory of Inventive Problem Solving* but essentially refers to a methodology for problem solving in the context of product design including a number of tools. Finally, the tools suggest the use of heuristic design principles, i.e. heuristics which have been found to be useful in order to find solutions to initially modeled problems. In this document, in order to facilitate the distinction between similar concepts originating in different domains – not always in conformity with the literature – certain complex concepts like e.g. TRIZ or Axiomatic Design Theory will be discussed according to the pattern *theory-methodology-tool-heuristic*. As a consequence of this, certain aspects of e.g. TRIZ will be introduced under the headline of Theory whereas other aspects will appear e.g. in the chapters dealing with methods or tools and heuristics.

2.5.2 Theory

2.5.2.1 General Creative Process and Problem Solving

A significant part of the theory of creativity and the creative process has been discussed in Subsection 2.4. Hence, only additional aspects of problem solving theory will be outlined in this paragraph.

2.5.2.1.1 Problem Solving Theory

As mentioned in Subsections 2.3 and 2.4, the concept of problem solving is often used in literature to describe creativity. The definition of a problem varies from a conflict or obstacle to an accepted task combined with a lack of known solution principles to a difference between 'what one has and what one wants' [Volkema, 1983, p.641].

A widely accepted description is the one given by Newell and Simon [1972 (cited in [Klahr, 2000])], which is based on the information processing view (cf. Paragraph 2.4.5.1). They refer to a problem as consisting of an initial and a goal state as well as of a set of operators which allow transformations between those states. According to this theory, which can be applied to a broad range of problems, the problem solving process consists in the search of a path of transformations which link the representation of the problem with the perceived solution. All three components of a problem, which build the problem space, can vary significantly from ill-defined to well-defined [Klahr, 2000, Jonassen, 2000].

The three components of the problem space, i.e. initial states, goal states and solution operators, can also vary, to a some extent, from one domain to another [e.g. Lenat, 1978, Goel and Pirolli, 1992]. Goel and Pirolli, for example, point to the missing definition of start state, goal state, and transformation function as being one distinctive criterion of design problems.

Jonassen [2000] presents a problem typology and assigns characteristics to every problem type (Table 13). In the continuum given by Jonassen, which varies from well-defined on the top to ill-defined on the bottom, design problems are among the most complex, ill-defined and ill-structured problems.

Several authors argue for the critical influence of alternative problem representations on the quality of the products of the problem solving process [Volkema, 1983; Massey and Wallace, 1996]. Volkema [1983], for example, identifies a lack of time and energy which are devoted to problem formulation as a major factor contributing to the risk of solving either the '"wrong" or a suboptimal problem' (p. 640).

Especially for problem solving in groups, graphical representations can be advantageous [Larkin and Simon, 1987; Rosenhead, 1989 (cited in [Massey and Wallace, 1996])]. These 'diagrammic' representations [Larkin and Simon, 1987, p. 90] are said to provide the problem solver 'at essentially zero cost' with a problem representation and thus can enable lay participation to problem solving [Rosenhead, 1989 (cited in [Massey and Wallace, 1996])]. However, these positive effects depend on the quality of the schemas and thus on the problem solver's knowledge about how to construct a good graphical representation [Larkin and Simon, 1987].

Table 13 : Problem typology varying from well-defined on the top to ill-defined on the bottom [Jonassen, 2000]

Problem type	Success criteria	Context	Structuredness	Abstractness
Logical Problems	Manipulation efficiency; number of required manipulations	Abstract task	Discovered	Abstract, discovery
Algorithmic Problems	Answer or product matches in values and form	Abstract; formulaic	Procedural predictable	Abstract, procedural
Story Problems	Answer or product matches in value and form; correct algorithm used	Constrained to pre-defined elements, shallow context	Well-defined problem classes; procedural and predictable	Limited simulation
Rule-using Problems	Productivity (number of useful answers or products)	Purposeful academic; real world, constrained	Unpredicted outcome	Need-based
Decision making Problems	Answer or product matches in values and form	Life decisions	Finite outcome	Personally situated
Trouble-shooting	Fault(s) identification; efficiency of fault isolation	Closed system real world	Finite faults & outcomes	Problem situated
Diagnosis-Solution Problems	Strategy used, effectiveness and efficiency of treatment; treatment justification	Real world, technical, mostly closed system	Finite faults & outcomes	Problem situated
Strategic Performance Problems	Achieving strategic objective	Real-time performance	Ill-structured strategies; well-structured tactics	Contextually situated
Case Analysis Problems	Multiple, unclear	Real world, constrained	Ill-structured	Case situated
Design Problems	Multiple, undefined criteria; no right or wrong – only better or worse	Complex, real world; degrees of freedom; limited input & feedback	Ill-structured	Problem situated
Dilemmas	Articulated preference with some justification	Topical, complex, interdisciplinary	Finite outcomes, multiple reasoning	Issue situated

2.5.2.2 Design

In this chapter, basic aspects of design theory, descriptive design models as well as major process steps of prescriptive design models will be briefly outlined without any claim for exhaustiveness.

2.5.2.2.1 Definition and Positioning of Design

Engineering design is defined as an activity during which the designer applies his or her 'scientific and engineering knowledge to the solution of technical problems, and then to optimise those solutions within the requirements and constraints set by material, technological, economic, legal, environmental and human-related considerations' [Pahl *et al.*, 2007, p. 1].
It has been put at the intersection of one 'cultural' [Pahl *et al.*, 2007, p.1] and one technical stream by Dixon [1966 (cited in [Pahl *et al.*, 2007])] and Penny [1970] (Figure 23). As a consequence of this positioning, engineering creativity, depending on the target domain of the artifact to design, relies on knowledge of fields like e.g. mathematics, physics, chemistry, mechanics, production engineering, and materials technology [Pahl *et al.*, 2007].

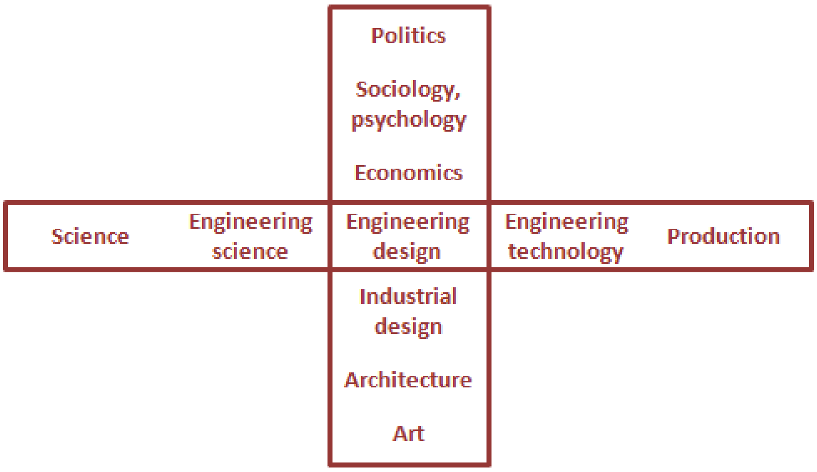


Figure 23: Positioning of Engineering Design, [Pahl *et al.*, 2007 (based on [Dixon 1966 (cited in [Pahl *et al.*, 2007]); Penny, 1970])]

2.5.2.2.2 Overview of Design Models

Several typologies of design models exist in literature. Finger and Dixon [1989a, 1989b] as well as Cross [2008] distinguish between descriptive and prescriptive design models. Finger and Dixon [1989a] further differentiate models which suggest ways to proceed in the design process and those which prescribe attributes of good design products. In Table 14, a non-exhaustive number of design models and theories are categorized according to their descriptive or prescriptive nature. These models will be briefly described in the following paragraphs. Whereas the first three models describe the classical product development or product refinement process, the fourth model describes processes which, at least partly, take place before the classical product design. The last to concepts, which are referred to as being essentially theories describe and/or prescribe reasoning processes in design regardless of specific phases. It shall be noted that the theories and models listed in Table 14 only present a subset of existing approaches. Other models like the *Unified Innovation Process Model for Engineering Designers and Managers* of Skogstad and Leifer [2010] are not described in detail in this report.

Table 14 : Categorization of set of design theories and models according to Descriptive and/or prescriptive characteristics with respect to design process and/or design product (partly based on [Finger and Dixon, 1989a, 1989b; Cross, 2008]); D = predominantly descriptive, P = predominantly prescriptive

Theory/model	Reference	Process	Product
Axiomatic Design	Suh, 2001	D/P	P
Systematic Design	Pahl *et al.*, 2007	P	
New Concept Development	Koen *et al.*, 2001	D	
Conceptual Design Model	Jansson, 1990 (cited in [Jansson and Smith, 1991])	D	
TRIZ	Altshuller and Seljuzki, 1983	P	D/P
C-K Theory	Hatchuel and Weil., 2003	D	

2.5.2.2.3 Axiomatic Design

According to the Axiomatic Design model [Suh, 2001] the design process is described as processing of information between four domains. From one domain to the next, the abstractness of the concepts decreases whereas their description becomes more and more detailed [Albano and Suh, 1994]. The content of each domain is the result of a mapping process between the present and the previous domain [Suh, 2001]. The four domains which build the model are (Figure 24):

- The customer domain, which is characterized by the needs or *Customer Attributes* (CA) a product or process have to meet
- The functional domain, in which the customer needs are translated into *Functional Requirements* (FR) and constraints
- The physical domain, which refers to the space of the *Design Parameters* (DP) defined in order to satisfy the functional requirements
- The process domain, in which the processes necessary for the concrete realization of the product or process are defined by *Process Variables* (PV).

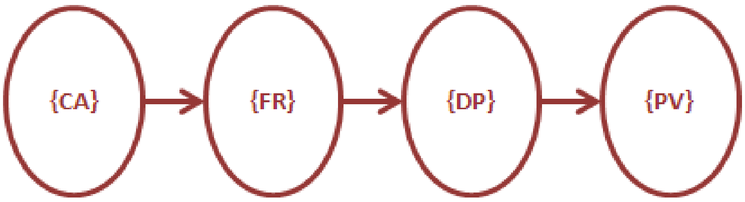


Figure 24: Axiomatic Design Model of the Design Process [Suh, 2001]

2.5.2.2.4 Systematic Design

Pahl *et al.*, [2007] developed the Systematic Design model, in which they describe in detail the planning and design process. This model, among other things, describes the main phases of the design process at the end of which stand decision making steps or concepts. Four design phases lead the designer from the task to a solution in form of the documentation of the product. At each decision making step, the designer or the design team decides whether to proceed with the subsequent phase or to go back to a previous phase. The design phases and intermediary decision making concepts are (Figure 25):

- *Planning and Clarifying the Task*, when the designer analyses market and business conditions, formulates a product proposal and elaborates a *requirements list* which contains the design specification.
- *Conceptual Design*, during which essential problems are identified, functional structures are established and working principles and structures are searched and evaluated. This process leads to the proposition of a *concept* which includes the basic working principles.
- *Embodiment Design*, at which the forms and structures are designed, material selection and calculations are performed and product weaknesses are eliminated. This phase, which can be divided into two processes, leads first to the *preliminary* and then to the *definitive layout* of the product.
- *Detail Design*, when the designer establishes detailed drawings and provides production and assembly instructions which are written down in the *product documentation*.

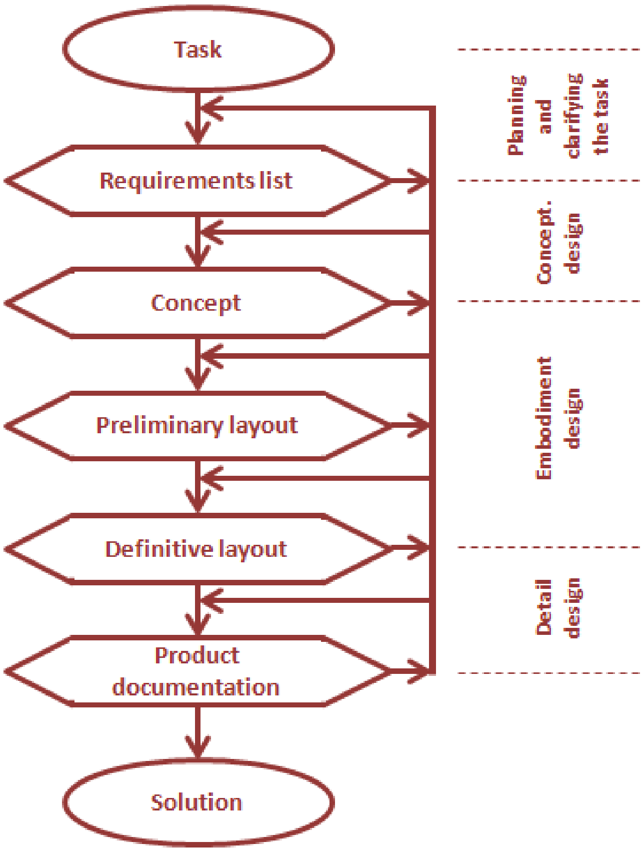


Figure 25: Main design phases and decision making steps in of the Systematic Design model [Pahl *et al.*, 2007]

2.5.2.2.5 New Concept Development

The New Concept Development (NCD) model, introduced by Koen *et al.*, [2001], refers to activities which product or process development teams perform anterior to the New Product or Process Development (NPPD) process. The NCD model describes activities, some of which are briefly outlined by other authors [e.g. Pahl *et al.*, 2007] in more detail. Among other concepts, like influencing and driving factors, the model essentially includes five elements which mutually influence each other and which cannot be put into a strict chronological order. Those elements, which are said to build the Front End of Innovation (FEI), are:

- *Opportunity Identification*, during which the developers identify technological and/or business opportunities which they want to pursue. This can range from the development of a new business to the improvement or extension of a product (line).
- *Opportunity Analysis*, at which previously identified opportunities are further analysed and put into a technological and market context. During this step, major trends and first market estimations are carried out in order to seize the attractiveness of the respective opportunities.
- *Idea Genesis*, which refers to the generation and iterative maturation of ideas concerning how to reach the previously identified opportunities. Here, contacts with other departments of the company as well as information about the customers' requirements are necessary.
- *Idea Selection*, during which the developers decide on which of the ideas generated in step 3 are chosen for further consideration. According to Koen and colleagues, due to the limited amount of reliable information, the selection process must be 'less rigorous' (p. 51) than during the NPPD process.

- *Concept and Technology Development*, which involves the design of a concrete business model including estimations about costs, quantified customer needs and unknown aspects about the selected technologies. This element is sometimes considered as the first stage of the NPPD process.

2.5.2.2.6 Conceptual Design Model

When it comes to the modelling of the conceptual design process, the model established by Jansson [1990 (cited in [Jansson and Smith, 1991])] should be mentioned. It describes conceptual design, i.e. the definition of 'a core technical concept around which the entire design will be built' [Jansson and Smith, 1991, p. 3], as movement between two imaginary spaces, the *Configuration Space* and the *Concept Space*. The former is supposed to contain mental representations of physically realizable configurations like sketches and combinations of physical elements. The latter serves as stock of abstractions like ideas or relationships, which are the source of potential elements in the configuration pace.

According to the model, conceptual designs are elements of the configuration space. However, in order to obtain those designs or modifications of them, the designer has to pass from the configuration space to the concept space – and often has to move within this second space – in order to find useful abstractions. New conceptual designs can only be proposed by means of those abstract concepts (Figure 26).

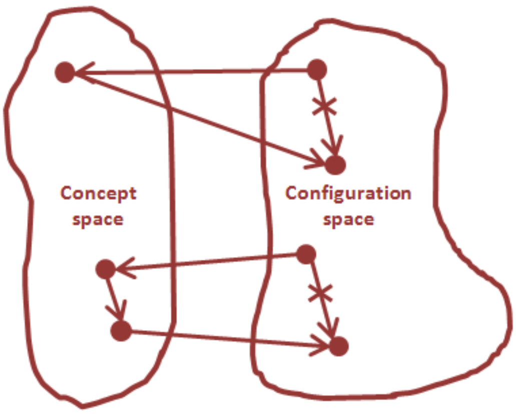


Figure 26: Model for conceptual design [Jansson and Smith, 1991]

2.5.2.2.7 TRIZ/TIPS

TRIZ is the abbreviation for the Russian теория решения изобретательских задач, which can be translated as Theory of Inventive Problem Solving [e.g. Altshuller and Seljuzki, 1983; Altshuller, 1988] (*TIPS*). The theory addresses several aspects of design. It is based on extensive analyses of documented technological inventions and on descriptive models of the development of technological systems over time, derived from the empirical data. Making reference to these descriptive observations, and taking into account philosophical and cognitive findings, Altshuller and other authors have developed different prescriptive models for the inventive process which is often performed in – but not limited to – product and process design [Savransky, 2000].

Whereas empirical observations of technological development translate into nine laws of technological evolution [Altshuller, 1988; see Salamatov, 1996 for a detailed discussion], the prescriptive process model of inventive problem solving contains four representations [e.g. Savranksy, 2000] (Figure 27). The first element is the specific problem which the inventor has identified. The second representation consists in an abstract model of this problem. Based on this problem model, the inventor is supposed to generate a – still abstract – solution model. By concretization of the latter model, i.e. by its transposition into the specific context, the designer is supposed to obtain a specific solution.

2.5.2.2.8 Derivatives of TRIZ

Over time, several authors have developed adaptations of TRIZ. Examples for the most well-known TRIZ derivatives are *Unified Structured Inventive Thinking* [Sickafus, 1997] (*USIT*) and *Advanced Systematic Inventive Thinking* [Horowitz, 1999] (*ASIT*). Based on these works, adaptations to the TRIZ model of inventive problem solving have been proposed [Nakagawa, 2005]. Nakagawa extends the initial TRIZ model in two points. First, he adds a representation of detailed problem definition as second element of the process. Second, he argues for the need to transform the solution model into different conceptual solutions, which are then developed into the specific solution.

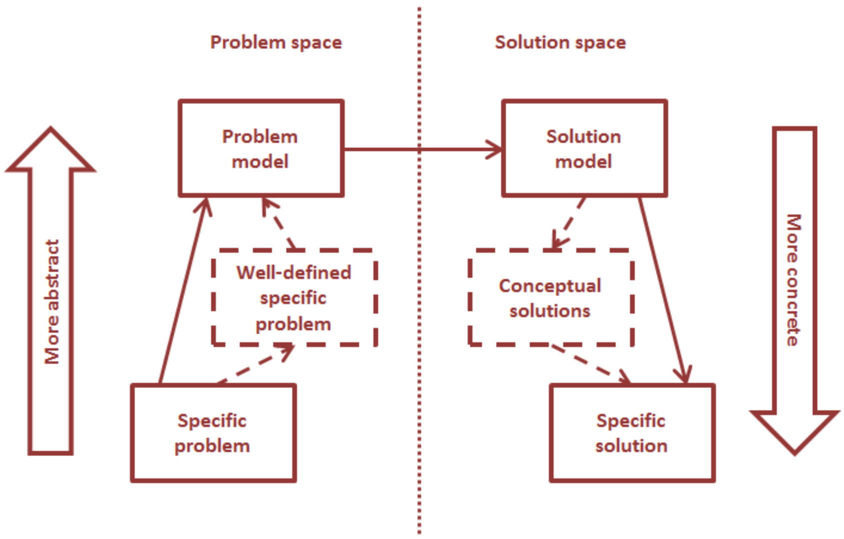


Figure 27: Suggested problem solving process in TRIZ [e.g. Savransky, 2000] and expansion suggested by [Nakagawa, 2005]

2.5.2.2.9 C-K Theory

C-K Theory, which has been introduced by Hatchuel and colleagues [e.g. Hatchuel and Weil, 2003; Le Masson *et al.*, 2006] is a 'formalism' used to describe 'design reasoning' [Le Masson *et al.*, 2006, p. 281] and to allow 'a better understanding of the organization and management of design in innovative projects' (p.282).

The theory distinguishes two spaces, the *Concept Space* (C-Space) and the *Knowledge Space* (K-Space), in which reasoning takes place. Elements of the K-Space, i.e. knowledge, differ from elements in the C-Space, i.e. concepts, in so far as they are given a logical status of 'true' or 'false' [Le Masson *et al.*, 2006]. According to that theory, design activity can be described in terms of four operators [Hatchuel and Weil, 2003]:

- The *K→C* operator describes the addition or subtraction of knowledge elements, which originate in the K space, to elements or sets in the C space. The generation of alternatives in design is given as an example for this operation.

- *C→C* operations consist in the expansion of the C space by mathematical operations of partition and inclusion, which results in a tree-like organization of concepts. The expanding the width of the concept tree refers to divergent thinking, whereas increasing its depth results from convergent thought processes [Le Masson *et al.*, 2006].
- Activities which usually occur at the end of the design process are described by the *C→K* operator. It models actions like the validation or rejection of design concepts by giving them a logical status in the K space.
- Finally, *K→K* operations are referred to as activities of expansions in the K space which are driven by either deduction or experimentation. Thus, typical activities of knowledge creation can be modeled by this operator [Le Masson *et al.*, 2006].

2.5.2.2.10 Design Problem and Design Product Classifications

As mentioned in Paragraph 2.5.2.1.1, there has been identified a variety of problem types with different outcomes, one type being design problems. In addition, also among design problems, further distinctions have been made with respect to problem and outcome characteristics [see Evbuomwan *et al.*, 1996 for an overview].

2.5.2.2.10.1 Typology of Design Problems

Based on Juster [1985] (cited in [Evbuomwan *et al.*, 1996]), Cagan and Agogino [1991], Sriram *et al.* [1989] and Pahl *et al.* [2007], Evbuomwan *et al.* [1996] distinguish routine design, redesign and non-routine design problems. The basic characteristics of those design problems are given in Table 15.

Table 15: Typology of Design Problems [Evbuomwan *et al.*, 1996]

Design problem type	Sub type	Characteristics
Routine design	-	Derived from common prototypes with same set of variables or features; structure does not change; design plan exists prototypical solutions known from the start
Redesign	Adaptive, configurational or transitional	Adaptations of known systems to changed tasks; solution principle remains unchanged; can include detail refinements
	Variant, extensional or parametric	Design by extra- or interpolation; generation of geometrically similar variants of differing capacities based on proven design
Non-routine design	Innovative	Based on new variables or features which still resemble to existing ones; known problem decomposition but sub-problems and their solutions must be synthesized; solving the same problem in different ways OR solving different problem in the same way
	Creative	Based on variable or features which are completely different from previous prototypes; design has very little resemblance to existing ones; no a priori known design plan

2.5.2.2.10.2 Typology of Product Designs

Regarding product designs as outcome of the design process, Evbuomwan *et al.* [1996], by citing Medland [1986 (cited in [Evbuomwan *et al.*, 1996])] and Clausing [1994 (cited in [Evbuomwan *et al.*, 1996])], also distinguish typologies based on market and product constraint aspects (Table 16).

Table 16: Typology of Product Designs with respect to market and constraint aspects [Evbuomwan *et al.*, 1996]

Product design type	Market/Constraint based typology	Characteristics
Static product design	Market based	Designs with undiminishing market share; no design changes required
Dynamic product design	Market based	Design with limited life time before replacement by subsequent design generation; development focused on product; focus on new, radical and alternative designs
Overconstrained product design	Constraint based	Designs often subjected to multiple and often conflicting constraints regarding function, materials, manufacturing processes, etc.; design processes consist in analysis and selection of most acceptable alternatives; typical for high-technology markets
Underconstrained idea centered product design	Constraint based	Satisfaction of specific market demand most important; focus more on product concept, functional requirements, aesthetics and ergonomics than on technology
Underconstrained skill based product design	Constraint based	Focus on manufacturing related aspects; design depends on available company skills and capabilities

2.5.2.3 Science

In the following paragraphs, some theoretical aspects of scientific activity will be discussed.

2.5.2.3.1 Definition of Scientific Activity

Science has been described as being 'dedicated to the extension of knowledge about the external world' [Langley *et al.*, 1987, p. 18]. According to Popper [2005], '[a] scientist, whether theorist or experimenter, puts forward statements, or systems of statements, and tests them step by step' (p. 3). The scientific method (in positivist research)[8] is defined as consisting of the steps theory construction, data collection in order to validate or reject the theory and, in the case of rejection, its modification and subsequent testing [Creswell, 2003].

2.5.2.3.2 Dual Search Model of Scientific Discovery

Similar to design, the production of scientific discoveries has been described as a sort of problem solving [e.g. Simon *et al.*, 1981]. Further, it is considered as a processes of search for solutions – or goal states [Klahr, 2000] – in two spaces, the *hypothesis space* and the *experiment space* [Simon and Lea, 1974; Okada and Simon, 1997].

Klahr and Dunbar [Klahr and Dunbar, 1988; Klahr, 2000] have developed a detailed model of scientific discovery, describing the search in two spaces. The *Scientific Discovery as Dual Search* (*SDDS*) model (Figure 28) divides the process of scientific discovery into three major steps, search in the hypothesis space, hypothesis testing and evidence evaluation, which, in turn, consist of several other heuristic [Klahr *et al.*, 1989] sub-steps.

[8] The term, contrary to what is referred to as methods in this report, relates to the overall process in science.

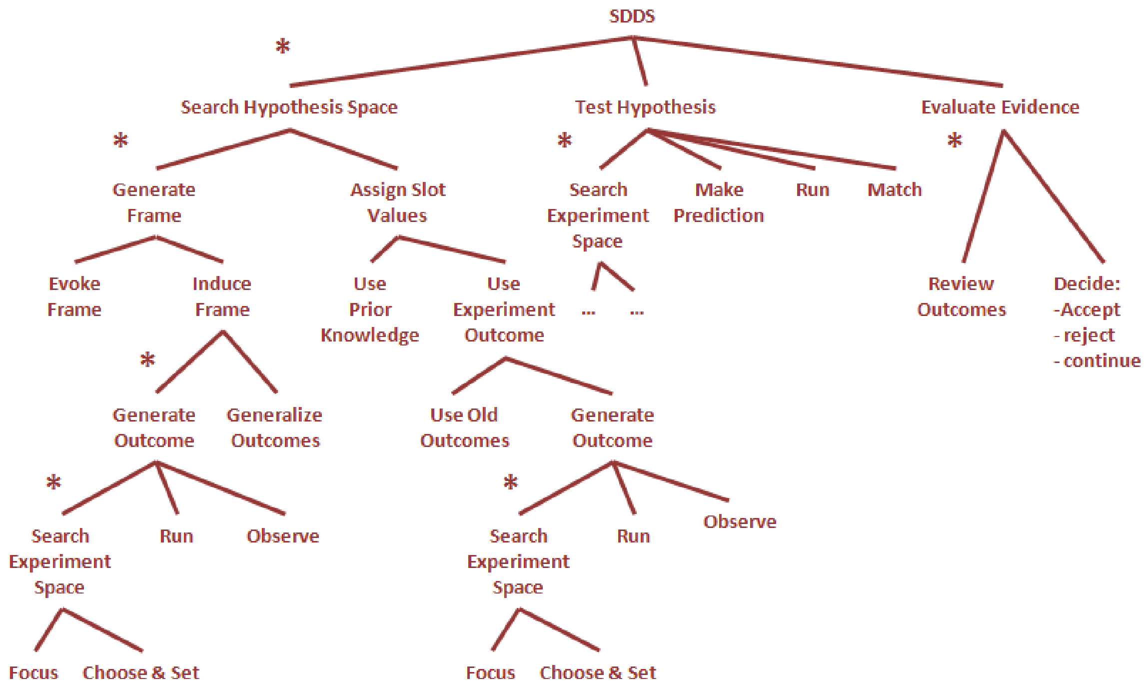


Figure 28: SDDS Model [Klahr, 2000]; *: Steps are carried out from left to right, else: alternative steps

2.5.2.3.3 Individual Differences in Search Strategies

The above mentioned model allows the distinction of individual strategies for discovery achievement [Dunbar and Klahr, 1989; Okada and Simon, 1997].

Dunbar and Klahr, based on a laboratory experiment, distinguish *experimenters* from *theorists* according to the search characteristics of an individual or team in the hypothesis and experiment space. Subjects or teams called experimenters put an emphasis on search in the experiment space by conducting an increased number of experiments which are not necessarily related to a specific hypothesis. Individuals or groups classified as theorists engage in the generation of an increased number of hypotheses, which they validate or reject by means of a smaller number of experiments [Dunbar and Klahr, 1989].

Okada and Simon [1997] give experimental support for the dichotomy of Dunbar and Klahr. They refer to empirical experimenters as individuals or teams who generate few hypotheses but conduct multidimensional experiments and to subjects who follow the opposite strategy as theory-guided experimenters. According to Okada and Simon, no one strategy can be estimated better or worse than the other. More likely, the theory-guided approach is supposed to be more effective when the subjects have strong background knowledge and a contemplative cognitive style whereas the empirical strategy is advantageous if no such knowledge or cognitive preferences exist.

2.5.3 Methods and Tools

Some of the models which are outlined in the previous paragraphs, especially in the domain of design, could also be referred to as methodologies as they suggest the use of specific methods in order to analyze and solve problems. Examples are the systematic design approach [Pahl *et al.*, 2007] and TRIZ [Altshuller, 1996]. In the following paragraphs, some of the most commonly used methods to enhance creativity in several domains will be briefly introduced.

2.5.3.1 Categorization of Creativity and Design Methods

Several overviews of creativity and design methods exist [e.g. Bonk and Smith, 1998; Shah *et al.*, 2000; Cross, 2008]. Shah and colleagues as well as Cross, however provide two rather congruent classifications. Whereas the former distinguishes *intuitive* and *logical* methods, the latter discerns *creative* and *rational* approaches. Even though those authors discuss the methods against the background of design, it seems appropriate to refer to intuitive and creative strategies as being applicable to *general creativity* problems and to classify logical and rational techniques as *design* methods. Shah and colleagues divide intuitive methods further into the following categories:

- *Germinal Methods* support initial idea generation
- *Transformational Methods* help with the generation of ideas based on existing ones
- *Progressive Methods* structure the idea generation process into steps which are repeated a several times
- *Organizational Methods* provide support for the meaningful synthesis of several ideas
- *Hybrid methods* are the result of the combination of multiple techniques

Similarly, logical design methods are classified as

- *History Based Methods* which rely on the use of solutions which have been generated elsewhere and are documented in databases as well as
- *Analytical Methods* which start from identified principles and are based on the systematic analysis of relationships and casual chains among system elements.

Table 17 gives a – yet not exhaustive – overview of methods identified in literature [Pahl *et al.*, 2007; Bonk and Smith, 1998; Shah *et al.*, 2000; Cross, 2008; Linsey and Becker, 2011]. The categorization has been performed based on Shah *et al.* [2000] and Cross [2008]. It should be noted that, contrary to the terminology of Paragraph 2.5.1.2, some methodologies like SIT and TRIZ are classified methods by Shah and colleagues. In this case, the methodology name points to the different methods it contains. Some of the methods displayed in Table 17 will be briefly outlined in the following paragraphs. Again, it shall be noted that the methods listed in Table 17 are only a subset of the existing methods and that methodological approaches like *Design for Six Sigma (DFSS)* [Staudter *et al.*, 2013] or *Design Thinking* [Plattner *et al.*, 2010] provide extensive sets of methods which are not listed here.

Table 17: Overview of general creativity and design methods

Method	Category	Sub category	Source	Secondary source
Brainstorming	General creativity	Germinal	Osborn, 2009	Shah et al., 2000; Pahl *et al.*, 2007; Cross, 2008; Linsey and Becker, 2011
K-J Method	General creativity	Germinal	Hogarth, 1980 (cited in [Shah *et al.*, 2000])	Shah *et al.*, 2000
Random Input	General creativity	Germinal		Cross, 2008
Why? Why? Why?	General creativity	Germinal		Cross, 2008
Counter-planning	General creativity	Germinal		Cross, 2008; Bonk and Smith, 1998
Morphological Analysis/Matrix/Chart	General creativity	Germinal/ Transformational	Zwicky, 1957	Shah *et al.*, 2000
Idea Spurring Checklists (e.g. SCAMPER)	General creativity	Germinal/ Transformational	e.g, Osborn, 2009; Eberle, 1971 (cited in Bonk and [Smith, 1998])	Shah *et al.*, 2000; Bonk and Smith, 1998; Cross, 2008
Random Stimuli	General creativity	Transformational	De Bono, 1970 (cited in [Shah *et al.*, 2000])	Shah et al., 2000
PMI Method	General creativity	Transformational	De Bono, 1970 (cited in [Shah *et al.*, 2000])	Shah et al., 2000
Thinking Role Assignment	General creativity	Transformational	De Bono, 1994	Bonk and Smith, 1998
Method 635	General creativity	Progressive	Rohrbach, 1969 (cited in [Pahl *et al.*, 2007])	Shah *et al.*, 2000; Pahl *et al.*, 2007; Linsey and Becker, 2011
C-Sketch	General creativity	Progressive	Shah *et al.*, 2001	Shah *et al.*, 2000; Linsey and Becker, 2011;
Gallery Method	General creativity	Progressive	Van Gundy, 1988 (cited in [Shah *et al.*, 2000]); Hellfritz, 1978 (cited in [Pahl *et al.*, 2007])	Shah *et al.*, 2000; Pahl *et al.*, 2007; Linsey and Becker, 2011
Delphi Method	General creativity	Progressive	Pahl *et al.*, 2007	
Affinity method	General creativity	Organizational	Mizuno, 1988 (cited in [Shah *et al.*, 2000])	Shah *et al.*, 2000
Storyboarding	General creativity	Organizational	Van Gundy, 1988 (cited in [Shah *et al.*, 2000])	Shah *et al.*, 2000
Fishbone Diagrams	General creativity	Organizational	Fogler and Le Blanc, 1995 (cited in [Shah *et al.*, 2000])	Shah *et al.*, 2000
Synectics	General creativity	Hybrid	Gordon, 1961 (cited in [Shah *et al.*, 2000])	Shah *et al.*, 2000; Pahl *et al.*, 2007; Cross, 2008; Bonk and Smith, 1998
Design Catalogues	Design	History based	e.g. Koller, 1985	Shah et al., 2000; Pahl *et al.*, 2007
TRIZ methods	Design	History based	Altshuller, 1988	Shah et al., 2000
Method of Forward Steps	Design	Analytical		Shah et al., 2000; Pahl *et al.*, 2007
Inversion	Design	Analytical	Shigley and Uicker, 1995	Shah *et al.*, 2000
SIT	Design	Analytical	Sickafus, 1997	Shah *et al.*, 2000
Function Analysis	Design	Analytical		Cross, 2008
Quality Function Deployment	Design	Analytical		Cross, 2008

2.5.3.2 General Creativity Methods

The general creativity methods have been subdivided by Shah *et al.* [2000] into germinal, transformational, progressive, organizational and hybrid methods. The first three of those categories will be explained in the following paragraphs.

2.5.3.2.1 Germinal Methods

Methods classified as germinal are sought to improve an individual's or a group's capability to generate ideas from a white paper [Shah *et al.*, 2000].

The most commonly known method of this subclass is *Brainstorming* [Osborn, 2009]. Several modalities have been developed over time for this method. The underlying concept is that a group of people deliberately produces ideas with respect to a given problem by building on the ideas stated by other group members. In order to maximize the number of generated ideas, the following aspects are important:

- The group should be composed of both experts and novices with regard to the problem domain.
- The participants should try to build on ideas of others and develop them further.
- Critique to ideas which are expressed by others is not allowed.
- The quantity of the produced ideas is more important than their quality.
- It is generally advised that a neutral facilitator assures that these rules are respected.

There also exist techniques which are supposed to enlarge the mental space in which ideas can be found [Cross, 2008]. An example for those methods is *Counter-Planning*, during which people are asked to merge an initial idea and its logical opposite (cf. Paragraph 2.3.4.3.2).

2.5.3.2.2 Transformational Methods

Once ideas have been generated, transformational methods can be applied in order to modify these initial concepts and thereby generate new ideas.

Morphological Analysis is a method developed by Zwicky [1957], which is sought to generate variations of concepts in a systematic way. First, the independent parameters which qualify the idea, e.g. elements and relations between them, are identified. Then, for each of the parameters, values are identified which are subsequently changed. The documentation of each parameter with the associated set of values leads to a matrix which is called *Morphological Chart* or *Box*. Each combination of values for the different parameters theoretically presents an alternative to the initial idea. However, the systematic use of this method bears the problem that the number of possible idea variants increases quickly with the number of independent parameters and the number of values the latter can take [Ritchey, 2006].

In order to produce variations of concepts or of their parameters, individuals or groups can use *Idea Spurring Checklists* like *SCAMPER* [Eberle, 1971]. These lists contain verbs or concepts which are supposed to point to insightful ideas and are considered to be valuable especially during 'dry spells' in the generation of new ideas [Bonk and Smith, 1998, p. 273].

2.5.3.2.3 Progressive Methods

This subclass of methods is characterized by iterative steps during which ideas are generated or refined [Shah *et al.*, 2010]. Most of the methods of this class also tackle problems of reduced creativity which are experienced with Brainstorming due to fear of criticism and mental fixation (cf. Paragraph 2.3.4.3.1). They do so by allowing the participants to generate ideas individually and sometimes anonymously.

Examples for progressive methods are *Method 635*, *Gallery Method* and *C-Sketch*. In all of those approaches, the introduction of the problem to all participants is followed by iterative steps of individual idea generation and idea presentation. However, the techniques vary with regard to the means of idea documentation, the number of ideas produced per participant and the modus of idea presentation. Whereas e.g. the participants are obliged to consider the ideas of each other when applying Method 635 or C-Sketch, this is not the case when the Gallery Method is used. Finally, contrary to the other methods, C-Sketch requires the participants to communicate their ideas via sketches, the reason for this restriction being that thereby generated ambiguity is supposed to foster creative thought [Pahl *et al.*, 2007; Shah *et al.*, 2001; Linsey and Becker, 2010].

2.5.3.3 Design Methods

Even though the methods outlined in the previous paragraphs can also be used in order to generate ideas during the design process, approaches classified as design methods have been explicitly developed for the purpose of problem analysis and solution generation in this domain. In this paragraph, some instances of history-based and analytical methods will be given. Further, axioms which describe characteristics of well-designed systems will be introduced. Finally, methodological elements of TRIZ and its derivatives which prescribe the process of problem solving in design are highlighted.

2.5.3.3.1 Axiomatic Product or System Characteristics

As noted in Table 14, both Axiomatic Design [Suh, 2001] Theory and TRIZ [Altshuller and Seljuzki, 1983] express axioms about the characteristics of what are considered good products. These axioms are presented briefly here.

2.5.3.3.1.1 Axiomatic Design Axioms

Besides the descriptive modeling of the design process, Axiomatic Design essentially provides two axioms [Suh, 2001]:

- *Axiom 1*, the *Independence Axiom*, states that independence of Functional requirements (cf. Paragraph 2.5.2.2.3) should be maintained in order to assure a good design. I.e., when there are two or more functional requirements, satisfaction of one requirement should not affect to any degree the satisfaction of the others. According to Suh, this axiom is of crucial importance to the mapping process between the Functional and the Physical Domain.
- *Axiom 2*, the *Information Axiom*, becomes important in those cases, when different potential designs satisfy the Independence Axiom. Under those circumstances, the design solution which has the smallest information content is considered the best. It can be inferred that the probability of a design to work properly is one major quality-related criterion.

Both axioms and their consequences for designs can also be expressed in mathematical terms. For space reasons, those formulas will not be presented here.

2.5.3.3.1.2 TRIZ axioms

TRIZ is based on a number of axioms [Cavallucci and Khomenko, 2007 (cited in [Cavallucci and Rousselot, 2011]); Cavallucci and Rousselot, 2011]. Three of these axioms, which can be considered both descriptive and prescriptive, are:

- Development of technological systems according to *Evolution Laws* [Salamatov, 1996; Cavallucci and Weill, 2001]: These ‘laws’ state a certain pattern in the development of technical products over time. Nine laws have been formulated, which describe, among other aspects, system characteristics in terms of functional composition, energy conduction, and working principles. Against the background of the present research, especially two laws shall be highlighted.

The *Law of System Completeness* describes mature technological systems as performing four sub functions, energy transformation, energy transmission, interaction with the functional object and control (Figure 29). This law further postulates that systems tend to integrate all of these functions during their evolution.

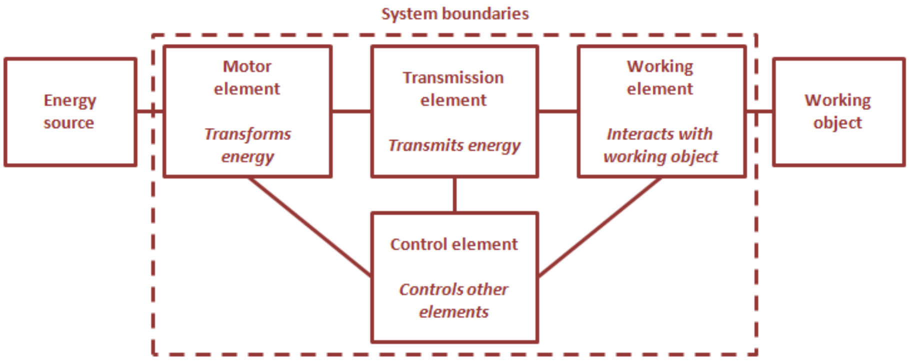


Figure 29: Model of technological system according to Law of System Completeness [Salamatov, 1996]

The second law, the *Law of Ideality*, states a tendency of technological systems to strive for increased *Ideality (I)*. Ideality, or the *Degree of Ideality (D)*, in mathematical terms, can be described in either one of the following terms[9]:

$$I = \lim_{\substack{M,C,E \to 0 \\ n \to \infty}} Fn\,(M, C, E) \qquad \text{(1) [Salamatov, 1996]}$$

Or

$$D = \frac{\sum Fu}{\sum Fh + \sum Fc} \qquad \text{(2) [Cavallucci and Weill, 2001]}$$

This means technical systems always strive towards maximization of useful functions by minimizing harmful side effects, costs, and consumption of both material and energy during their life cycle.

- Inventive technological systems overcome contradictions. These contradictions can be of several types. In technical terms there exist technical or pair [Savransky, 2000] contradictions and physical or point [Savransky, 2000] contradictions. The former type describes a situation in which the improvement of one technical parameter causes the deterioration of a second parameter. The second sort refers to a situation in which either the system or one or more of its sub elements have to accept two opposed values for the same parameter. This axiom is essential to problem modeling techniques which are described in more detail in Paragraph 2.5.3.3.3.4.
- Each technological problem has to be solved while taking into account constraints and conditions which are specific to that problem. I.e., problems cannot be solved only by using general principles.

These axioms have both descriptive and prescriptive character and are the basis of several problem analysis and problem solving methods of TRIZ methodology.

[9] *I*: Ideality of a system; *Fn*: functioning (or number of functions) of a system; *M*: mass of the system; *C*: consumption of the system; *E*: energy capacity of the system; *D*: degree of ideality a system has obtained; *Fu*: useful functions a system performs; *Fh*: harmful side effects of a system and its functioning; *Fc*: costs of a system and its functioning

2.5.3.3.2 Methods for the Mapping between Domains or Design Phases

Besides descriptions of good design products and depending on the underlying design theory, there exist several methods which shall help the designer to map between the different domains [Suh, 2001] or to go through the different design phases [Pahl *et al.*, 2007]. Two of those methods shall be briefly described in the following paragraphs.

2.5.3.3.2.1 Functional Analysis

The *Functional Analysis* aims at the identification of functions which a product has to perform in order to satisfy the needs of the user. Further, it helps setting the system boundaries. Thus, this method can be located at the early phases of the design process. Cross [2008] divides the application into the following five steps:

1. The overall function of the future design product is expressed in terms of inputs and outputs. The description should be broad and the system boundaries, which are to some extent modeled by the limits of a black box, should be wide.
2. The external functions which the product has to perform are broken down into internal sub-functions. The resulting sub-functions are noted inside the black box drawn in Step 1.
3. The previously identified sub-functions inside the black box are linked following a cause-effect logic. If necessary, the sub-functions are further detailed.
4. Concrete system boundaries are drawn, which define the functional limits of the designed system. There can be different boundaries for different solution types.
5. The last step, according to Cross, consists in the search for appropriate components which can perform the sub-functions. However, no concrete description is given for this step.

2.5.3.3.2.2 Quality Function Deployment

Quality Function Deployment (*QFD*) is an extensively applied method whose primary purpose is to improve the quality of a designed system from the perspective of the customer [Prasad, 1997]. The method is mainly applied to translate *Customer Requirements* (*CRs*) [Prasad, 1997; Cross, 2008] – or Customer Attributes in Axiomatic Design terms – into *Key Product Characteristics* (*KPCs*) [Prasad, 1997] or *Engineering Characteristics* [Cross, 2008] – which have no direct correspondence in Axiomatic Design. However, its principles and notations can also be used at other stages of the design process like e.g. the identification of *Process Characteristics* [Prasad, 1997], i.e. Process Variables in Axiomatic Design terms. The extensions of the method, which are not described here, also allow the evaluation of an existing system in terms of quality against alternative systems like e.g. benchmark solutions.
The core concept of QFD is the *House of Quality* (*HoQ*), which allows the notation of the different parameter sets. Four areas or ‘rooms’, two vectors and two two-dimensional matrices, build the core of this notation scheme (Figure 30):

- The first vector represents a list of variables (V1) the satisfaction of which is the goal of the design process. Depending on the design stage, these can be e.g. Customer Requirements.
- The second vector features a list of variables (V2) which represent a certain set of characteristics of the product or the manufacturing process. Examples for those variables are Key Product Characteristics.
- The first matrix which is called *Correlation Matrix* (*CM*) allows the designer to map between the elements of the two vectors. I.e., the designer documents in qualitative and quantitative terms which of the elements of V2 influence the elements of V1.

- The second matrix is the triangular *Sensitivity Matrix* (*SM*). It serves for the indication of the influence which the elements of V2 exert on each other. By filling in this area of the HoQ, the designer can detect trade-offs which are linked to the change of product or process characteristics.

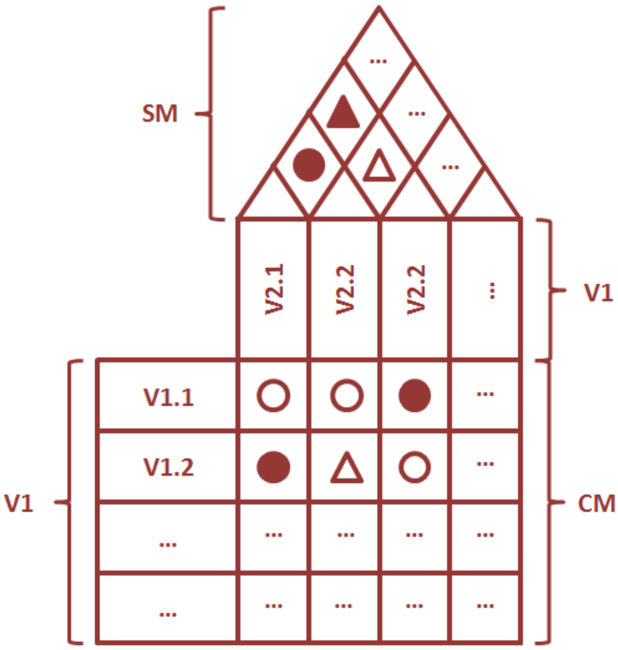


Figure 30: Basic elements of the House of Quality [Prasad, 1997; Cross, 2008]; The circles and triangles of different colors indicate positive or negative correlations between the different parameters.

2.5.3.3.3 Problem Solving Methods of TRIZ and Derivatives

The methods of TRIZ and its derivatives (SIT, ASIT/USIT), are currently assigned to different phases of the problem solving model described in Paragraph 2.5.2.2.8. Thus it can be distinguished between methods and tools for problem definition, for problem analysis or problem modeling and models and heuristics for problem solving. In the following paragraphs, some examples for the former two types, problem definition and problem modeling tools, will be described. For further and more detailed information, the work of Savranksy [2000] can be advised.

2.5.3.3.3.1 Similarities and differences between the Methods

On the one hand, TRIZ and its derivatives are similar in respect to a set of underlying principles, like the notion of ideality or the strategy to foster analogy by abstraction or dialectical principles. On the other hand, there exist some qualitative as well as quantitative differences. Whereas for example the concept of *Contradictions* is used in TRIZ to introduce dialectical reasoning (cf. Paragraphs 2.3.4.3.2 and 2.4.2.2.2), it is replaced by a concept called *Qualitative Change* in TRIZ derivatives without changing the underlying problem modeling principle. Other differences concern the degree of detail to which problems are analyzed or the designer’s degree of freedom during the application of the methodology. Whereas TRIZ is considered to prescribe the problem solving process in a very detailed and somewhat strict way by suggesting a very detailed *Algorithm for Solving Inventive Problems* (*ARIZ*; Russian acronym for Алгоритм решения изобретательских задач; English: Algorithm for Inventive Problem Solving) [Altshuller, 1989, 1999], the methods suggested by SIT, ASIT and USIT are less strict and less detailed [Sickafus, 1997] but also contain less domain-specific knowledge [Horowitz, 1999].

2.5.3.3.3.2 Typology of Methods and Tools of TRIZ and Derivatives

Over time, a large set of TRIZ tools have been developed. Similarly, the developers of methods like SIT, ASIT and USIT have introduced several new methods. Table 18 gives an overview of these concepts, categorizes them into problem definition, problem analysis as well as problem modeling tools and indicates those methods serving a similar purpose. It shall be mentioned that most of the presented problem analysis models are closely related to specific problem solving heuristics. The latter, however, will be described in a subsequent chapter. Four methods of TRIZ and, in three cases, corresponding methods of USIT are presented in more detail in the following.

Table 18: Mapping of TRIZ and USIT methods (based on [Savransky, 2000] and [Nakagawa *et al.*, 2003]); USIT has been chosen for this comparison because it contains the methods of SIT and ASIT.

		USIT	Problem Definition					Problem analysis							
								Closed-World Method					Particles Method		
TRIZ			Unwanted effect	Problem statement	Sketch	Plausible root causes	Minimum set of objects	Closed-World diagram	Qualitative change graphs	OAF diagram	Time characteristics	Space characteristics	Ideal solution	Particles (agents)	Action and property diagrams
Problem definition		Psychological inertia tools		(X)	(X)		(X)								
	System Operator	System hierarchy		x											
		Time evolution													
	Problem/ Opportunity Explorer	Benefits analysis	x	x											
		Identification of resources					x								
		Constraints				x									
		'Sore points'	x			x									
		S-Curve Analysis													
Problem analysis		Funct. An. (Su-Field Analysis)						x							
		Function/attribute analysis						x	x						
		Technical Contradictions							x						
		Physical Contradictions							x		x	x			
		Trends of Technol. Evolution											x		
		Ideality/Ideal Final Result (IFR)											x		
		Smart Little People / Agents												x	

2.5.3.3.3.3 Multi-Screen Approach

The *Multi-Screen Tool* combines the TRIZ axiom of technological development according to Evolution Laws with a systemic thinking approach (Figure 31). When facing a problem solving task related to a technical system, the problem solver is asked to consider not only the target system but also to take into account the direct and indirect environment (*Super System(s)*) as well as the components (*Sub System(s)*) of the system under investigation. Further, the problem solver is required to analyze the historical development at the different systemic levels as well as factors which are responsible for this development. The number of both systemic and temporal levels depends on the problem at hand. The next step consists in an extrapolation of the development of the different super- and sub systems from past and present into the future. Once, this is done, the problem solver can, to a certain extent, predict what the 'future' technological system should look like in order to optimize performance under future conditions, like resources, customer requirements, trends and so on. As the Multi-Screen Approach allows the identification of specific problems in complex and ill-structured socio-technological problem settings, it is considered a problem definition tool in this work [Savranksy, 2000].

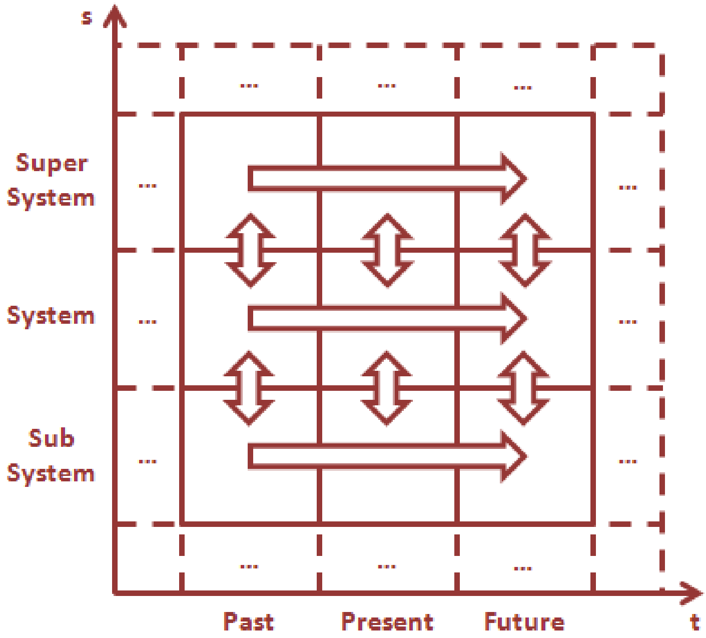


Figure 31: Schema of Multi-Screen Tool; horizontal arrows: evolution on different systemic levels; vertical arrows: mutual influence between systemic levels

2.5.3.3.3.4 Contradiction Models

Once the technical problem is identified, the TRIZ methodology suggests an analysis of the problem using the concept of contradiction. According to this model every technological problem can be described as the need to satisfy two a priori conflicting requirements. A requirement conflict can be due to two phenomena. In the first case, the problem solver wants to improve one *Evaluation Parameter* of a system or object but the improvement will *a priori* cause the deterioration of a second *Evaluation Parameter* [Cavallucci and Khomenko, 2007 (cited in [Baldussu *et al.*, 2011])]. The situation is called a *Technical* or *Pair* [Savranksy, 2000] *Contradiction*. In the second scenario, the problem arises from the requirement that either the system or one of its elements must accept two a priori opposed states in terms of one *Control Parameter* [Cavallucci and Khomenko, 2007 (cited in [Baldussu *et al.*, 2011])]. This case is named *Physical* or *Point* [Savransky, 2000] *Contradiction*. Figure 32 schematically explains the two types of contradictions.

In USIT, the concept of contradiction is replaced by *Qualitative Change Graphs* which draw a link between system parameters and the functional performance of system elements [Sickafus, 1997]. The drawing of several Qualitative Change Graphs for one system can also lead to the identification of contradictions.

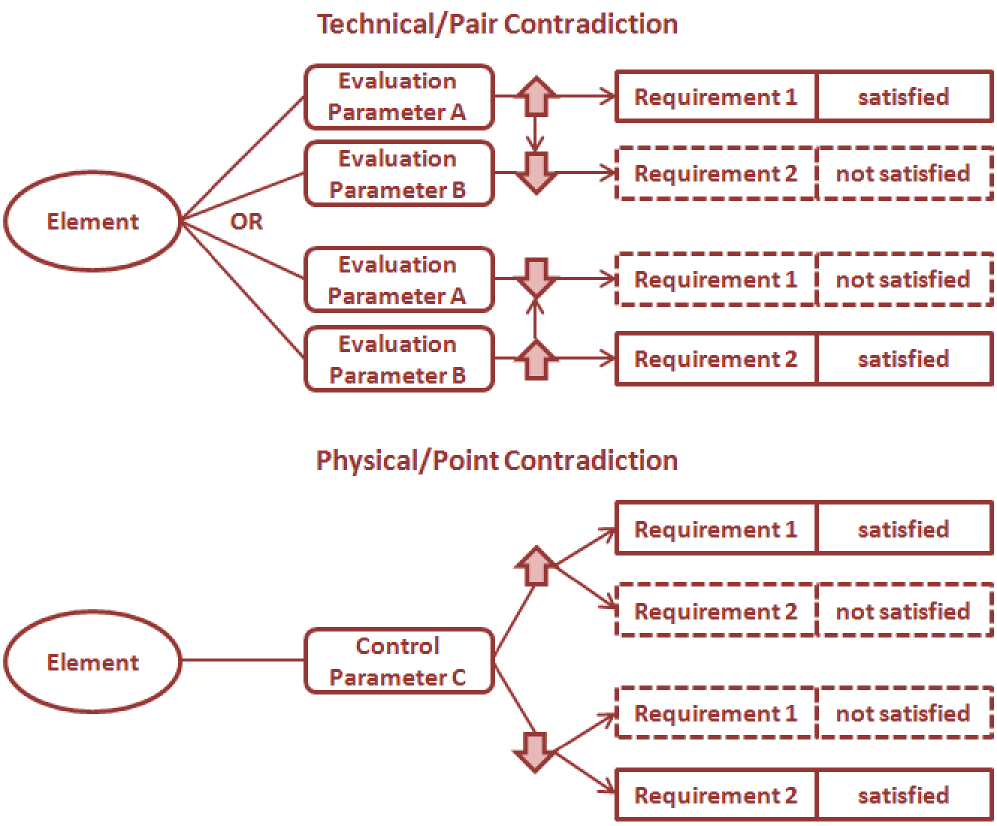


Figure 32: Schematic representation of Technical/Pair and Physical/Point Contradictions [after Cavallucci and Khomenko, 2007 (cited in [Cavallucci and Rousselot, 2011] and Baldussu *et al.*, 2011])

2.5.3.3.3.5 Detailed Analysis of Object Interactions by Su-Field Analysis

The *S-Field* (*Substance-Field*) *Analysis* is considered to allow the most elementary and thus most detailed analysis and modeling of problems in TRIZ methodology. Using the S-Field Model, every technical problem can be described as elements, so called *Substances* which are modified or sought to be modified by either other Substances or *Fields*. The latter term is somewhat misleading in so far as it also describes for example mechanical forces or heat flows. Following this model, a problem can be described as deficient, i.e. harmful, insufficient or excessive interactions among Substances or between Fields and Substances. Further, TRIZ methodology proposes to classify the problem representations generated by this means according to criteria such as the type of deficient interaction or the ‘completeness’ of the documented S-Fields [Altshuller and Seljuzki, 1983; Altshuller, 1996]. Figure 33 exemplifies the notation used in S-Field Analysis.
USIT methodology provides a comparable tool for problem analysis with the *Closed World Approach*. The differences between those two concepts concern the information context of the established models as well as subsequent approaches for problem solving (cf. subsequent chapters).

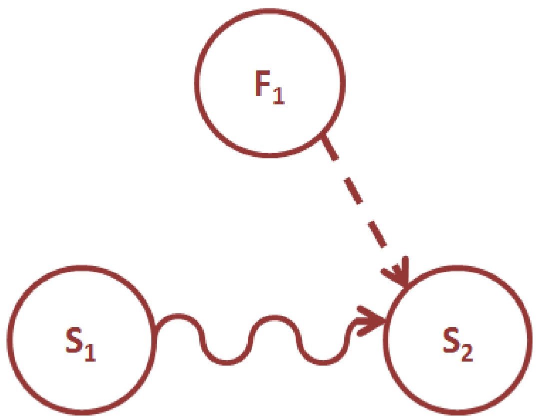


Figure 33: Example of S-Field modeling a harmful interaction between two Substances (S_1 and S_2) as well as an insufficient interaction between a Field and a Substance (F_1 and S_2)

2.5.3.3.3.6 Methods for Analogical Problem Solving

In TRIZ and its derivatives, there exists a set of methods which share two common purposes. The first goal is to facilitate solution generation by analogy (cf. Paragraph 2.4.4.2). The second purpose is to draw a link between the initial problem setting – the problem state – and the desired goal – the solution state (cf. Paragraph 2.5.2.1.1). Methods like the *Model with Miniature Dwarves* [Altshuller, 1996] of TRIZ methodology or the *Magic Particles Approach* of USIT [Sickafus, 1997], which can all be classified *Agent Methods* [Savransky, 2000], are proposed in order to meet these requirements. The suggested procedure of the Magic Particles approach, which is quite similar to the other variants, reads as follows [Sickafus, 1997; Savranksy, 2000] (Figure 34):

1. At first, the problem solver is required to draw a sketch of the initial problem situation (a), of the desired goal situation (c) and, if possible, of intermediate situations (b).
2. The second step consists in a comparison of the established sketches and in the insertion of the '*Magic Particles*' in those areas of the sketches (a) and (b) where the latter differ from the sketch of the desired solution (c).
3. At step three, the problem solver briefly notes the *Ideal Result* which the Magic Particles shall cause in order to transform the problem state into the desired state. That statement builds the top of a so called AND/OR tree. On the next levels of this tree diagram, a list of *Particle Actions*, which are necessary for the realization of the Ideal Result, is established. Depending on whether a combination of actions is necessary or whether specific actions represent alternatives to each other, they are linked with AND respectively OR conjunctions. Then, the problem solver is required to think about specific properties which are necessary for the Particles in order to perform the previously identified actions. These properties are noted, again with AND or OR conjunctions on the bottom line of the tree.
4. Finally, the set of required *Particle Properties* can be used in order to carry out an objective search for specific technologies, items or combinations thereof which can be applied in order to solve the initial problem.

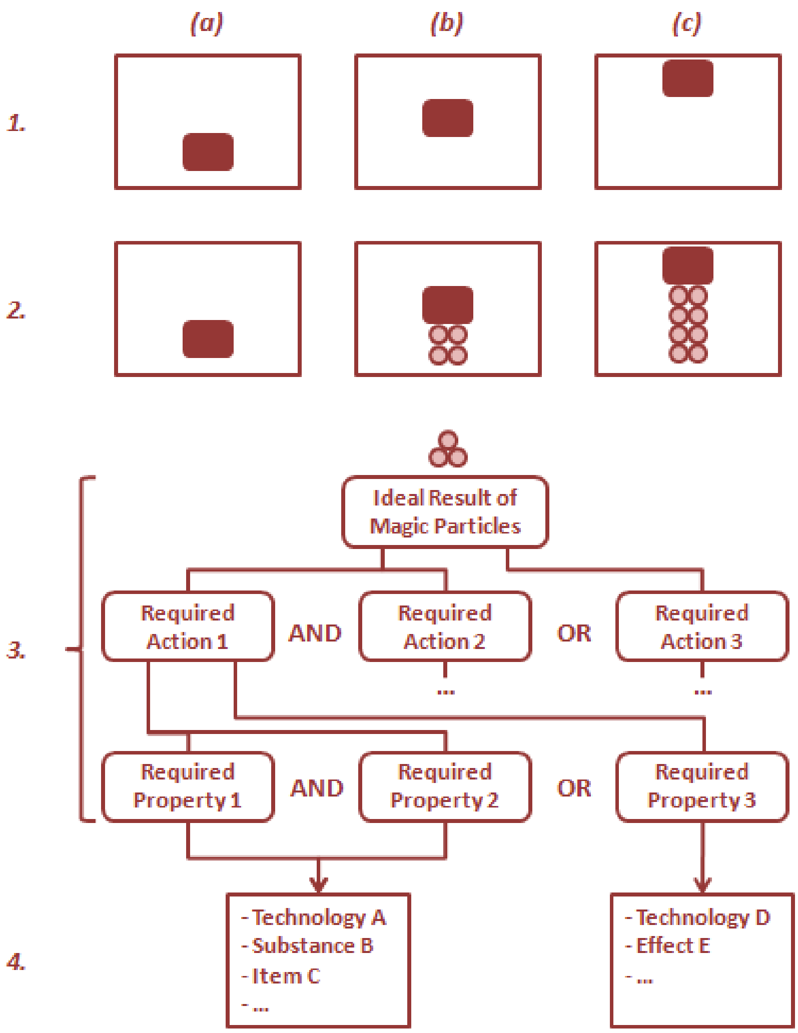


Figure 34: Procedure of the Magic Particles Approach [Sickafus, 1997]

2.5.3.4 Methods in Science

Design research and industrial companies have developed a plethora of design problem solving methods which can be applied throughout different design disciplines and which are widely explained by literature. However, to the best of the author's knowledge, there exists only little literature explicitly describing specific problem solving methods for natural science. For that, at least two reasons can be identified.

First, scientists learn about scientific methods and how to apply them during research projects. As they develop a rather close relationship to their teachers, i.e. senior scientific researchers, many of the methods are tacitly acquired. Zuckerman's [1977] empirical finding that a high percentage of the most performing scientific researchers had had a very performing scientific researcher as Ph.D. supervisor supports this argument.

A second reason for the lack of documentation of scientific methods is the difficulty to distinguish them from heuristics used in science. It is for example difficult to draw a clear cut line between the Weak Methods [e.g. Klahr, 2000] which are supposed to be widely used in science and which are described in the following paragraph, and the heuristics which are suggested by Lenat [1978] and which will be described in Chapter 2.5.4.

In the following paragraph, a list of methods which are widely applied in science is given.

2.5.3.4.1 'Weak' Methods

Simon *et al.* [e.g. Simon *et al.*, 1981] distinguish between *Strong* and *Weak Methods* in Science. Whereas Strong Methods are considered 'powerful techniques that are carefully tailored to the specific structure' of a given domain [Simon *et al.*, 1981, p. 5], Weak Methods are defined as 'problem solving techniques of quite general application whose generality is assured by the fact that they do not use or require much prior knowledge of the structure of the problem domain' (p. 5).

Five major weak methods are distinguished [Langley *et al.*, 1987; Klahr, 2000]:

- *Generate and Test*: The method corresponds to what is currently referred to as 'trial and error' and consists in the application of a solution operator (cf. Paragraph 2.5.2.1.1) to a given problem setting and testing if the operation has led to the desired goal state.
- *Hill Climbing*: The problem solver first applies different operators in parallel to the initial problem state. Then he or she compares the different products of the transformation process in terms of similarity to the desired goal state. The product featuring the highest similarity is then taken as starting point for a subsequent iteration.
- *Means-Ends Analysis*: The first step of this method is the analysis of current problem state and goal state in order to identify a set of differences between them. Then, operators for the reduction of those differences are searched and applied until the goal state is achieved. In some cases, the application of an operator requires a specific intermediate state. In this case, a sub-problem can be formulated in order to achieve that specific sub-goal by another operator.
- *Planning*: This method consists in five steps. First, the initial problem space is transformed into an abstract one by suppression of certain details of the problem state and available operators. Second, the specific initial problem setting is translated into this abstract problem space. The third step consists in the resolution of the abstract problem (by using weak methods or by other means). The by this means generated abstract solution is then used in order to provide a pattern for resolving the initial problem. Finally, the original specific problem is solved by back-translation of the abstract plan into specific terms and plan execution.
- *Analogy*: This method refers to analogical problem solving, which is explained in Paragraph 2.4.4.2.

As stated earlier, many of the methods described in this chapter are closely linked or point to heuristics or problem solving operators. Some examples for those will be given in the following chapter.

2.5.4 Heuristics

As mentioned in Paragraph 2.5.1.2, heuristics are defined as principles or tactics which are selected on the basis of experience or judgment and which have a certain probability to yield a reasonable solution after relatively short search [Newell and Simon, 1972; Silver, 2004]. It is important to state that, in the vast majority of cases, even if heuristics provide a 'relatively good chance of success without extraordinary effort' [Langley *et al.*, 1987, p. 13], there is no guarantee that an appropriate result will be obtained using this type of solution operator.

Feigenbaum [1977] postulates an inverted relationship between the generality of a heuristic, i.e. its applicability on problems of different domains, and its power, i.e. its probability to yield reasonable results. According to that theory, which obtains support by case studies with computer programs (cf. Paragraph 2.4.5.1), experts are better problem solvers in their domain because they use more appropriate problem solving heuristics. However, contrary to the more general ones, the specialized heuristics are difficult to apply successfully in other domains (Figure 35).

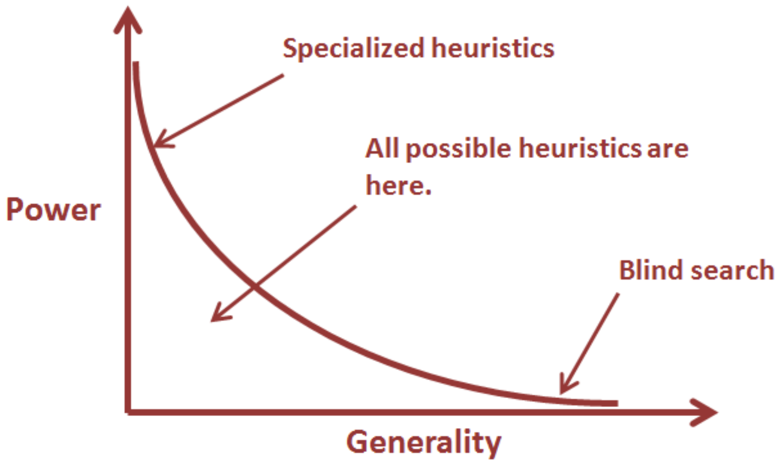


Figure 35: Inverted relationship between generality and power of heuristics [after Lenat, 1978 (based on Feigenbaum, 1977)]

According to Bianchi *et al.* [2009] there exist two types of heuristics: *constructive algorithms*, which are considered heuristics in this context, and *local search algorithms*. Whereas the former generate an overall solution by joining components or partial solutions, the latter modify pre-existing solution states of a problem in order to find improved solutions.

As mentioned before, the distinction between methods and heuristics is not always clear. Further complicating matters, some methodologies such as TRIZ and USIT suggest the application of problem solving heuristics following certain problem modeling methods. In the following paragraphs, some examples of different generic and domain specific heuristics shall be given.

2.5.4.1 General Heuristics

First of all, even though they have been formulated from the modeling of scientific problem solving, the Weak Methods introduced in Paragraph 2.5.3.3.1, can be considered general heuristics.

Other examples of very general (and thus not very powerful) heuristics are given by Lenat [1987] (Table 19).

For the search of insight problems, Kaplan and Simon [1990] experimentally show that the use of the heuristic principle to pay attention to invariant features of the problem situation can often lead to a considerable reduction of the search space and thus to quicker insights.

A good overview of classes of general heuristics is given by Silver [2004], who identifies seven types of heuristics and discusses certain instances (Table 20).

Finally, it shall be mentioned that elements of certain idea spurring checklists like SCAMPER (cf. Paragraph 2.5.3.2.2) can be considered heuristic strategies for solution generation.

Table 19: Instances of general heuristics [Lenat, 1978]

No.	Heuristic
1	If X is often true, try to find out exactly where it does and doesn't hold.
2	If you must do some new, complicated task, try to arrange things so that the tools, subtasks, etc. are very familiar.
3	Look at the extreme cases of the known relationships.
4	Ignore minor details until a basic plan is formed.

Table 20: Overview of Heuristic classes [Silver, 2004]

Heuristic class	Explanation
Randomly generated solutions	Cf. Generate and Test (Paragraph 2.5.3.3.1)
Problem decomposition/partitioning	Decomposition or partition of a complex problem into sub problems which are presumably easier to solve; cf. also Means-Ends-Analysis (Paragraph 2.5.3.3.1)
Inductive heuristics	Generalization from a simpler or more narrow version of the problem or from a closely related problem OR Analogical Problem solving (Pragraph 2.5.3.3.1)
Heuristics for solution space reduction	Reduction of the space of possible solution e.g. by introduction of extra constraints or by considering only solutions which satisfy specific properties; [cf. also Kaplan and Simon, 1990]
Approximation methods	Manipulation of established (mathematical) model
Constructive methods	Cf. constructive algorithms (Paragraph 2.5.4)
Local improvement	Cf. local search algorithms (Paragraph 2.5.4)

2.5.4.2 Heuristics in Design

Heuristics have been the subject of extensive analyses in design research. The identification of design heuristics are the result of either empirical analysis (e.g. in the case of TRIZ [e.g. Altshuller and Seljuzki, 1983; Altshuller, 1996]), analyses of laboratory experiments [e.g. Daly *et al.*, 2012] or deduction from design theory [Suh, 1998]. Table 21 gives a non-exhaustive overview of existing sets of heuristics for problem solving in design, their nature and, if applicable, the methodological framework in which they are supposed to be primarily used. Some of the mentioned heuristics are briefly introduced in the following paragraphs.

Table 21: Examples of sets of heuristics for technological and design problem solving

Set of Heuristics	Nature of heuristics	Methodological framework	References
Inventive Principles	Induction from empirical analysis	Supposed to be primarily used after identification of Technical/Pair Contradictions (TRIZ)	e.g. Altshuller, 2004
Separation Principles	Induction from empirical analysis	Supposed to be primarily used after identification of Physical/Point Contradictions (TRIZ)	e.g. Savranksy, 2000
Standard Solutions	Induction from empirical analysis	Supposed to be primarily used after establishment of Su-Field Models (TRIZ)	e.g. Altshuller and Seljuzki, 1983
Solution Operators	Induction form empirical analysis	Supposed to be primarily used after establishment of problem structure (SIT) or Closed World Model (USIT)	Horowitz, 1999; Sickafus, 1997
Design Heuristics	Aggregation from laboratory experiment	-	Daly et al., 2012
AD Corollaries	Deduction from design axioms	Derived from axioms of Axiomatic Design theory	Suh, 1998

2.5.4.2.1 Separation Principles

The Separation Principles are used in TRIZ methodology in order to solve problems which have been modeled using Physical or Point Contradictions (cf. Paragraph 2.5.3.1.3.4). Savranksy [2000] for example gives a list of eleven such heuristics, which can be applied once the characteristics and conditions of the Contradiction to overcome have been identified (Table 22). The Separation Principles are proposed depending on the nature of Physical Contradiction to overcome. Whereas for example the first heuristic is supposed to be used in order to solve problems due to requirements of simultaneous opposite parameter states, the second principle is sought to solve problems which require opposite parameter states at the same spot.

Table 22: Separation Principles as heuristics for problem solving in TRIZ

No.	Separation Principle
1	Separation of contradicting properties in space
2	Separation of contradicting properties in time
3	Joining of homogeneous and heterogeneous elements or systems at higher systemic levels
4	Change from an element with a given property into an element with the opposed property or into a combination of elements with opposed properties
5	Use of aggregation of elements with a property whereas the composing elements feature the opposed property
6	Transition into a solution working at micro-level / use of physical effects
7	Use of changes of phase states of system parts or system environment
8	Use of easily reversible changes of phase states as a function of working conditions
9	Use of by-effects of changes of phase states
10	Use of multi-phase materials
11	Use of physical/chemical alteration of materials

2.5.4.2.2 Standard Solutions

Standard Solutions are suggested in TRIZ methodology in order to provide support for the solving of problems which have been modeled by S-Field Models (cf. Paragraph 2.5.3.1.3.5). These problem solving heuristics are categorized in groups in order to guide the problem solver in the selection of a specific heuristic (e.g. Salamatov, 2005; Table 23). The groups contain subsets of solution principles which are considered to be used for certain types of problem models (e.g. Class 2: Evolution of S-Field Model Systems) or for certain types of specific problems (Class 4: Measurement and Detection Standards). Several authors [e.g. Savranksy 2000, De Carvalho and Tessari, 2011] have identified correspondences between some TRIZ heuristics like Inventive Principles, Separation Principles and Standard Solutions.

Table 23: Classes and groups of Standard Solutions [Salamatov, 2005]

Standard Solution Class	Standard Solution Group
Class 1: Composition and decomposition of S-Field Model Systems (SFMS)	Group 1-1: Synthesis of SFMS
	Group 1-2: Decomposition of SFMS
Class 2: Evolution of SFMS	Group 2-1: Transition to complex SFMS
	Group 2-2: Evolution of SFM
	Group 2-3: Evolution by coordinating rhythms
	Group 2-4: Complex-forced SFMS (F-SFMS)
Class 3: Transitions to supersystem and microlevel	Group 3-1: Transitions to bisystem and polysystem
	Group 3-2: Transition to microlevel
Class 4: Measurement and detection standards	Group 4-1: Change instead of measurement and detection
	Group 4-2: Synthesis of measurement system
	Group 4-3: Improvement of measurement systems
	Group 4-4: Transition of ferromagnetic measurement systems
	Group 4-5: Evolution of measurement systems
Class 5: Helpers	Group 5-1: Introduction of substances under restricted conditions
	Group 5-2: Introduction of fields under restricted conditions
	Group 5-3: Use of phase transitions
	Group 5-4: Use of physical effects
	Group 5-5: Obtaining substance particles

2.5.4.2.3 AD Corollaries

A set of corollaries[10] is suggested by Suh [1998] based on the work of Strogatz [1994]. Those concepts are derived from the Axiomatic Design Axioms (cf. Paragraph 2.5.3.1.1.1) and are supposed to help in the design process. Table 24 gives an overview of some of Suh's corollaries, which are considered heuristics in this report.

[10] Suh [1998] refers to corollaries as 'inference[s] derived from axioms or propositions that follow from axioms or other propositions that have been proven' (p. 205).

Table 24: Heuristics derived from axioms of Axiomatic Design Theory [Suh, 1998]

No.	Title	Description
1	Decoupling of coupled designs	Decoupling or separation of parts or aspects of a solution if FRs are coupled or become interdependent
2	Minimization of FRs	Minimization of the number of FRs and constraints
3	Integration of physical parts	Integration of design parameters into a single (physical) part if FRs can thus be independently satisfied
4	Use of standardization	Use of standard or interchangeable parts if consistent with FRs and constraints
5	Use of symmetry	Use of symmetrical shapes and/or components if consistent with FRs and constraints
6	Largest tolerance	Specification of FRs using the largest possible tolerance
7	Uncoupled design with less information	Reduction of required information by design of uncoupled instead of decoupled system

2.5.4.3 Heuristics in Science

Also in scientific activity several heuristics have been identified. Some of these 'informal rules of thumb' [Lenat, 1978, p. 262] have been documented following laboratory experiments [Klahr *et al.*, 1989], others are derivatives of more general search heuristics (cf. Chapter 2.5.4.1) and are applied in computer programs which perform scientific tasks [Lenat, 1978].

Klahr *et al.* [1989], having analyzed strategies which help test subjects designing experiments which effectively constrain the search space (Experiment Space; Paragraph 2.5.2.3.2), identify several heuristics. Those are briefly described in Table 25.

Table 25: Heuristics used in science in order to conduct experiments efficiently [Klahr *et al.*, 1989]

No.	Title	Description
1	Maintain observability	Design of experiments which perform 'short' steps, thus allowing to remember what happened and to compare results with predictions; design of experiments in order to obtain easily observable results
2	Design experiments giving 'characteristic' results	Design of experiments which perform 'distinct' steps in order to identify what specific steps are repeated an in what order they are repeated, thus reducing the experiment space and maximizing observability
3	Focus on one dimension of an hypothesis	Design of experiments which, compared to the previous one, change only one aspect, thus changing only one aspect of one hypothesis
4	Exploit surprising results	Change of goal of the experiment when surprising result occurs, e.g. induction of new hypotheses
5	Use *a priori* strength of an hypothesis to choose experimental strategy	Design of experiments to demonstrate key features of hypotheses if the latter are highly likely; set up of experiments discriminating between rival hypotheses if the latter have low a priori strength

Lenat [1978] proposes a list of heuristics which have been proven successful in specific scientific domains and mathematics. The heuristics and the corresponding domains are given in Table 26. Lenat highlights, that the heuristics (a) and (b) of the more specific domains are only specializations of more general heuristics and correspond in fact to the general Heuristics 1 and 2 of Table 19.

Table 26: Heuristics used in science and mathematics [Lenat, 1978]

No.	Domain	Description
1	Science or mathematics in general	Execution of very easy tests of theories even if the latter predict results strongly
2		Maintain correlation between importance of steps (e.g. proofs, experiments) and the stringency of their verification
3		Design of experiments in order to assure relevance also of negative results
…		…
5 (a)	Biology	Study of presence of mechanisms across species
6 (b)		Choice of species for experiments about which much is already known
7	Mathematics	If $f: A \times A \times \ldots \times A \to B, and\ A \subset B$,verification if in fact $f: A \times A \times \ldots \times A \to A$; Else search for subset S of A for which $f: S \times S \times \ldots \times S \to S$.
8		If a set S has only a few elements, S is no longer of interest. But one should investigate why S is so small.
9 (a)	Molecular genetics	Study of presence of gene control signals across species
10 (b)		Use of E. Coli for experiments because much is known about its genetics and many of its plasmids are characterized and available
11		Use of plasmids and lysogenic viruses for DNA introduction between strains of bacteria
12		Check for host gene modification by reintroduction into donor

2.5.5 Summary of General and Domain Specific Theory, Methods and Heuristics

In the Chapters 2.5.2 to 2.5.4, a brief overview of theory, methods and heuristics in creative problem solving in general as well as in the specific domains of engineering design and science was given. The aim was to distinguish between these concepts even though they are often mixed in literature and in practice.

In the following chapter, an overview of theoretical and methodological approaches which are of importance for interdisciplinary knowledge and technology transfer is given.

2.5.6 Approaches for Knowledge and Technology Transfer

The present chapter discusses theoretical and methodological aspects which are considered to be of interest for interdisciplinary knowledge and technology transfer in design. The highlighted approaches (e.g. the FBS model), however, do not necessarily have the initial purpose of facilitating multidisciplinary problem solving processes.

First of all, the theory and problems of interdisciplinary systems and methodology for the design of the latter are discussed. It follows a brief introduction of models for the systematization and structuring of knowledge, i.e. ontologies. The chapter concludes with a brief overview of methods for the search for and the integration of potential technologies.

2.5.6.1 Theory and Problems of Multidisciplinary Problem Solving in System Design

Modern product and service systems become increasingly complex and integrate knowledge and technologies from more and more distinct disciplines [Tomiyama, 2006; Qureshi *et al.*, 2013]. The need to integrate expertise from different engineering and non-engineering disciplines arises from trends like system miniaturization, increased quality requirements, higher product or service functionality, and product life cycle issues like end-of-life treatment [Tomiyama, 2006]. Conventional top-down design processes predominantly divide the design task into smaller, often monodisciplinary tasks. As a consequence, strong relationships between these sub-tasks due to physical laws which affect several disciplinary domains are not taken into account by current processes [Tomiyama, 2006; Erden *et al.*, 2008]. A need for basic mutual understanding of the concepts of other involved disciplines arises especially when the integration of a technology causes trade-off problems related to e.g. efficiency or costs [Batzias and Siontorou, 2012]. However, several investigations [Tomiyama *et al.*, 2009; Gericke and Blessing, 2011; Chulvi *et al.*, 2013] reveal that interdisciplinary collaboration in design starts to be discussed only recently in the literature.

One theoretical approach in this respect comes from Tomiyama [2003], who, in order to deal with the above mentioned problems, models a so-called *Knowledge Deployment* process on a meta-level. According to the model, in order to effectively deploy knowledge for knowledge-intensive designs, it has to be systemized, structured and, finally, integrated.

Knowledge systematization means creation, modeling and representation of (domain) knowledge in terms of axioms, facts, theorems and inference rules in order to allow reasoning. The result of knowledge systematization is a collection of still independent theories. In order to model the above-mentioned relationships between domain theories, knowledge has to be structured. According to Tomiyama [2003, 2006], four types of relationships between theories exist: On the one hand, the axioms of the two theories can be irrelevant for each other but the theories share common (physical) entities (1) or (abstract) concepts (2). On the other hand, the axioms of the theories can be of mutual relevance (3) or an entire theory may be a sub entity of another one (4).

The last stop of Knowledge Deployment, Knowledge integration, is a process at which *Abduction for Integration* [Tomiyama, 2003; Tomiyama *et al.*, 2003] plays a major role. A two-step algorithm is proposed for the integration of multiple theories. First, structurally or ontologically relevant theories are identified by analogy (analogical abduction [cf. Tomiyama *et al.*, 2003]). The second step consists in integrating several theories by second-order abduction, which can be driven for instance by extrapolation or unification of background knowledge [cf. Tomiyama *et al.*, 2003].

The above-mentioned Knowledge Deployment process points to several practical issues. The first one concerns the question of how to systematize and structure knowledge. The second one relates to the problem of how to search for appropriate knowledge and how to integrate it for effective (design) problem solving. The concept of *ontology* has been proposed in order to give answers to the former problem whereas several methods have been developed in order to tackle the latter issue. In the following, ontologies as well as methods for the search and integration of knowledge and technologies will be briefly introduced.

2.5.6.2 Ontologies

The term O*ntology* has its origins in philosophy [Gruber, 1993]. It is defined as 'an explicit, partial specification of a conceptualization that is expressible as a meta-level viewpoint on a set of possible domain theories […]' [Hung and Choy, 2013, p. 2; based on Gruber, 1993 and Guarino, 1997]. Ontologies are used to provide shared understanding of domains which can be communicated between persons or persons and software. Ontologies usually describe classes of things and taxonomies for those classes, relations between those things as well as axioms for those relations [Batres *et al.*, 2007]. Brewster and O'Hara [2007], by taking over Davis *et al.*'s [1993] functional requirements of knowledge representations, describe five functions of ontologies, the latter of which mainly concerns the use of software:

- Ontologies are surrogates for actual objects and relations. The fidelity of an ontology depends on what aspects of represented concepts are captured or omitted.

- As a set of ontological commitments, ontologies reflect decisions about what aspects of represented concepts are left away, thus allowing the reduction of complex systems to their most important features.
- Ontologies, by the way they are designed and how they model knowledge, provide insight into reasoning processes of the author of the modeled system.
- Maybe most important for the purpose of this research, ontologies serve as mediums of expression between human beings or between humans and machines.
- Finally, some specific ontologies, by the way they represent knowledge, allow to increase the computational speed during information processing.

Ontologies which are of interest for this research originate from different domains, like design theory or natural sciences. Table 27 presents some examples. Some of the mentioned ontologies will be briefly described in the following paragraphs.

Table 27: Overview of ontologies originating from several domains

Ontology	Purpose	Application	Authors	Domain
e.g. *SBF-Model*; *FBS-Model*	Functional modeling in design science; modeling of design process	Various applications	Goel and Chandrasekaran, 1989 (SBF-Model); Gero, 1990; Umeda *et al.*, 1990 (FBS-Model)[11]	Design science
Multilayered structure ontology	Knowledge management/sharing; R&D support	E.g. biosensors	Batzias and Siontorou, 2012	Industrial management / chemical engineering
Situated Knowledge Model	Knowledge management and discovery support in science	E.g. geosciences	Pike and Gahegan, 2007	Geography
AGENTCO	Knowledge management (domain independent)	-	Dieng-Kuntz *et al.*, 2001	Information/knowledge management
Empirical Knowledge Ontology	Knowledge management (domain independent)	E.g. financial diagnosis	Chen, 2010	Information/knowledge management

2.5.6.2.1 Function-Behavior-Structure Model

The Function-Behavior-Structure (FBS) Model of Gero [1990] is one of many instances of ontologies in design [see Erden *et al.*, 2008 for an overview]. It describes the design process and its outcomes, i.e. designs, in terms of *Functions* (*F*), *Behaviors* (B_e, B_s), *Structures* (*S*), and *Design Descriptions* (*D*). The design process, as it is modeled by the FBS ontology, is partially depicted in Figure 36.

According to this model, the design process consists in the transformation of Functions into Design Descriptions. This process occurs by occasional transformation of the required functions into different propositions of Structures, i.e., the elements of a design proposition and their relationships, as well as by evaluation. The latter activity is a comparison between the set of *Actual Behaviors* (B_s) of the proposed structures and the set of *Expected Behaviors* (B_e) which are

[11] According to Goel *et al.* [2009], the FBS ontology was independently developed by Gero and colleagues as well as by Umeda and colleagues.

sufficient for the required functional performance. It shall be mentioned that several design methods (cf. e.g. Paragraph 2.5.3.1.3.6) and methods for technology search and integration (cf. Chapter 2.5.6.3) rely on this or on similar ontologies.

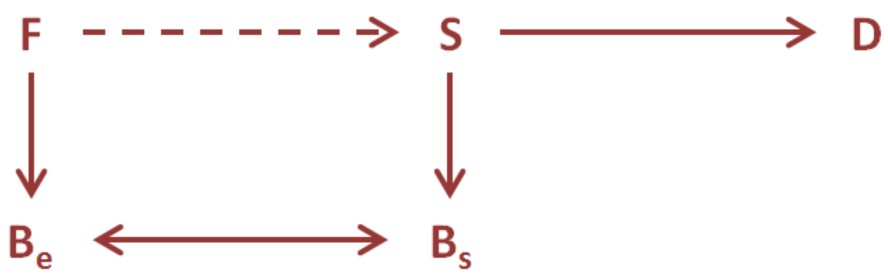


Figure 36: Partial representation of the design process as modeled by FBS ontology [Gero, 1990]

2.5.6.2.2 Situated Knowledge Model

Pike and Gahegan [2007] propose the Situated Knowledge Model in order to support the discovery and inference process in science. Their model integrates two approaches to the problem of knowledge representation. The ontological 'top-down' (p. 660) approach focuses on sharable knowledge representations and cooperative 'bottom-up' approaches emphasize the joint construction of knowledge from different situational perspectives.

The model allows the description of (the same) concepts having different structural relations and describing different contexts of creation or usage (by metadata) depending on the (disciplinary) situation in which the concepts are used (Figure 37).

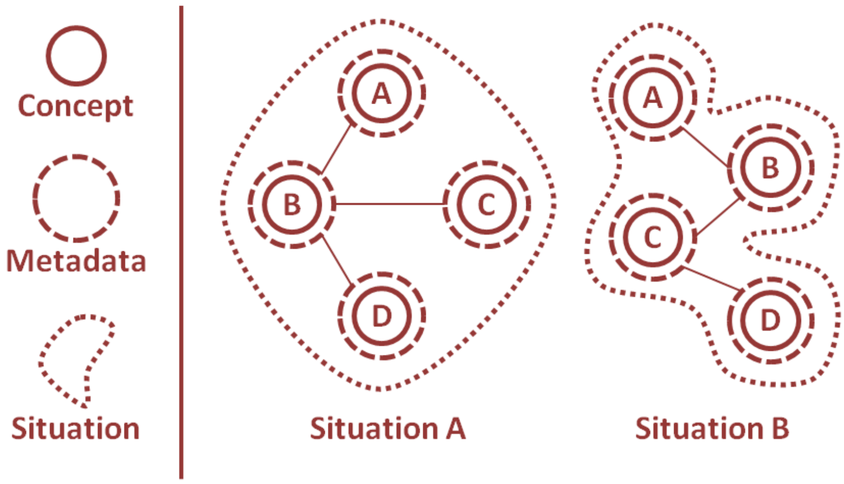


Figure 37: Representation of knowledge according to Pike and Gahegan [2007]

2.5.6.3 Methods for Technology Search and Integration

Several methods exist for the search of knowledge and technologies in the context of design problem solving. Most of those methods make use of ontologies or at least taxonomies during the search process.

Verhaegen *et al.* [2011] distinguish four types of methods:

- Methods based on engineering knowledge: Methods using case-based reasoning in the engineering design domain
- Methods based on the analysis of a text corpus: Approaches which analyze relational similarity of words in different corpuses of text
- Methods for bio-inspired design: Methodological concepts sought to systematically screen documentation of biological organisms in order to find solutions to design problems
- Explicitly schema-based methods: TRIZ is given as the only example of this class of methods.

It is not possible do make a clear distinction between those methods as e.g. some methods for bio-inspired design use TRIZ methodology for problem modeling and candidate solution finding [e.g. Vincent *et al.*, 2005, 2006]. Nevertheless, that classification will be used here in order to briefly introduce instances of established categories of methods.

2.5.6.3.1 Case-based Reasoning

Methods and software tools which work with the principle of *Case-Based Reasoning* (*CBR*) to some degree imitate human reasoning for the resolution of problems [Yang and Chen, 2012]. By means of an ontology, the (design) problem is modeled in a way which allows the search and retrieval of similar problems in a database. It is then tried to use the solution of the retrieved problem or modifications of the same in order to solve the initial problem [Cortes Robles *et al.*, 2009].

Examples for Case-Based Reasoning systems are *KRTIK* [Goel and Chandresakaran, 1989; Goel, 1992] and *IDEAL* [Bhatta and Goel, 1996], which use SBF ontology (cf. Chapter 2.5.6.2) for problem and solution modeling. One aspect distinguishing IDEAL from KRITIK is the use of *Generic Teleological Mechanisms* (*GTM*) [Goel, 1989 (cited in (Bhatta and Goel, 1996]); Bhatta and Goel, 1996]. Those represent a second abstraction layer over the SBF model and contain knowledge about modifications which are necessary for the adaptation of a retrieved solution to the original problem. One additional interesting approach against the background of CBR is the concept of *Adaptation-Guided Retrieval* (*AGR*), which has been proposed by Smyth and Keane [1995] and is implemented in the *Déjà Vu* system. Here, the retrieval process of solutions is not primarily guided by the a priori similarity of the problems but by the effort necessary in order to adapt the retrieved solution to the initial problem.

2.5.6.3.2 Methods and Tools for Systematic Text Analysis

There exist several approaches for search and retrieval of large text corpuses like the internet or other agglomerations of texts like patent databases [e.g. EPO, 2014]. The key parameters by which those approaches and tools can be distinguished are the accessed databases and the applied algorithms.

Verhaegen *et al.* [2011] describe approaches like the *WordTree Method* [Linsey, 2007], which combines the search of *synonyms*, *antonyms*, *hyponyms*, *hypernyms*, *meronyms*, *holonyms* and *troponyms*[12] in a database called WordNet [Miller, 1995] and creativity methods like Brainstorming or Method 635 (cf. Chapter 2.5.3.1) in order to stimulate analogical problem solving and design-by-analogy. A very recent classification of approaches for text analysis was developed by Abbas *et*

[12] Miller [1995] gives the following definitions : *synonymy* : symmetric relation between word forms; *antonymy*: opposing-name; *hyponymy*: sub-name; *hypernymy*: super-name; *meronymy*: part-name; *holonymy*: whole-name; *troponymy*: manner-name (for verbs)

al. [2014] who distinguish Natural Language Processing (NLP)-, Property-Function-, Rule-, Semantic Analysis-, as well as Neural Network based approaches.

2.5.6.3.3 Methods for Bio-inspired design

Methods and computer tools for the stimulation of bio-inspiration (cf. Paragraph 2.1.2.1) can be distinguished into two classes. Approaches of the first class establish databases of biological systems which can be accessed using specific algorithms [Vincent *et al.*, 2005, 2006; Biomimicry-Institute, 2012]. The second class contains approaches using semantic text analysis specialized on text corpuses originating from biosciences [e.g. Chiu and Shu, 2005].
The approaches of the first class differ in terms of description of the retrieved biological organisms. Whereas the tool ASKNATURE [Biomimicry-Institute, 2012] only provides examples of organisms which perform specific functions, the database of Vincent *et al.* [2005, 2006] was designed in order to give further information, e.g. regarding the systemic level or the physical environment in which the organism acts.
The method of Chiu and Shu [2005] was developed in order to overcome the problem of incongruent vocabulary in the domains of biology and e.g. engineering through the identification of so called bridge words. The term refers to key words which are used in both disciplines in order to describe the same or similar concepts but which feature no lexical link to each other.

2.5.6.3.4 TRIZ-based Approaches

There exist multiple TRIZ-based approaches for the formulation of interdisciplinary problems, the search and retrieval of candidate sources for solutions to these problems. As mentioned before, a clear cut distinction between those approaches and e.g. those used for semantic text analysis is not possible as several approaches combine both TRIZ principles and semantic analysis. Two examples for such a combination are Cavallucci *et al.*'s [2011] method for the population of a design problem model and Dewulf's [2006] method for the search and retrieval of technologies and the modification of their properties in order to fit new applications.
The method proposed by Cavallucci *et al.* [2011] aims at the creation of problem graphs which integrate knowledge from several design disciplines in a parallel process of automated patent mining and human expert problem analysis. The aim of this method is to build a consensus on the resulting problem representation which can be shared by all domain experts and which builds the basis for subsequent TRIZ-based problem solving.
Finally, the *Directed Variation* Method and the software in which the method is implemented [Dewulf, 2006] assign to a given technology a set of attributes like functions, properties and the spectrum within which those properties are variable. By establishing a similar set of required attributes to a given problem situation and using semantic-based data mining, the method suggests candidate solutions to given problems and vice versa. Moreover, the method provides the user with a set of heuristics in order to change the properties of the candidate solution in case an adaption to the initial problem is necessary.

2.5.7 Concluding Remarks Concerning Methodology

Even though problem solvers in design and other domains can benefit from the use of methodology, several authors have identified a lack of application of methods. Based on an analysis of several studies, Geis *et al.* [2008] state that a lot of methods are not appropriately implemented in industry. Furthermore, the applied methods are found to be inefficient, rigid and not suitable to user requirements [Zanker, 1999 (cited in [Geis *et al.*, 2008])].

As reasons for the somewhat deceptive acceptance and performance of methods, several issues have been identified [Jänsch, 2007 (cited in [Geis *et al.*, 2008])]:

- The representation and documentation of methods is found to be too scientific and abstract and seems to lack standardization.
- Teaching of methods often does not include appropriate exercises and information about the selection and adaptation of methods with regard to specific tasks.
- Acceptance and usage problems are traced back to the fact that concrete advantages and benefits of method application are often not proven.

In order to deal with the above mentioned problems of missing method acceptance, Geis *et al.* [2008] suggest the following strategies:

- Methods should be simplified and made more goal oriented. Development of new methods should focus on their application and on real user requirements.
- Methods should be more adaptable to day-to-day tasks and availability of resources, like team members, available time and expertise.
- The introduction of methods in companies should follow approaches of change management.
- The training of methods should integrate different learning concepts, like lectures, workshops, and seminars.

Support for some of the postulates of Geis *et al.* and Jänsch comes from Bender and Blessing [2003] who have compared the performance of designers using a 'hierarchical approach of established [d]esign [m]ethodology' (p.22) and those who use a more opportunistic design strategy. The results of the experiment suggested that, even though hierarchical object-oriented approaches support certain refinement stages like embodiment design, opportunistic approaches lead to superior design performance. Comparing opportunistic approaches to strictly phase-oriented strategies, the performance difference is even higher. As a consequence, Bender and Blessing suggest a somewhat prescriptive but flexible model of the design process which allows the combination of systematic and opportunistic approaches and methods.
One – against the background of this research important – example for the above mentioned problems of method performance and method acceptance is TRIZ methodology. The methodology is judged by industrial applicants to be effective [Gundlach and Ulbricht, 2006; Birdi *et al.*, 2012; Ilevbare *et al.*, 2013] and to lead to significant economic gains [Schauffer, 2008 (cited in [Tomiyama *et al.*, 2009])]. However, in the cases in which designers and engineers did not apply TRIZ methodology, this was due to the high effort which is necessary for method acquisition [Ilevbare *et al.*, 2013] and deployment [Gundlach and Ulbricht, 2006].

2.5.8 Conclusion

Creative problem solving is essential for activities in design and science. Both design and science feature distinguishing aspects and common activities in this regard. Literature and other contributions to problem solving in general and in the domains of design and science can be divided into theories and methodologies or methods. The latter often feature problem solving heuristics of some kind. Methods – in design, science or in general – mostly rely on theoretical aspects of problem solving like search processes in spaces of different levels of abstraction. Explicit heuristics have been identified either by induction from empirical analyses or by deduction from theoretical axioms. Even though multiple specific domain heuristics have been found to be specialized versions of their more general counterparts, the power of heuristics seems to be negatively correlated to their general applicability.

The observed technology convergence in current R&D activities and the increasing importance of overconstrained product designs cause problems which cannot be solved with existing monodisciplinary domain theories and methods. Yet, research and methodological approaches related to the facilitation of interdisciplinary problem solving are still rare. Existing approaches focus on the modification of existing solutions in the same knowledge domains (CBR), automated text analysis or on specific source domains like biology. To the best of the author's knowledge, no methodological approach for interdisciplinary – i.e. design and natural science – creative problem solving and technology integration exists. Such an approach which is capable of linking and integrating methods and heuristics from the design and the natural science domains would probably bear the potential to improve modern research and development processes. Figure 38 synthesizes Subsection 2.4 in a schematic way.

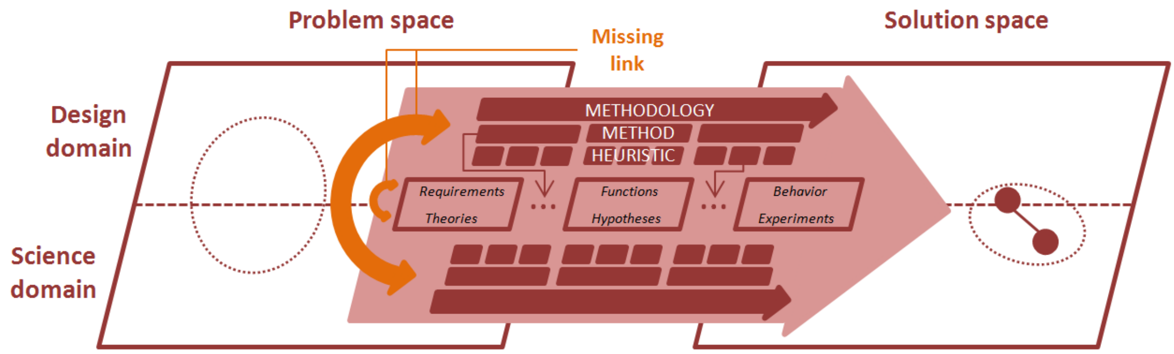


Figure 38: Schematic representation of problem solving theory, -methodologies, -methods and -heuristics in science and design

2.6 Summary and Conclusion of Literature Review

2.6.1 Summary of Literature Review

Table 28 to Table 32 sum up key facts, problems and solutions which have been identified related to interdisciplinary collaborative problem solving and the integration of natural science related technologies on the global -, institutional-, team-, individual-, and problem level of analysis.

Table 28: Summary of literature review on global level

2.1 Global Level		
Facts	**Problems**	**Solutions**
Innovations can be described as new combinations of elements.		
Combinations of distant knowledge often have the highest innovative impact.		
The conditions of knowledge creation have changed towards higher uncertainty, shorter collaboration times, and the need to apply the capabilities of institutions to new markets and applications.		
Natural, social and engineering disciplines can be classified according to cognitive as well as social aspects.	→ Collaboration suffers from cultural differences between science and industry partners.	

Table 29: Summary of literature review on institutional level

2.2 Institutional Level		
Facts	**Problems**	**Solutions**
In order to innovate, institutions must alter between processes of (knowledge) exploration and exploitation.		
Exploration and exploitation are related to different types of conversion of tacit and explicit knowledge.		
The application of existing knowledge to new problems can lead to radical innovation.		
Knowledge/technology (K/T) transfer consists in K/T sharing and K/T integration.	→ Knowledge integration is difficult due to the need to bring together several knowledge areas and due to problems of technology adaptation to a product. → Cognitive routines create barriers to the application of new knowledge. → Codification of knowledge often leads to excessive simplification and decontextualization. → Lack of mutual understanding and communication problems are important barriers to knowledge transfer.	→ Increasing an entity's Absorptive Capacity improves its capability to identify, assimilate and apply new knowledge BUT requires intensive knowledge processing capabilities and extensive interdisciplinary knowledge bases.

Table 30: Summary of literature review on team level

2.3 Team Level		
Facts	**Problems**	**Solutions**
Cross-functional teams can increase an entity's Absorptive Capacity and thus help reducing product development times.	→ Findings on team performance compared to the performance of individuals are mixed. → Disciplinary diversity reduces short term team effectiveness and efficiency. →Reasons for that are: ▪ Groupthink ▪ Majority influence ▪ Sharing of only commonly held information ▪ Incoherent interpretative schemes ▪ Unmanaged conflicts	→ Methodological approaches like modifications of Brainstorming and conflict introduction/simulation can overcome those problems. → Shared mental models and → Conflict management can improve group performance.

Table 31: Summary of literature review on individual level

2.4 Individual Level		
Facts	**Problems**	**Solutions**
Some categories of creative products result from deletion of barriers and constraints.		
Scientific creativity can result from theoretical reasoning or from technological inventions.		
Expertise and creativity-related reasoning (meta) strategies are important conditions for creativity.		
Domain expertise can be modeled as a huge number of chunks of structural as well as of procedural knowledge.		
Expertise knowledge leads to more abstract problem representations, which foster more systematic and distant analogical problem solving.	→ Drawing distant analogies is difficult even for experts. → Expertise can interfere with creative achievement.	→ Instructions for analogical reasoning can help in problem solving. → Meta-cognitive strategies help overcoming cognitive limitations (e.g. limited memory capacity). → The parallel development of opposite concepts and their subsequent synthesis can lead to creative products.
Creativity can be modeled as generation of elementary (often ambiguous or incongruent) concepts and later transformation or synthesis of these concepts.		
Individual disciplinary background is related to preferences in cognitive styles as well as to employed problem solving (meta-)strategies.		

Table 32: Summary of literature review on problem level

2.5 Problem Level		
Facts	**Problems**	**Solutions**
Design and science activities focus on different but somewhat overlapping goals.		
Problem solving in design and science can be described as search for solutions in different spaces.		
Processes in design and science are characterized by the use of methods and heuristics which are – to some extent – generic.	→ There has been found a negative relationship between the general applicability and the power of heuristics.	
Technological systems become increasingly complex and integrate more and more diverse domain knowledge.	→ Problems of communication and understanding hinder the design process of technological systems. → No appropriate methodology exists to solve this problem.	
Methods shall be flexible and adaptable to both user needs and the problem to which they are applied.	→ Current methods lack those properties.	

2.6.2 Conclusion of Literature Review

From the literature review it can be seen that current economic and technological trends oblige companies as well as research units to solve problems of increasing inter- and transdisciplinarity in order to apply their knowledge on new markets and applications. In addition, those institutions are obliged to undertake current and future R&D projects respecting ever shorter timeframes.

Against that background, the findings that communication problems and a lack of mutual understanding between scientific and industrial actors are among the predominant causes for failure of knowledge and technology transfer activities, gain importance. In order to deal with issues like excessive simplification and decontextualization of knowledge, R&D teams and their superordinate entities must develop an increased absorptive capacity, for which a broad interdisciplinary knowledge base is important. Most of the problems related to the integration of knowledge and technology originating from distant knowledge domains cannot be solved in a remote way. Therefore, face-to-face problem solving sessions appear to be important aspects of current and future R&D projects, especially in New Product/Process Development.

However, even though scientific as much as design experts could take advantage from complementary cognitive styles as well as from associated problem solving strategies and heuristics, no operational methodological framework exists to support that knowledge transfer. Requirements for such methodological support are an improved ease of learning as well as adaptability to both the requirements of the user and the problem to solve.

3 Research Question and Hypotheses

The research presented in the present report investigates the question of how to improve an organization's capacity to develop creative solutions to technology based problems. The focus is put on the identification and integration of distant domain knowledge into product and process design. Distant domain knowledge here explicitly refers to knowledge originating from natural science based disciplines. The systemic frame of inquiry is the R & D team, i.e. a group of individuals featuring a certain degree of expertise in one discipline and the associated cognitive and cultural characteristics.

To this effect, existing theories, methods and tools originating in the domains of psychology, management and design have proved valuable to some extent. However, to the best of the author's knowledge, there exists no research which explains how those concepts impact the search for and integration of knowledge and technologies by interdisciplinary teams – i.e. teams composed of designers and natural scientists – into product and process designs.

It shall be noted that the perimeter of this research is limited to aspects of creativity and inventiveness thereby excluding other aspects which are also important for a creative solution to be applied on the market and thus to become an innovative solution.

3.1 Research Question

The research question of the present Ph.D. report, which was briefly introduced in Chapter 1 and the relevance of which was proven in Subsection 2 of the present Ph.D. report, reads as follows:

> How to support methodologically the search for and evaluation and integration of knowledge and technologies originating from knowledge-intensive and natural science-related domains in product- and process design processes?

3.2 Choice of Methodologies/Methods

3.2.1 Methodological Choice

In order to test the impact of different methodological approaches on interdisciplinary problem solving and on the integration of knowledge and technologies from knowledge intensive and natural science-related domains, Brainstorming and Mind Mapping as well as TRIZ and its derivatives were selected.

The chosen approaches present to some extent the two extreme ends of the methodological spectrum.

On the one hand, Brainstorming and Mind Mapping as germinal general creativity methods require little effort from the user in order to become capable of applying them. Further, they can be seen as techniques which foster opportunistic problem solving and design approaches.

Methods and axioms of TRIZ and its derivatives like USIT, on the other hand, can be classified as history based analytical techniques. Here, the problem solver or – against the background of this research – the problem solving team is sought to follow a more hierarchical process. In the case of TRIZ, that process translates into problem analysis and modeling, generic solution generation and, finally, implementation of the generic solutions to solve the initial problem. In addition, the different methods and underlying axioms of TRIZ and its derivatives are considered to require considerable learning effort and application training. Notwithstanding these drawbacks of techniques of the TRIZ/USIT complex, four reasons for that methodological choice can be given:

- The so called ‘Weak Methods’, which have been found to be widely, even though implicitly, used in science (cf. Paragraph 2.5.3.3.1), except for one method, correspond well to the problem solving process as well as to the axioms and methods provided by TRIZ and USIT (Table 33).
- The concepts of contradictions (TRIZ) and Qualitative Change Graphs (USIT) have the same underlying dialectical principle as reasoning processes which have been found to be important for individual [Rothenberg, 1983; Simonton, 2004; cf. Paragraph 2.4.2.2.2; Finke *et al.*, 1992; cf. Paragraph 2.4.5.3] and group creativity [Schwenk, 1990; cf. Paragraph 2.3.4.3.2].
- The TRIZ and USIT methods for analogical problem solving like e.g. the Magic Particles Approach correspond to concepts which have been reported to be used in natural science problem solving by e.g. Demokrit and Maxwell [Savranksy, 2000].
- Problem modeling tools and problem solving heuristics, especially of USIT, feature a certain ambiguity [Sickafus, 1997], a concept which has been found to be an important aspect of creative problem solving and Design Thinking [Plattner *et al.*, 2010].

Table 33: Weak methods of science and corresponding TRIZ/USIT axioms and concepts [after Schoefer *et al.*, 2013b]

Weak methods in science	Axioms and concepts of TRIZ/USIT
Generate and Test	To be avoided according to TRIZ
Hill Climbing	**TRIZ:** STC-Operator **USIT:** Parameter Change
Means-Ends Analysis	***Detection of differences between current and goal state:*** **TRIZ:** Ideal Final Result; Contradictions; S-Field Modeling; Model with Miniature Dwarves **USIT:** Magic Particles Approach ***Operators:*** **TRIZ:** Inventive Principles; Separation Principles; Inventive Standards **USIT**: Solution Operators
Planning	The process of the ‘Planning’ Method well corresponds to the problem solving process of TRIZ and USIT.
Analogy	***Surface mappings:*** **TRIZ:** Laws of Technical System Evolution ***Relational mappings:*** **TRIZ:** Contradictions; Law of System Completeness ***Structural mappings:*** **TRIZ:** Model with Miniature Dwarves

3.2.2 Drawbacks of TRIZ and Derivatives

Even though methods and methodologies from TRIZ and its derivatives like USIT are among the most structured approaches for problem solving in technological domains, they feature some considerable drawbacks with regard to knowledge and technology transfer.

- The problem solving process prescribed in TRIZ is characterized by the transformation of a specific problem into more generic problem models (1), the development of generic solution models based on the analysis of those problem models (2), and finally the transformation of those generic solution models into concrete and specific solutions (3). The first two steps are well described in the literature and a considerable amount of methods and tools is provided in order to support the problem solver (cf. Chapter 2.5.3.1.3). For the third step, however, no methodological support could be identified from the literature review. That means, the integration of technologies which were previously identified as potential solutions – a task which has been identified as a major problem in the literature (cf. Paragraphs 2.2.4.2.2 and 2.7.7) – remains an issue for problem solvers and problem solving teams.

- The issue of technology integration is somewhat linked to a unilateral perspective on problems. In TRIZ and related approaches, the problem solving process is focused on
    - the –often single – problem solver
    - the problem setting with relative narrow boundaries and
    - an – often single – ideal solution from the problem solver's perspective.

  Those focuses, even though they favor the generation of highly inventive solutions, interfere with the resolution of bilateral or multilateral problems. Yet, those problems might arise from the need to integrate specific solutions or technologies into a given problem setting.

Addressing those drawbacks of TRIZ and its derivatives in view of technology transfer and technology integration problems remains an important issue.

3.3 Hypotheses

In the previous chapters (cf. Chapters 2.6 and 3.2), a several problems related to the research question have been identified. Those problems concern different phases of the NCD/NPPD process and are investigated in the present dissertation by the testing of three hypotheses. *Hypotheses 1* and *2* are of particular interest during the process of New Concept Development (NCD), i.e. the fuzzy front end of New Product/Process Development processes. *Hypothesis 3* relates to the latest step in NCD as well as to the more formalized NPPD process.

3.3.1 Hypothesis 1

The first hypothesis relates to the aspect of disciplinary and thus knowledge diversity in creative problem solving and its impact on three parameters, the problem solving process in general, information processing during this process and, finally, its outcome in terms of creative products. In the context of this research, the concept of multidisciplinarity refers to interactions between the domains of design and natural science. In this respect, the present research differs from other work where interactions between different sub-disciplines within the domain of (engineering) design are investigated. *Hypothesis 1,* which concerns the Idea Genesis – as well as the Idea Selection Phase of the NCD process, reads as follows.

H1: Group diversity in terms of disciplinary and knowledge background has impact on

H1a: the process of creative problem solving in knowledge and technology intensive domains.

H1b: knowledge processing during this process.

H1c: quantitative aspects of the creative products.

H1d: qualitative aspects of the creative products.

3.3.2 Hypothesis 2

The second hypothesis concerns methodological aspects of creative problem solving in teams and compares two different approaches for the facilitation of creative reasoning. Methods classified as germinal general creativity methods, which can be applied regardless of the subject at hand, are tested against rational history based methods originating from design theory. In accordance to the previous hypothesis, *Hypothesis 2* states:

H2: The methodology applied during the group problem solving process has impact on

H2a: the process of creative problem solving in knowledge and technology intensive domains.

H2b: knowledge processing during this process.

H2c: quantitative aspects of the creative products.

H2d: qualitative aspects of the creative products.

3.3.3 Hypothesis 3

The third hypothesis relates to the drawbacks of the analytical approaches of the TRIZ complex which have been identified in the Paragraphs 3.2.1 and 3.2.2. The value of methods and tools stemming from TRIZ and its derivatives for the generation of inventive concepts to technological problems has been proven empirically (cf. Paragraph 2.5.7). Those tools have also proven useful for the identification of technologies which are *a priori* suitable for solving a given problem. However, for the important problem of the integration of a once identified technology into a given technical and business application (cf. Paragraphs 2.2.4.2.2, 2.7.7 and 2.5.6.1) no significant methodological support could be identified in the literature. In addition, especially TRIZ has been found to require considerable effort to be learned and applied, a factor hindering more extensive dissemination in industry. The third hypothesis suggests a possibility to address those drawbacks of TRIZ and related methodology. It states that the integration of basic concepts of TRIZ into a meta-model designed to describe and prescribe the process of knowledge integration is possible. The meta-model should

- be grounded on TRIZ axioms like Ideality and dialectical principles (cf. Paragraph 2.5.3.3.1.2)
- allow the application of different methods originating from TRIZ and other approaches which are widely used in industry
- be essentially bilateral in nature, i.e., shall address technology integration problems from the perspective of the application for which a technology shall provide a solution but also from the perspective of the technology (bearer) itself.

Hence, Hypothesis 3 states:

H3: Axioms and methods from TRIZ and its derivatives can provide a useful framework for the search for and a priori evaluation of knowledge intensive technologies as well as for the integration of the latter in order to solve industrial NPPD problems.

3.4 Summary of Research Question and Hypotheses

The validation or rejection of those three hypotheses is considered to shed light on the question of how industrial R&D processes in general and NCD and NPPD processes in particular can profit from multidisciplinarity. Especially, the value of complementary sets of knowledge and technologies, cognitive styles, problem solving strategies which are supposed to be found in the different disciplinary domains, shall be tested (*Hypothesis 1*). Further, two approaches which represent two extremes of the methodological spectrum shall be compared with respect to possible advantages and drawbacks in the facilitation of the interdisciplinary processes (*Hypothesis 2*). A third and final point of investigation is the possibility to extract central concepts of TRIZ and its derivatives into a pragmatic meta-model which is sought to structure the interdisciplinary process of technology integration in order to solve given design problems (*Hypothesis 3*).
The hypotheses (cf. Table 34 for an overview) will be tested in an experiment and an industrial case study which will be outlined in Chapter 4.

Table 34: Overview of Hypotheses 1 to 3

	Group composition impacts…	Methodology impacts…	TRIZ and derivatives are of value for the search for as well as the evaluation and integration of knowledge intensive technologies in order to solve NPPD problems.
…the creative problem solving process.	H1a	H2a	
…knowledge processing.	H1b	H2b	
…creative products quantitatively.	H1c	H2c	
…creative products qualitatively.	H1d	H2d	
			H3

4 Hypotheses Testing

In the present chapter, the experiments which were performed in order to test the previously formulated hypotheses are reported.

4.1 Overview

In the course of this Ph.D. work, two tests, in the following referred to as *Experiment* and *Case Study*, were performed. The tests differ along two criteria. The first criterion relates to the covered NCD/NPPD process phases and the second pertains to the experimental typology (Figure 39).

The Experiment investigates several aspects of group processes during *Idea Genesis* and *Idea Selection* Phases of the NCD process in knowledge intensive domains under laboratory conditions. The Case Study relates to the phases *Idea selection* and *Concept and technology development* of NCD and NPPD processes in industry.

In this way, the present test set up allows to shed light on different crucial phases of industrial R&D processes. The first investigation (*Experiment*) starts at the *idea generation* phase of the NCD framework, which is considered a crucial step of the generation of knowledge during new product or process development. It finishes at the *idea selection* phase, where previously produced concepts are selected for further development. As those early process steps require comparably few resources, a laboratory experiment with 60 participants could be set up, which yielded quantitative results related to *Hypotheses 1* and *2*. To some extent, the *Case Study* also covers the phases idea generation and idea selection while focusing on the phase of *concept and technology development*. This last phase of the NCD process cannot be easily distinguished from more formalized NPPD processes and often requires considerable personal as well as financial resources. This is the main reason why the *Case Study*, which investigates *Hypothesis 3*, was designed as an industrial field study.

Both tests are described in detail in the Chapters 4.2 and 4.3 of the present subsection.

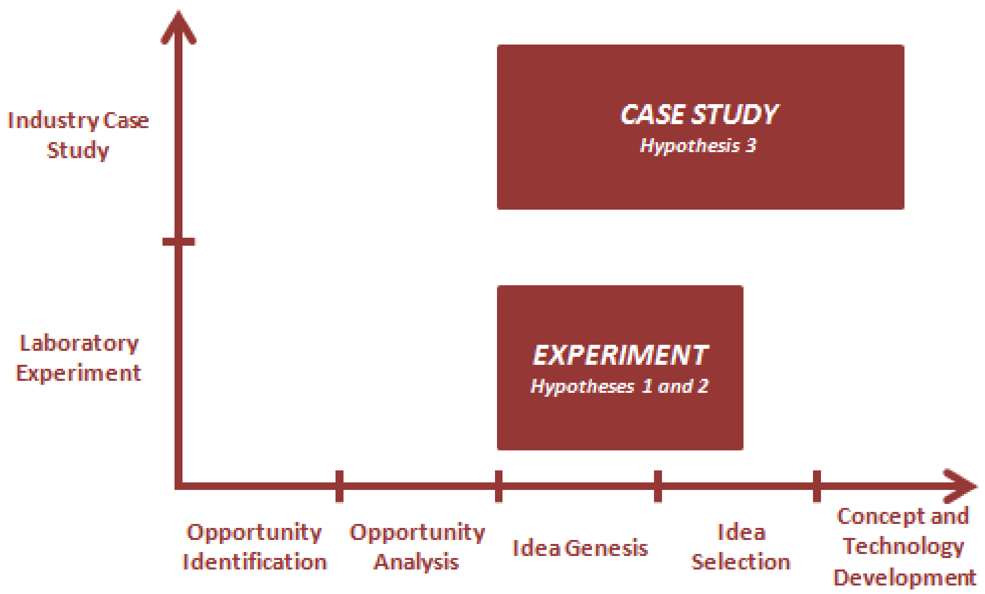


Figure 39: Overview of the tests described in the present chapter

4.2 Experiment

4.2.1 Introduction

As outlined in Subsection 3, the developed hypotheses relate to the impact of group composition and the applied methodology on the creative problem solving process in knowledge intensive and science related domains. The experimentation outlined in this chapter was designed in order to test *Hypothesis 1* and *2* under conditions which are as realistic as possible. The choice of the experimental procedure, the problem to solve and the training of the participants take account of this goal.

In the following chapters, first the experimental procedure will be described. Then, detailed descriptions of the statistical analysis of the experimental output will be given. The results of that analysis will be discussed against the investigated hypotheses and, whenever applicable against previous research. The subsection concludes by highlighting the limitations of the experiment.

4.2.2 Method

During the experiment, several teams were asked to solve a design problem stemming from a knowledge-intensive natural science related domain. Those teams were composed of individuals with different academic and thus knowledge background and trained in different creative methods. The problem solving process, its outputs, as well as the participant's subjective opinion regarding a number of aspects were documented and evaluated.

4.2.2.1 Procedure

In the following paragraphs, the experimental procedure, which includes the participants, their methodological training, the task, etc., will be outlined.

4.2.2.1.1 Participants

As one goal of the experiment consisted in investigating the impact of group composition in terms of disciplinary and knowledge diversity, two sets of participants took part in the experiment. The first group consisted of 45 graduate students from *Ecole de Biologie Industrielle*. The students of that engineering school have followed undergraduate studies in the fields of biology, biotechnology, pharmacology and medicine and therefore have an academic background in *life sciences* (*LS*). The second group of participants was composed of graduate students from *Arts et Métiers ParisTech*, an engineering school specialized in mechanical and industrial engineering. These participants have followed undergraduate as well as graduate classes in the field of *mechanical engineering* (*ME*). All 60 participants validated one part of their innovation classes in exchange for their participation.

4.2.2.1.2 Methodological Training

The participants were divided into two groups in order to compare the impact of rational analytical design methodology and of germinal general creativity methods on the process of creative group problem solving and its products. Half of the participants (23 with LS background and 7 with ME background) obtained a 4.5 hour training in Brainstorming and Mindmapping, both being instances of *intuitive general creativity techniques* (*GC*). The other half of the participants (22 with LS background and 8 with ME background) obtained à 4.5 hour training in basic concepts of *TRIZ* and its *derivatives* as *rational creativity methods* (*TD*). As the latter methods are considered to be complex and thus to require far more time in order to be understood and successfully applied (cf. Paragraph 2.5.7), a dedicated training had been designed.

The design of the training had to solve three problems. First, as previously mentioned, TRIZ and, to a lesser extent, its derivatives like ASIT and USIT are considered to be complex compared to other creativity methods. Second, even though the methods share underlying principles, they differ with respect to certain aspects, like e.g. process and problem modeling or problem solving heuristics (cf. Paragraph 2.5.3.1.3.1). Third, as the audience of the training featured significantly different knowledge backgrounds, a problem arose with respect to the examples of method application.

The problem of the very short time frame of the training was tackled by the presenting the different methods and tools of TRIZ and its derivatives according to an overall reasoning model similar to the model presented in Paragraph 2.5.2.2.8 (Figure 40). Further, an instruction strategy based on Anderson [1987] was applied in order to foster the successful acquisition of methodological knowledge. Following that strategy, the introduction of each method was followed by the presentation of examples and by short application tasks the results of which were then discussed and corrected.

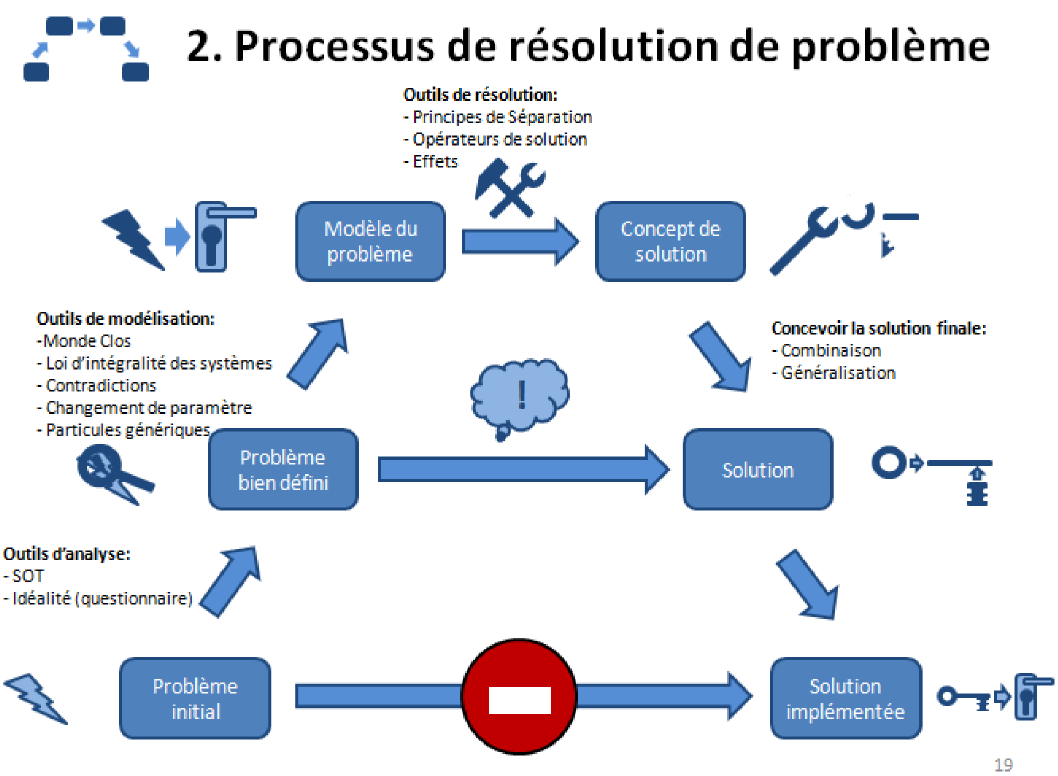


Figure 40: Extract from the training in TRIZ and its derivatives presenting the model of the reasoning process (in French) (cf. Paragraph 2.5.2.2.8)

In order to help the participants to select from the wide range of – often complementary – TRIZ and USIT methods, the different techniques had been mapped based on Savranksy [2000] as well as on Nakagawa *et al.* [2002, 2003]. As shown in Table 35, the concepts of those methods had been distinguished into three categories: tools and approaches for problem definition, methods and concepts for problem modeling and heuristics for solution generation (cf. also Paragraph 2.5.3.1.3.2). Based on that mapping, the concept of *Ideality* and the *Multi-Screen/System Operator Approach* (both TRIZ) were chosen as instances of problem definition tools. The *Law of System*

Completeness, and (*Physical*) *Contradictions* (TRIZ) as well as the *Closed-World Model*, the *Parameter Change Diagrams* and the *Magic-Particles Method* (USIT) were selected as problem analysis techniques. *Separation Principles* (TRIZ), *Solution Operators* ((A/U)SIT and *Physical Effects* (TRIZ and USIT) were presented as techniques and heuristics for the generation of conceptual solutions. In addition, two heuristics, *Combination* and *Generalization* (USIT), were introduced in order to support the development of complete solutions out of conceptual ones.

Table 35: Mapping of models, methods and heuristics for problem definition, problem analysis and problem solving (based on Savranksy [2000] and Nakagawa *et al.* [[2]2002, [1]2003])

		USIT	Problem Definition[1]					Problem analysis[1]								Solution Generation[2]				
								Closed-World Method					Particles Method							
		TRIZ	Unwanted effect	Problem statement	Sketch	Plausible root causes	Minimum set of objects	Closed-World diagram	Qualitative change graphs	OAF diagram	Time characteristics	Space characteristics	Ideal solution	Particles (agents)	Action and property diagrams	Object Pluralization Method	Attribute Dimensionality Method	Function Distribution Method	Solution Combination Method	Solution Generalization Method
Problem definition		Psychological inertia tools		(X)	(X)		(X)													
	System Operator	System hierarchy		X																
		Time evolution																		
	Problem/ Opportunity Explorer	Benefits analysis	X	X																
		Identification of resources					X													
		Constraints				X														
		Sore points'	X			X														
		S-Curve Analysis																		
Problem analysis		Funct. An. (Su-Field Analysis)						X												
		Function/attribute analysis						X	X											
		Technical Contradictions							X											
		Physical Contradictions							X		X	X								
		Trends of Technol. Evolution											X							
		Ideality/Ideal Final Result (IFR)											X							
		Smart Little People (IFR)												X						
Solution generation		Inventive Principles														X	X	X	X	
		Inventive Standards														X	X	X	X	
		Trends of System Evolution														X	X	X	X	
		(Sickafus' Heuristics)														X	X	X	X	
		Separation Principles																	X	
		Trimming														X				
		Self-X Principle																X		

As stated in Paragraph 2.5.4.2.2, different sets of problem solving heuristics of TRIZ and its derivatives have been found to share similar underlying principles [e.g. Savransky, 2000]. In order to provide the participants with a minimal but representative set of heuristics, a mapping had been established based on several comparative pieces of literature (Table 36). As a result of this mapping,

- the original set of *Separation Principles* (TRIZ)
- *Dimension Change* (USIT)
- *Multiplication* (USIT)
- *Distribution* (USIT)
- *Effect Transformation* (USIT)
- *Combination* (USIT)
- *Generalization* (USIT)

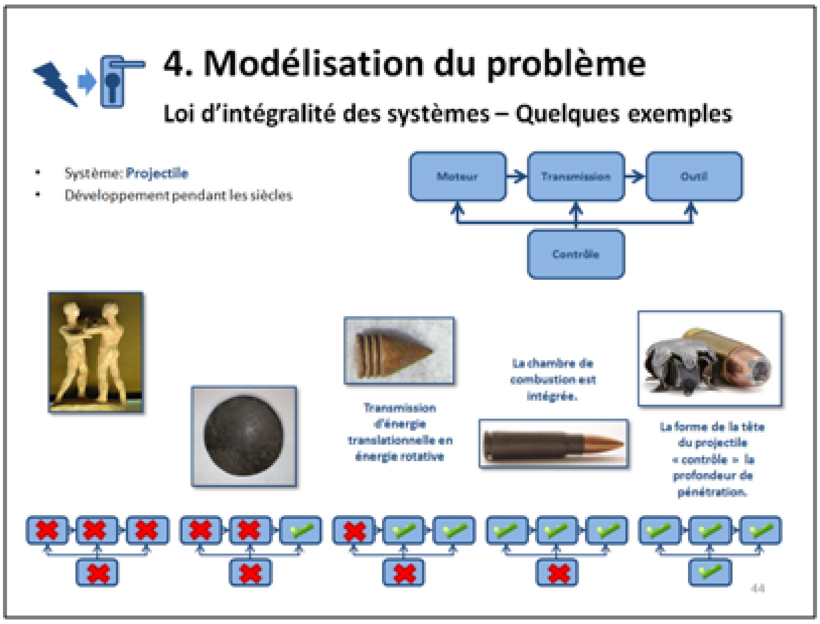
were considered as a minimal set of heuristics to present in the training.

Table 36: Mapping of problem solving heuristics (based on indicated literature and 1: Sickafus, 1997; 2: Nakagawa et al., 2002; 3: Horowitz, 1999; 4: Altshuller, 1988; 5: Altshuller, 1996; 6: Savransky, 2000; 7: Mitrofanov, 1998)

	Separation Principles	Dimension change	Multiplication	Distribution	Effect Transformation	Combination	Generalization
USIT[1]	Uniqueness (time, space, attribute)	Dimensionality (attributes)	Pluralization (objects)	Distribution (functions)	Transduction		
USIT[2]		Dimensional change	Pluralization (objects)	Distribution (functions)		Combination	Generalization
(A)SIT[3]		Breaking symmetry	Division (objects and associated functions)				
			Multiplication (obects)	Unification (functions)			
			Object removal (objects)				
TRIZ[4,5]	Operational time analysis[1]	IP7[6]	IP1[6]		Su-Field Modelling	P3[6]	
	IP9[6]	IP14	IP2		S1-2[6]	P15	
	IP10	IP17	IP3		Asymmetry as effect explanation[7]	S3-1	
	IP14	IP3	IP15				
	IP15	IP40	S2-2				
	IP16	IP13	S5-1				
	IP18	IP15					
	IP21	S5-1					
	IP27	S2-2					
	Operational space analysis[1]	S2-4					
	IP1[6]						
	IP2						
	IP3						
	IP4						
	IP7						
	IP17						
	IP24						
	IP26						
	IP30						

From a pedagogical viewpoint, the disciplinary diversity of the training participants can lead to two significant problems. First, methodological procedures are not understood because the initial example by which the method is explained stems from a non-familiar knowledge domain. Second, even though the underlying principles of a method are understood, participants might fail to decontextualize and hence to transfer them to another context [Perkins and Salomon, 1989]. In order to solve this problem, each method or heuristic was explained using at least two examples from different knowledge domains, engineering design and life sciences. Further, when possible, a third example from daily life was provided, which should be understood by both groups, students with life science background and students with mechanical engineering background. An example for this instruction strategy is given in Figure 41.

At the end of the training in TRIZ and its derivatives, the participants obtained a sheet which synthesized the process of problem solving according to these methodologies. Further, they were allowed to keep the printed training support for the problem solving sessions.



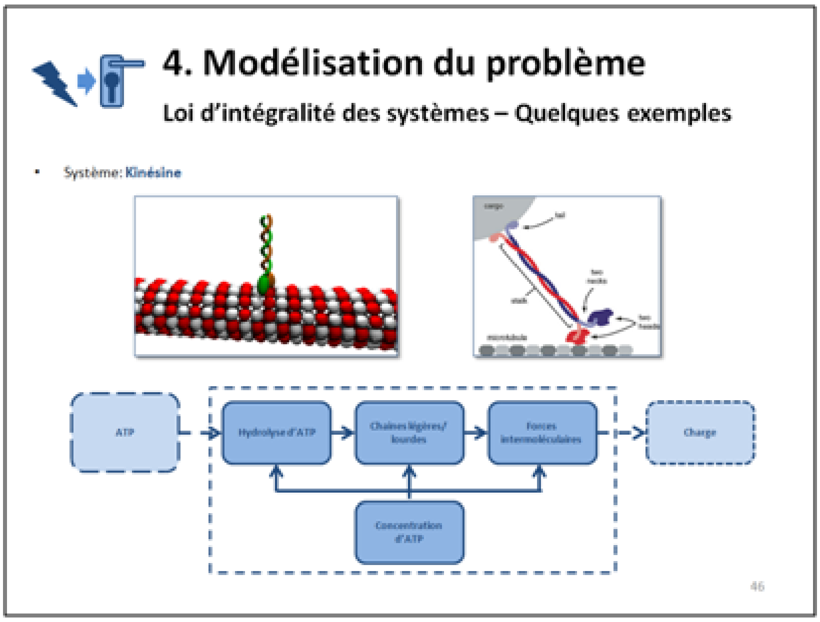


Figure 41: Explanation of methodological principles based on two examples originating from different knowledge domains (above: engineering design; below: life sciences)

4.2.2.1.3 Group Composition

After the training, the 60 participants were randomly assigned to groups in order to obtain 20 groups of three persons each. Half of those groups had previously followed the training in general creativity (GC) methods while the other half had been trained in TRIZ and its derivatives (TD). The GC groups were split into six monodisciplinary groups (five with only LS participants and one with only ME participants) and four multidisciplinary groups in which one ME participant joined two LS students (L2M). The participants trained in TD built five monodisciplinary groups (four with only LS participants and one with ME students) and five multidisciplinary groups with the same disciplinary distribution as in the GC condition. The group setting according to the three dimensions method (GC-TD), group composition (LS/ME-L2M) and background (LS-ME) is synthesized in Figure 42.

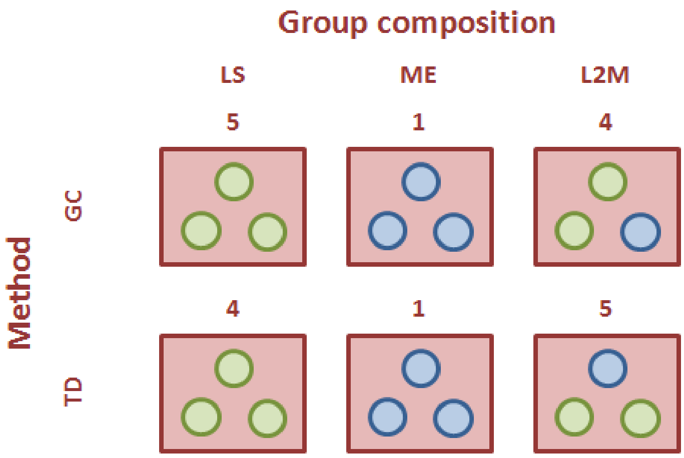


Figure 42: Group setting along the two independent variables, method and group composition (green: LS student; blue: ME student)

4.2.2.1.4 Instructions and Pedagogical Case Study

The participants were then instructed to follow a process model of creativity consisting in problem definition, idea generation, idea analysis, idea selection and improvement, and solution (generation), which resembles the models presented in Subsection 2.4. Further, they were told to write the results of each process step on special sheets. In order not to privilege one of the two methodological approaches, i.e., the GC or TD condition, the sheets were designed following a generic creativity process (cf. Paragraph 2.4.4). Initial reasoning and analysis of the problem was sought to be documented on 'problem structuring sheets' (*PIS*), problem statements and associated sub problems were to be documented on 'problem identification sheets' (*PIS*), the results of the divergent idea generation processes should be filled in 'concept sheets' (*CS*) and final solution propositions were sought to be noted in 'solution sheets' (*SS*). Further, the participants were asked to trace links between the documentation sheets, e.g. to indicate which problem statement led to which concept and so on. In addition to this, the participants who had followed the TD training were required to note, whenever possible or applicable, the method or heuristic which led to a notation. For those indications, dedicated cases had previously been inserted into the sheets.

In order to foster methodological understanding and application and to familiarize the participants with the documentation process and team work, the groups where then asked to engage for two hours in an initial creative problem solving task. During this *pedagogical case study*, the participants had to generate propositions for cancer treatment using ionizing radiation without harming the patient's healthy tissue. This problem was derived from the so called *Duncker Radiation Problem* [Duncker, 1945 (cited in [Gick and Holyoak, 1983])]. During this case study, phases of autonomous work were followed by phases during which the participants were provided with some results which had been obtained by application of the different methodological approaches (Figure 43).

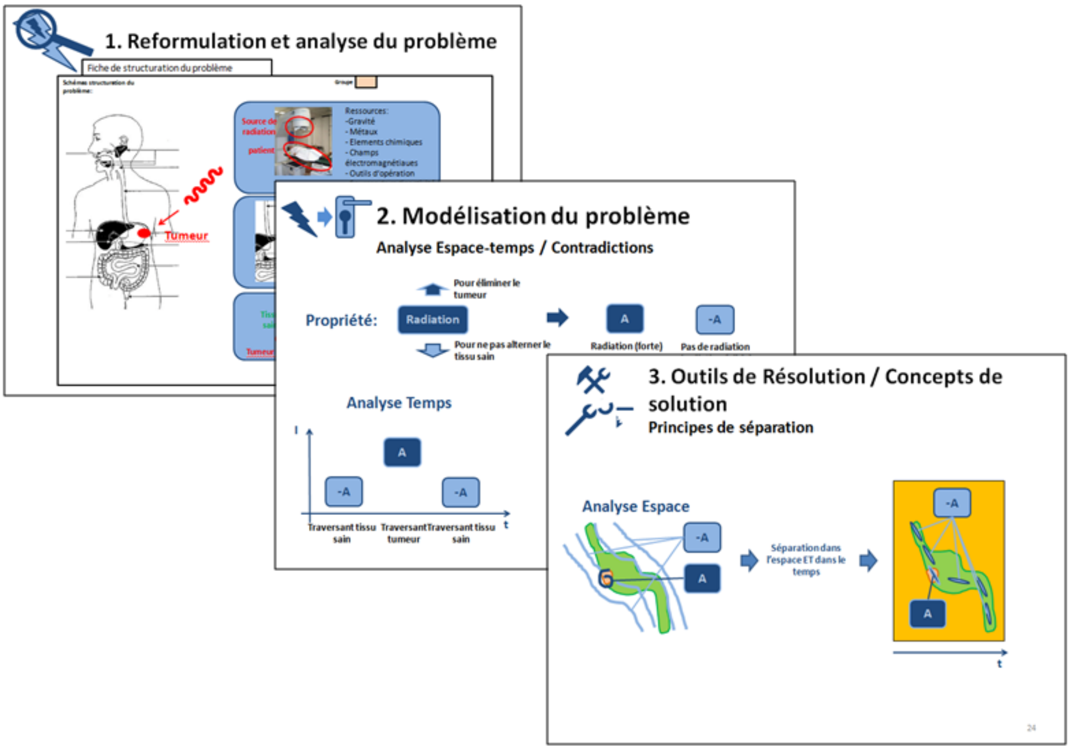


Figure 43: Examples of possible results of the different phases of the creative process provided during the pedagogical case study

4.2.2.1.5 Questionnaire 1

After the pedagogical case study, the participants in the TD condition had to reply to a questionnaire on a seven-point Likert-type scale. The questionnaire inquired into aspects like their personal perception of the value of their knowledge with respect to the problem at hand and their motivation to solve the problem. In addition, the participants were required to judge the value of the method for problem understanding, problem solving and intra-group communication. The Questionnaires 1 and 2 (cf. Paragraph 4.2.2.1.7) served the quantitative analysis of subjectively perceived method performance. The questions are documented in Table 37.

Table 37: Questions to answer in the questionnaire (Q1 was to be answered only in the questionnaire following the investigated second problem solving process)

2Q1	I have prepared the problem at hand (adenovirus infection) (by reading the provided papers, internet inquiry, etc.) before the treatment of the problem.	Questions inquiring into personal knowledge
1/2Q2	Before the preparation of the problem at hand, I possessed a certain amount of knowledge in the problem domain (adenovirus infection).	
1/2Q3	My knowledge about the problem seemed adequate for the treatment of the problem.	
1/2Q4	I believe to have understood the content of the training which preceded the case study.	Questions inquiring into methodological understanding and motivation
1/2Q5	I was motivated to treat the problem (adenovirus infection).	
1/2Q6	The methods acquired during the training helped me to better understand the problem.	Questions inquiring into method value perception
1/2Q7	The methods acquired during the training helped me during the generation of solutions.	
1/2Q8	The methods acquired during the training helped my group to better communicate.	

4.2.2.1.6 Problem to Solve

After the pedagogical case study and the filling in of the first questionnaire, the participants had to generate solution propositions to a second problem. The description of the problem, for which the participants had 3.5 hours and which was subject to the experimental analysis, is summed up in Table 38.

Table 38: Summary of information which was given to the problem solving teams in order to solve the second problem

Scenario	The problem solvers are members of a team in the domain of medicine who have any freedom to propose new research projects and any type of treatment.
Problem	Propose creative solutions to the problem of opportunistic adenovirus infections of children which are in an immunosuppressed state due to hematopoietic stem cell transplantation.
Fictional resources	Sufficient financial, scientific and technological resources
Real resources	Internet; scientific databases; scientific publications [Howard *et al.*, 1999; Gonçalves and de Vries, 2006; Robin *et al.*, 2007; Russel, 2009; Yaghobi *et al.*, 2011] in order to give an overview of the problem and existing solution strategies

The problem setting had been selected because of the following reasons:

- The problem stems from a highly science and technology based domain.
- The initial and goal states are very ill-structured and a variety of problem analyses, problem statements and solution strategies can be imagined, which classifies this problem as a design problem.
- The problem statement as well as the provided literature use codified language which is difficult to understand for non-experts.
- There are existing propositions in the literature to which the participant's propositions can be compared by domain experts (cf. Paragraph 4.2.3.3).

4.2.2.1.7 Questionnaire 2

After the problem solving session, all the participants had to fill in a second questionnaire similar to the first one. This time, however, the questions were exclusively related to the second problem solving session.

4.2.2.1.8 Synthesis of the Procedure and Further Indications

The protocol of the experiment is synthesized in Figure 44. During the problem solving process, the participants were free to decide on the amount of time they assign to each problem solving step as well as on when to have a break. However, the students were asked not to discuss about the process or the productions with participants outside their team.

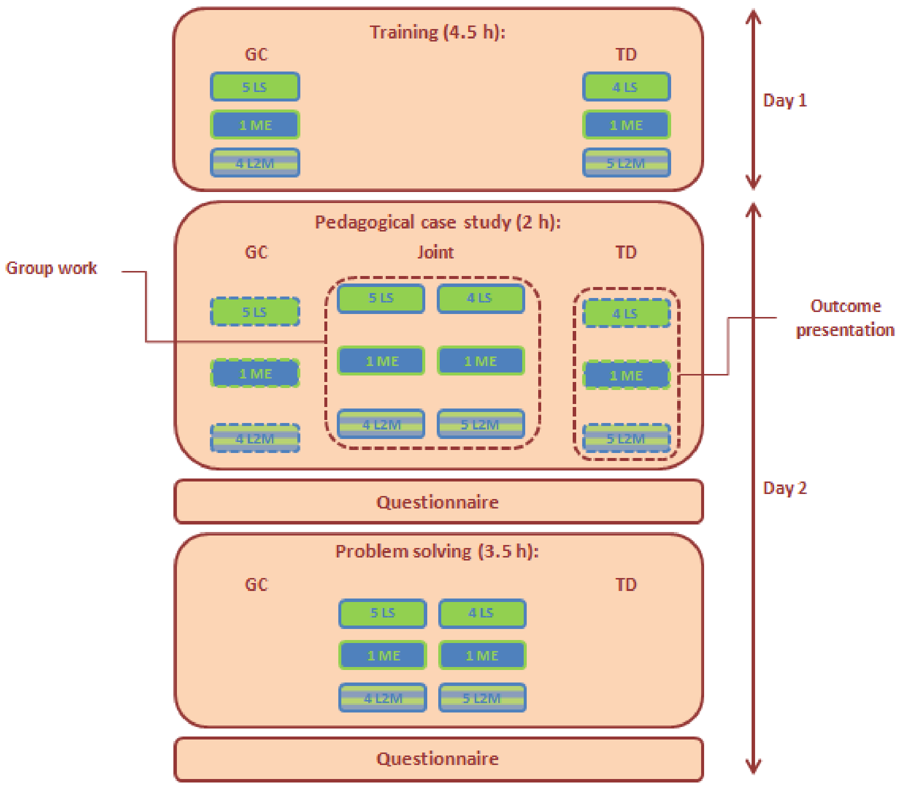


Figure 44: Synthesis of the procedure of Experiment

4.2.3 Results

4.2.3.1 Descriptive Results

The 20 groups produced a total outcome of

- 83 problem identification sheets (PIS)
- 62 problem structure sheets (PSS)
- 162 concept sheets (CS)
- 46 solution sheets (SS)

of different types and degrees of detail. Figure 45 to Figure 47 show examples of the PIS, PSS, CS and SS.

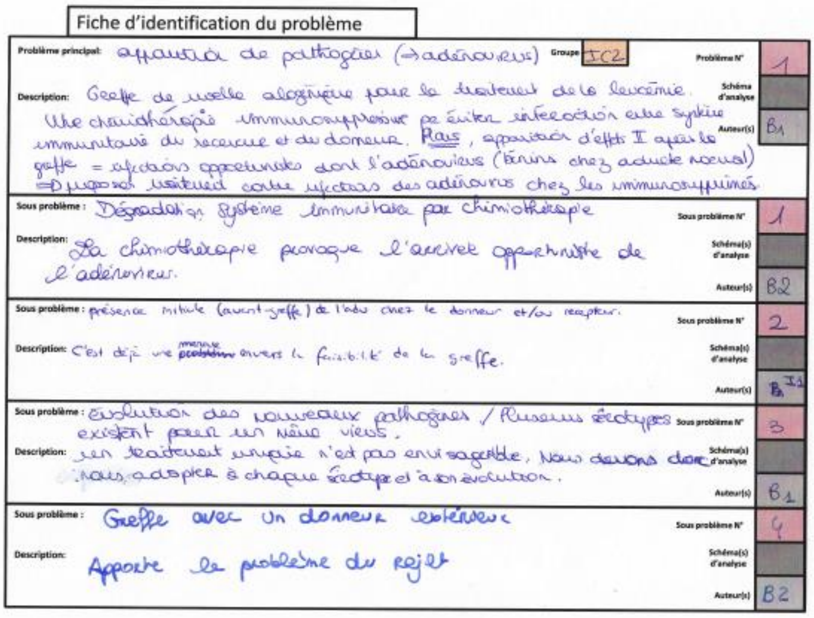


Figure 45: Example of problem identification sheets (PIS)

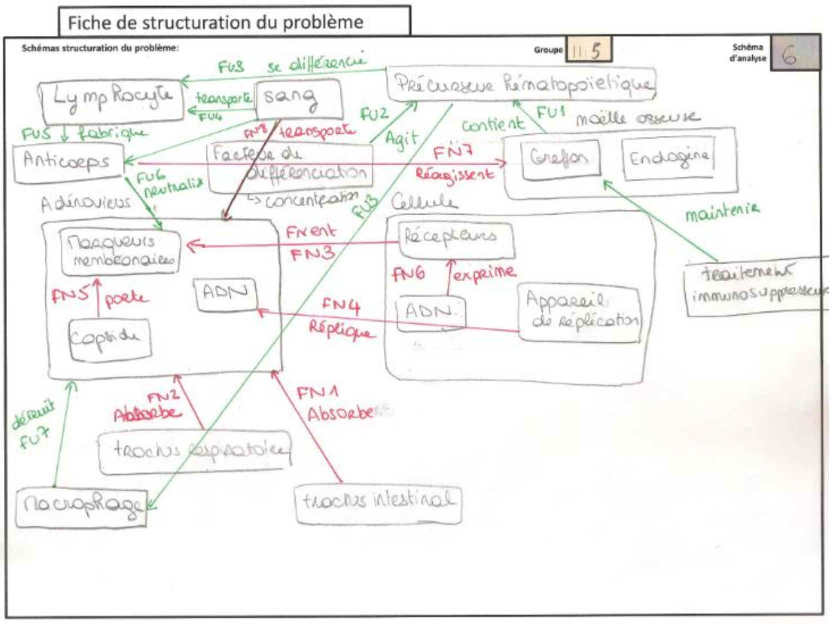


Figure 46: Example of problem structuring sheets (PSS)

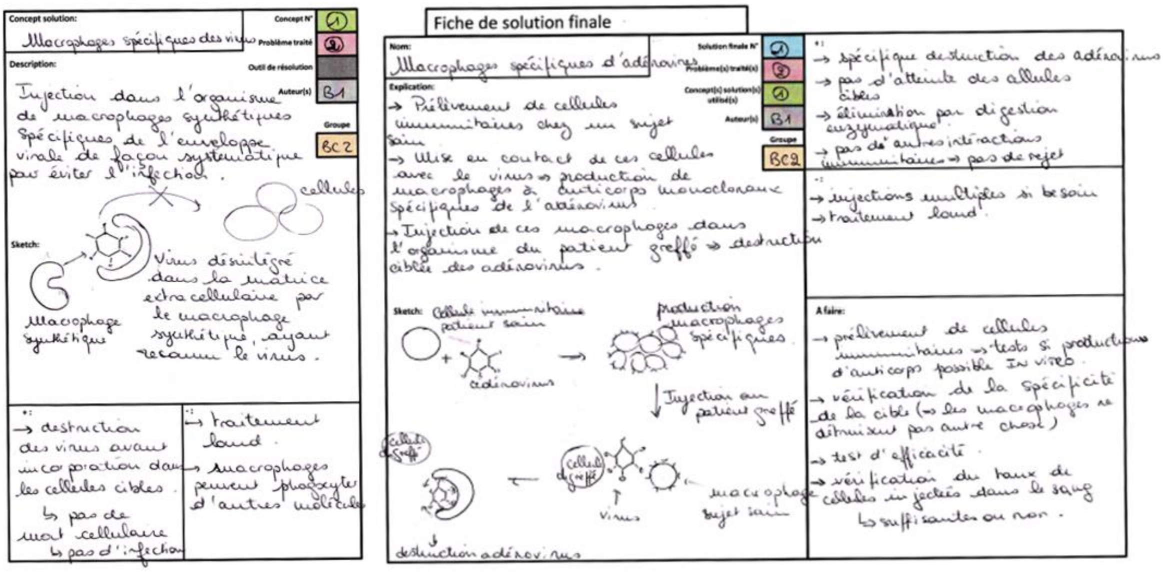


Figure 47 : Examples of creative group production; left: concept sheet (CS); right: solution sheet (SS)

4.2.3.2 Qualitative Categorization of Problem Models Generated in the TD Condition

The problem structuring sheets which had been generated by the groups in the TD condition were analyzed and assigned to the TD tools which had been introduced during the training.

4.2.3.3 Quantitative Evaluation of Generated Concepts and Solutions

The produced concepts and solutions were evaluated by two domain experts, i.e. researchers in microbiology, on seven-point Likert-type scales according to the following five independent creativity evaluation criteria [Dean *et al.*, 2006]:

- Feasibility
- Applicability
- Effectiveness
- Depth (mixture of implicational explicitness and completeness [see Dean *et al.*, 2006 for a discussion]) and
- Originality

The overall interrater-reliability for the generated concepts and solution propositions amounts to a Cronbach's alpha of α = 0.728, which is considered an acceptable value. Three concepts and one solution proposition could not be evaluated due to ambiguous or indistinct documentation. Hence the total of concepts which entered the statistical analysis amounts to 159 and the total of solution propositions amounts to 45.

4.2.3.4 Qualitative Categorization of Generated Concepts

The qualitative categorization of the generated concepts was performed in two steps.
First, the 26 concepts which obtained the highest scores in terms of applicability, effectiveness and originality were categorized according to the systemic level and the moment of time of their interaction.

Second, all generated concepts were categorized according to the following criteria which, according to TRIZ and its derivates, are used in order to describe and model complex systems and problem settings (Figure 48):

- The *sub problem* to which the concept is supposed to be a solution. In order to distinguish the sub problems, three problem categories have been distinguished using S-Field Analysis (cf. Paragraph 2.5.3.1.3.5). *Example: Virus-Organism-Immune System*
- The *systemic level* of the problem setting on which the concept mainly operates. *Example: Immune system*
- The element of the problem setting which represents the main object of interaction of the concept (*object*). *Example: Infected Cell*
- The functional sub area of the main element with which the interaction expressed in the concept occurs (*object component*). *Example: Membrane of infected cell*
- The moment of the infection process at which the main interaction in the concept takes place (*interaction time*). *Example: Before virus docks on cell*
- The means which are suggested in the concept in order to perform the main interaction (*means*). *Example: Antibody*

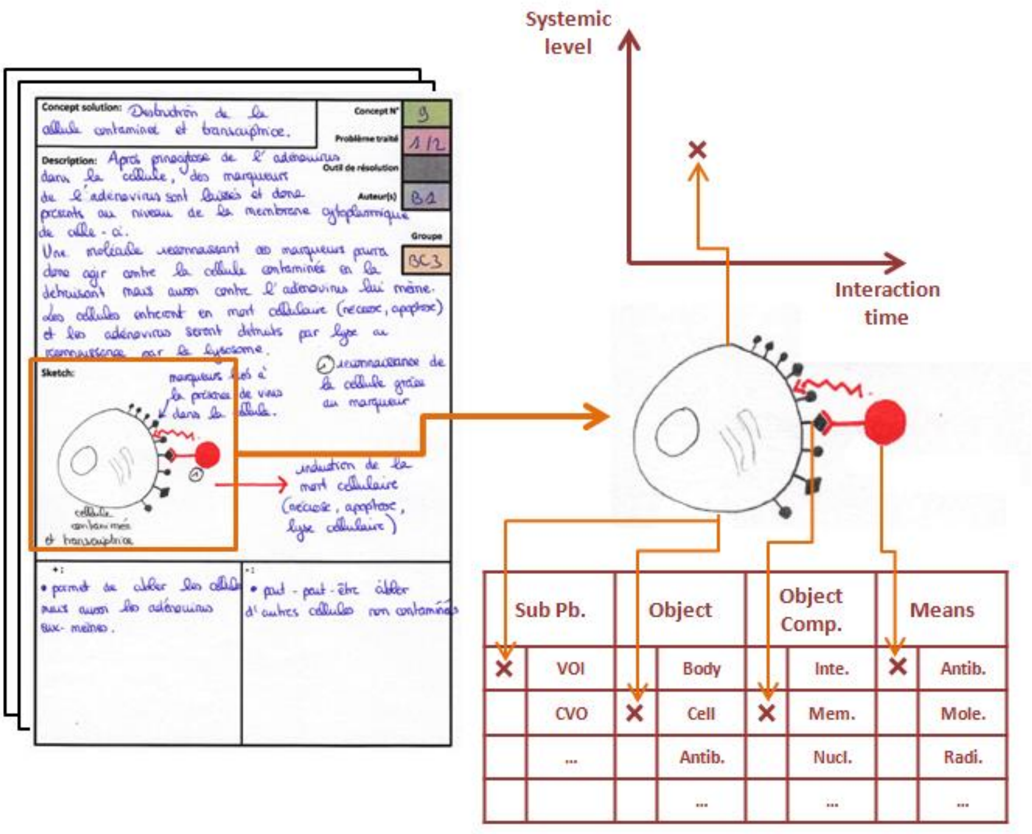


Figure 48: Schema of concept sheet categorization

4.2.3.5 Overview of Statistical Analyses

The output of the experiment, i.e.

- the replies on the two questionnaires
- the number of filled in PIS, PSS, CS and SS
- the creativity-related scores of the concepts and solutions,

was analyzed using *analysis of variance* (ANOVA) and calculation of *correlation parameters*. Further, *attractions rates* between the independent variables − *g*roup composition and method − and the classification of concepts according to the criteria of Chapter 4.2.3.1 were calculated for the generated concept sheets. Table 39 gives an overview of the results and the types of analysis which have been performed.

Table 39: Overview of analyses performed on experimental output

<table>
<tr><th colspan="2"></th><th>Analysis of variance</th><th>Correlation parameters</th><th>Qualitative categorization</th><th>Attraction rates</th></tr>
<tr><td colspan="2">Replies to questionnaires</td><td>X</td><td>X</td><td></td><td></td></tr>
<tr><td rowspan="4">Produced documents</td><td>PIS</td><td>X</td><td></td><td></td><td></td></tr>
<tr><td>PSS</td><td>X</td><td></td><td>X</td><td></td></tr>
<tr><td>CS</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>SS</td><td>X</td><td>X</td><td></td><td></td></tr>
</table>

4.2.3.6 Results of Analysis of Variance

The results of the analysis of variance (ANOVA) are documented in Table 40.

Table 40: Relevant results of the ANOVA calculation (↑: positive impact on dependent variable; ↓: negative impact on dependent variable; *: p<0.05; **: p<0.01)

No.	Independent variable(s)	Dependent variable	Result
1.1	Group composition and background	1Q2	$F(1, 26)=3.26$; $p=0.084$ (L2M: LS: ↑, ME ↓; LS/ME: LS ≈ ME)
1.2	Background	1Q4	$F(1, 26)=4.59$; $p=0.043$* (LS ↓; ME ↑)
1.3	Group composition	1Q6	$F(1, 26)=14.3$; $p=0.001$** (L2M ↓; LS/ME ↑)
1.4	Method	2Q2	$F(1, 57)=3.67$; $p=0.061$ (GC ↑; TD ↓)
1.5	Background	2Q2	$F(1, 57)=62.53$; $p<0.001$** (LS ↑; ME ↓)
1.6	Background	2Q3	$F(1, 57)=21.58$; $p<0.001$** (LS ↑; ME ↓)
1.7	Group composition	2Q4	$F(1, 57)=3.98$; $p=0.052$ (L2M ↑; LS/ME ↓)
1.8	Method	2Q6	$F(1, 54)=4.7$; $p=0.035$* (GC ↓; TD ↑)
1.9	Method	Number of PIS	$F(1, 18)=10.0$; $p=0.005$** (GC ↑; TD ↓)
1.10	Method	Number of PSS	$F(1, 18)=22.62$; $p=0.0002$** (GC ↓; TD ↑)
1.11	Group composition and method	Concept originality	$F(1, 59)=4.83$; $p=0.029$* (L2M: GC ↓, TD ↑; LS/ME: GC ↑, TD ↓)
1.12	Method	Concept depth	$F(1, 59)=11.77$; $p=0.001$** (GC ↑; TD ↓)
1.13	Group composition	Solution depth	$F(1, 45)=4.42$; $p=0.042$* (L2M ↑; LS/ME ↓)
1.14	Group composition and method	Solution originality	$F(1, 45)=7.83$; $p=0.008$** (L2M: GC ↓, TD ↑; LS/ME: GC ↑, TD ↓)
1.15	Group composition	Number of applied TD tools	$F(1, 7)=4.60$; $p=0.069$ (L2M ↑; LS: ↓)

The analysis of variance indicates main as well as combined effects of the three independent variables disciplinary group composition, disciplinary participant background and applied method on different dependent variables.

The data show an impact of disciplinary group composition on the perceived method value for problem understanding during the pedagogical case study (*Result 1.3*) as well as on the participants' perception of method understanding after the adenovirus case study (*Result 1.7*). In addition, disciplinary group composition was found to impact the degree of depth to which solution propositions were described (*Result 1.13*). Finally, the number of problem modeling tools in the TD condition was also found to be impacted by that variable (*Result1.15*).

The educational background of the participants, i.e. whether the group members had a LS or ME background, had an impact on perceived method understanding after the pedagogical case study (*Result 1.2*). Furthermore, the disciplinary background was also found to influence the evaluation of personally held knowledge with regard to the problem at hand (*Results 1.5* and *1.6*).

The methodological support used by the teams impacted the group members' evaluation of personally held knowledge (*Result 1.4*). The methodological approaches were also evaluated differently with regard to their value for problem understanding (*Result 1.8*). In addition the number of generated Problem Identification Sheets (*Result 1.8*) and Problem Structuring Sheets (*Result 1.9*) varied depending on the methodological condition. Finally, the applied methodology impacted the depth of the generated concepts (*Result 1.12*).

ANOVA also allowed detecting a small number of combined effects. Disciplinary background mediated by disciplinary group composition seems to have an impact on the participants' evaluation of personally held knowledge before the preparation of the adenovirus problem (*Result 1.1*). In addition, a combined effect of disciplinary team composition and applied methodological support on both concept- (*Result 1.11*) and solution (*Result 1.14*) originality could be detected.

4.2.3.7 *Results of Calculation of Correlation Parameters*

For the generated concepts (CS) and solution propositions (SS) respectively, the correlation parameters have been calculated. Relevant results of these calculations are given in Table 41.

Table 41: Synthesis of relevant results of the calculation of correlation parameters (*: p<0.05; **: p<0.01)

No.	Variable	Correlated variable	Result
2.1	Feasibility (concepts) (mean)	Depth (mean) (concepts)	r(159)=0.452; p<0.001**
2.2	Feasibility (solutions) (mean)	Depth (mean) solutions)	r(45)=0.433; p=0.003**
2.3	Depth (solutions) (mean)	2Q2 (standard error)	r(45)=0.383; p=0.009**
2.4	2Q1 (mean)	2Q6 (mean)	GC: r(79)=0.304; p=0.006** TD: r(72)=0.228; p=0.054
2.5	2Q1 (mean)	2Q7 (mean)	GC: r(79)=0.424; p<0.001** TD: r(72)=-0.040; p=0.738
2.6	2Q1 (mean)	2Q8 (mean)	GC: r(79)=0.530; p<0.001** TD: r(72)=0.332=0.004**
2.7	2Q2 (mean)	2Q7 (mean)	GC: r(79)=-0.327; p=0.003** TD: r(72)=-0.308; p=0.009**
2.8	2Q2 (standard deviation)	2Q8 (mean)	GC: r(79)=0.435; p<0.001** TD: r(72)=-0.295; p=0.012*
2.9	2Q3 (standard deviation)	2Q8 (mean)	GC: r(79)=0.453; p<0.001** TD: r(72)=-0.339; p=0.004**
2.10	2Q6 (mean)	2Q7 (mean)	GC: r(79)=0.542; p<0.001** TD: r(72)=0.548; p<0.001**
2.11	2Q7 (mean)	2Q8 (mean)	GC: r(79)=0.743; p<0.001** TD: r(72)=0.338; p=0.004**

The calculation of correlation parameters allows drawing links between creativity-related aspects of the output of the problem solving process. In addition, correlations between problem-related knowledge held within groups and the perceived value of methodological support could be shown statistically.

First, a positive correlation between the depth to which concepts and solutions were described and the feasibility of those concepts and solutions was detected (*Results 2.1* and *2.2*). The depth of solution descriptions was also correlated to differences of personally held problem-related knowledge among the group members (*Result 2.3*).

Second, the degree to which the adenovirus problem had previously been prepared by the participants influences evaluation of method value for problem understanding (*Result 2.4*) and problem solving (*Result 2.5*) in the GC condition. For the perceived value of methodological support for intra-group communication (*Result 2.6*), such a correlation was detected in both methodological conditions – GC and TD.

However, the perceived value of the methodological support for problem solving was found to be negatively correlated to the degree to which the participants disposed of problem-related knowledge before the preparation of the problem (*Result 2.7*).

Differences regarding problem-related knowledge among members of a same group were correlated to the group member's evaluation of method value for group communication (*Results 2.8* and *2.9*).

Finally, the judgment of methodological support regarding the facilitation of problem solving was correlated to both the value of that method for problem understanding (*Result 2.10*) and for intra-group communication (*Result 2.11*).

4.2.3.8 *Qualitative Categorization of Problem Models Generated in the TD Condition*

The results of the qualitative categorization of the problem models which were noted on the Problem Structuring Sheets (PSS) in the TD condition are synthesized in Table 42. Two points seem important. First, groups in the L2M condition (L2MTD1, L2MTD3 and, to a lesser degree, L2MTD5) seem to use the TD tools in a more extensive way than do LS groups (*Result 3.1*). Second, the concept of Ideality and the Closed World Diagram are the tools which are most often used by the groups (*Result 3.2*).

Table 42: Comparison of LS and L2M groups with respect to the use of problem analysis and problem modeling tools; (X): method applied rudimentarily

		Groups									
		LS				L2M					
Tools		LSTD1	LSTD2	LSTD3	LSTD4	L2MTD1	L2MTD2	L2MTD3	L2MTD4	L2MTD5	Σ
Problem Analysis	Reform + Sketch			X		X		X		X	4
	SOT + Resources			X	X	X	(X)	X		X	5 (6)
	Ideality	X	X	X	X	X	X	X	X	X	9
	Law of System Completeness		X			X		X	X	X	5
Problem Modeling	Magic Particles	X		X		X	X	X			5
	Closed World	X	X		(X)	X	X	X	X	X	7 (8)
	Space/Time An. + Contradict.				X	X	X	X			4
	Σ	3	3	4	3 (4)	7	4 (5)	7	3	5	
	ΣΣ	13 (14)				26 (27)					
	Average Σ	3,25 (3,5)				5,2 (5,4)					

4.2.3.9 *Results of Qualitative Categorization of the Most Creative Concepts*

The result of the qualitative categorization of the 26 most creative concepts is a two-dimensional matrix (Figure 49). It shows the distribution of the most creative concepts over a concept space, which is built along two axes, a temporal one and a systemic one.

Two observations can be made. Multidisciplinary teams (L2M) generated five concepts which target the problem on the upper two systemic levels (human (10^{-2} m) and cell/macrophages (10^{-4} m)). For the monodisciplinary teams with LS students, this was only the case for one concept (*Result 3.3*). Comparing the generated concepts with respect to the moment of interaction, it was found that the vast majority (17 out of 19 or 89.5 %) of the concepts proposed by the L2M / TD, L2M / GC and LS / TD groups target the problem at its early steps (i.e. before the virus docks onto the cell). For the LS / GC teams, however, this was only the case for the minority of the concepts (2 out of 7 or 28.6 %; *Result 3.4*).

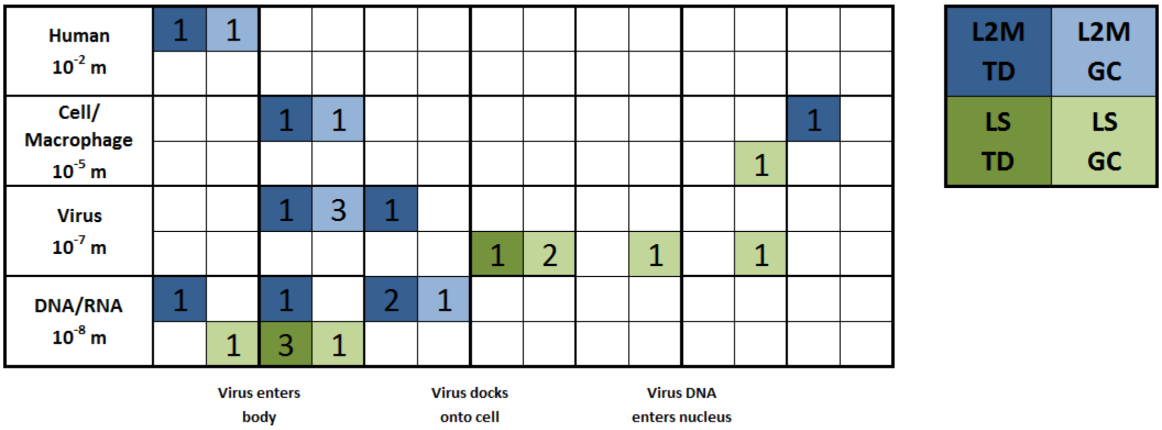


Figure 49: Two-dimensional matrix representing the concept space according to two criteria: the moment at which the principal interaction suggested in the concept occurs (abscissa); the systemic level at which the principal interaction suggested in the concept takes place (ordinate)

4.2.3.10 Results of the Calculation of Attraction Rates

The results of the calculation of attraction rates between the independent variables group composition (LS / L2M) and method (GC/TD) and the qualitative criteria of the generated concepts (cf. Paragraph 4.2.3.1) are given in Table 43 and Table 44.

Table 43: Results of attraction rate calculation; effect of group composition (*: TxL>0.5; **: TxL>1)

No.	Independent variable	Dependent variable	LS	L2M
4.1	Group composition	Sub problem	Virus-cell-organism*	Virus-immune system-stem cell*
4.2		Systemic level	No trend	Organism*
4.3		Object	Infected cell*	Organism* Stem cell*
4.4		Object component	Healthy cell: all components** Infected cell: endosome** Infected cell: DNA** Stem cell: all components Virus: capside*	Organism* Infected cell: receptors* Stem cell: receptors* Virus: DNA*
4.5		Interaction time	Before viral DNA enters cell nucleus* Before virus is expressed*	Before diagnosis of infection* Before virus enters cell* Before graft*

Table 44: Results of attraction rate calculation; effect of method (*: TxL>0.5; **: TxL>1)

No.	Independent variable	Dependent variable	GC	TD
4.6	Method	Sub problem	Virus-cell-organism*	Virus-immune system-stem cell*
4.7		Systemic level	No trend	Organism**
4.8		Object	Infected cell*	Immune system* Stem cell*
4.9		Object component	Organism: Ways of entry* Healthy cell: no trend Infected cell: Membrane, receptors, endosome, nucleus* Stem cell: no trend	Stem cell: receptors, DNA*
4.10		Interaction time	Before diagnosis of infection* Before viral DNA enters cell nucleus* Before virus is expressed**	After virus is expressed*

The results suggest an impact of disciplinary group composition (Table 43) and methodological support (Table 44) on qualitative aspects of the concepts which were generated by the problem solving teams.

For both independent variables, the differences between the generated concepts relate to the tackled sub-problem (*Results 4.1* and *4.6*), the systemic level at which concepts interact with the problem setting (*Results 4.2* and *4.7*), the target objects of the interaction (*Results 4.3*, *4.4*, *4.8* and *4.9*), as well as the time of the infection process at which an intervention is suggested (*Results 4.5* and *4.10*).

4.2.4 Discussion

The results presented in Chapter 4.2.3 allow a differentiated insight on the impact of disciplinary group composition and method application on the process of creative group problem solving in knowledge and technology intensive domains. Although only few research inquiring into similar questions could be found in the literature, the found results are discussed before the background of other work whenever possible.

4.2.4.1 Discussion of Results with Respect Hypothesis 1

Hypothesis 1 relates to the impact of group composition on the creative process, its outcome and information processing during this process.

4.2.4.1.1 Discussion of Results with Respect to Hypothesis 1a

Hypothesis 1a suggests an impact of group composition on the process of creative group problem solving.

Results 1.15 and *3.1* provide some support of this hypothesis for the case when the teams used TD methodology. L2M groups tend to use problem analysis and problem modeling tools of the TD complex more often (*Result 1.15*) and in a more systematic way (*Result 3.1*) than do LS teams (see also Table 42). Those findings can be at least partially explained by the fact that individuals with

ME background reported a better understanding of the methodological content (*Result 1.2*). Hence, it can be argued that the presence of one group member which is more familiar or at ease with a method can effectively foster the application of this method within group problem solving.
That argument is supported by the fact that members of interdisciplinary teams reported to have a better understanding of the training content than did participants in the monodisciplinary condition (*Result 1.7*). It shall be noted that the effect in *Result 1.15* is marginal (p=0.069), which is probably due to the small sample size in the TD condition. Therefore, more research is required in order to be able to confirm this finding.
Whether multidisciplinary teams composed of individuals without any link to (engineering) design and thus to design methodology would also more likely use TD tools, cannot be investigated with the present experimental setup.

4.2.4.1.2 Discussion of Results with Respect to Hypothesis 1b

Hypothesis 1b suggests an impact of team composition on information processing during the problem solving process.
Even though quantitative and qualitative differences regarding the produced outcome of the problem solving task can also be considered as indications for that impact, *Result 1.1* is more directly related. Comparing the team members' perception of the value of their own knowledge, a marginal combined effect of group composition and personal background has been observed. After the pedagogical case study, members of the monodisciplinary LS and ME groups considered the value of their knowledge with respect to the problem at hand more equally than did the members in L2M groups. In the latter groups, the LS participants, who are considered as 'experts' with respect to the problem at hand, evaluated their knowledge as more valuable than did the ME participants, who are considered as novices (Figure 50). One can argue that knowledge which is considered not valuable with respect to a problem by the knowledge owner has a higher risk of remaining unshared. Likewise, the excessive consideration of knowledge which is estimated superior by the majority of the group members risks dominating group problem solving processes. In that sense, *Result 1.1* confirms the view of Nemeth *et al.* [Nemeth, 1986; Nemeth and Nemeth-Brown, 2003], who argue that majority influence in groups leads to convergent thinking in both majority and minority individuals. Hence, *Result 1.1* provides marginal, indirect evidence for the impact of group composition on information sharing and hence information processing in groups. The fact that the result could not be reproduced after the investigated second case study can be explained by a learning effect among the participants. The experience that *a priori* non-problem relevant knowledge can contribute to interesting results of problem solving processes could have led to a reevaluation of non-domain knowledge with respect to the second problem by both experts and non-experts. Hence, the more equal estimation of personally held knowledge with respect to the second problem can be interpreted as an indicator that exemplary case studies can help reducing problems related to knowledge transfer by personal movement [Kane *et al.*, 2005].

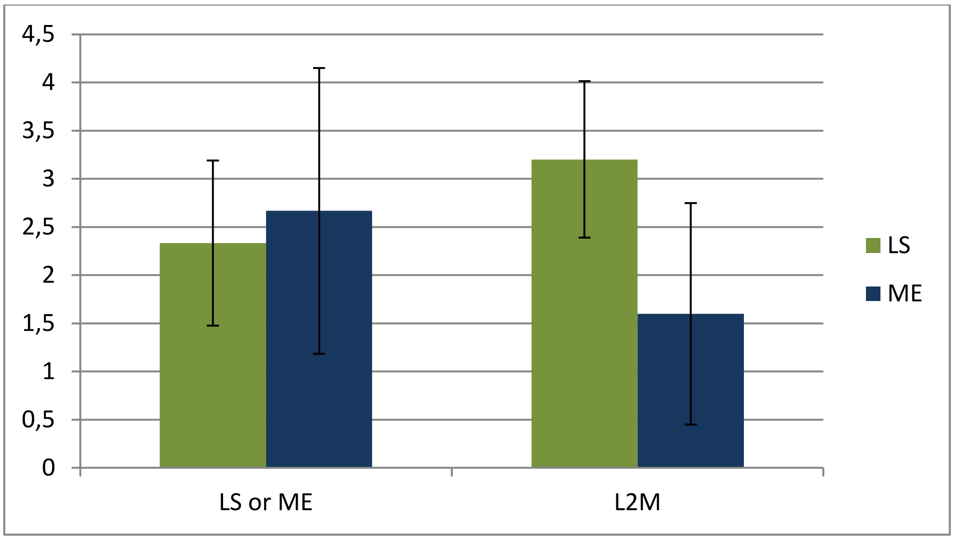


Figure 50: Combined effect of group composition and participant background on perceived value of personal knowledge

4.2.4.1.3 Discussion of Results with Respect to Hypothesis 1c

Hypothesis 1c relates to the impact of group composition on quantitative aspects of the generated concepts and solution propositions.

Result 1.13 indicates that solutions generated by interdisciplinary L2M groups are described in more detail than solutions produced by monodisciplinary LS and ME groups. Two explanations for that result can be offered. First, multidisciplinary group composition is likely to add several types of conflicts to group processes [Gebert *et al.*, 2006; van Knippenberg and Schippers, 2007]. Especially value conflicts, which relate to the desired outcome [Gebert *et al.*, 2006], and task conflicts, which describe disagreements with regard to problem solving strategies [Pelled *et al.*, 1999], can be the result of disciplinary diversity. Under certain conditions, those conflicts have been found to improve the consideration of previously unshared knowledge within a group [Brodbeck *et al.*, 2002]. The revealing and integration of that knowledge during the idea generation phase can improve the degree to which solutions are analyzed and documented, hence increasing solution depth. A second and probably more trivial explanation would be that the presence of a non-expert, for reasons of missing understanding, forces the expert group members to describe their idea propositions in more detail. In order to do so, the expert group members must explain aspects like casual relations within their concepts which would otherwise remain undeveloped. Once those explanations are shared among the group members, they are more likely to improve the documentation of the results.

Further, *Result 2.3* states a positive correlation between differences regarding the perceived value of personal knowledge between members of a group (measured by the *standard deviation* of replies to *2Q2*) and the degree of detail to which solution propositions are described. Together, those results suggest that interdisciplinary groups, due to individual differences in terms of possessed knowledge, generate more deeply reflected creative outcomes than do monodisciplinary groups. Those findings support *Hypothesis 1c* and are particularly important in view of the *Results 2.1* and *2.2*. Those results indicate that concepts and solutions which are documented in more depth are considered more feasible by experts and thus have a higher chance to be considered in subsequent product or process development phases.

4.2.4.1.4 Discussion of Results with Respect to Hypothesis 1c

Finally, *Hypothesis 1d* suggests an impact of group composition qualitative aspects of the generated concepts and solution propositions.

Results 3.3 and *4.1* to *4.5* provide clear support for the hypothesis of the impact of disciplinary team diversity on qualitative aspects of the generated outcome.

Result 3.3 shows that the most creative concepts generated by L2M groups occupy different locations in the concept space than do the most highly evaluated concepts of LS teams.

The comparison of the generated concepts of all groups except for those of the monodisciplinary ME groups (Table 43) shows that L2M concepts can be located predominantly on the systemic level of human organism (*Result 4.2* and *4.3*) whereas LS groups generated concepts which interact on the cell level.

Further, the concepts generated by teams of those two conditions also differ in temporal terms (*Result 4.5*). On the one hand, L2M concepts tackle the problem at different process steps before the virus enters healthy cells. On the other hand, the concepts produced by LS teams intervene at later process steps like the introduction of viral DNA into the cell nucleus or the expression of virions by infected cells.

4.2.4.2 Discussion of Results with Respect to Hypothesis 2

Hypothesis 2 states an impact of the applied methodology on the creative process, its outcome and information processing during that process.

4.2.4.2.1 Discussion of Results with Respect to Hypothesis 2a

Hypothesis 2a, which suggests that the choice of the method used during the problem solving process impacts the latter, obtained support by *Results 1.8*, *1.9* and *1.10*.

Result 1.8 indicates that the participants evaluated TD significantly more useful when it comes to problem understanding, which obviously exerts influence on the problem solving process. The result experimentally confirms Ilevbare *et al.*'s [2013] empirical finding that the use of TRIZ leads to improved problem analysis in teams.

Further, impact of support methodology is somewhat confirmed by the difference of the number of sub problems (PIS; *Result 1.9*) and problem structuring sheets (PSS; *Result 1.10*) which were identified respectively generated in the two conditions. Whereas the GC groups identified significantly more sub problems, the number of problem structuring sheets produced by TD teams was significantly higher than the one of the GC groups. One possible interpretation of those results is that the value of TD for problem structuring and problem modeling, which translates into an increased numbers of PSS, leads to more focused problem identification at TD groups. At the same time, due to a lack of methodological support for problem analysis and problem understanding, GC groups engage in more extensive and divergent problem identification processes.

Those results are interesting if one takes into account the findings of Fricke [1996], who suggests that 'balanced' strategies, which are characterized by reasonable expansion of the search space, are most likely to help designers to find quality solutions in limited time frames. On the assumption of an extrapolation of Fricke's findings to group processes, the *Results 1.9* and *1.10* suggest that the choice of the methodological support can help teams to adjust their meta-strategies for problem solving. In initial problem solving phases, TRIZ and derived approaches seem to lead to the restriction of the problem space. In subsequent phases of deeper problem analysis, those approaches, compared to intuitive methods, allow an enlargement of the search space.

4.2.4.2.2 Discussion of Results with Respect to Hypothesis 2b

Results 2.4 to *2.9* provide some insight into the influence of methodology on group information processing (*Hypothesis 2b*).

Results 2.4 and *2.5* indicate a correlation between the participants' preparation of the problem to solve and the perceived support from GC methods for problem understanding ($0.400>r>0.300$) (*Result 2.4*) and problem solving ($r>0.400$) (*Result 2.5*). Interestingly, for TD, these correlations were either not significant or non-existent.

There was also found to be a relation between problem preparation and perceived methodological value for intra-group communication (*Result 2.6*). Whereas that correlation was found to be strong ($r>0.500$) for GC, the effect was only moderate ($0.400>r>0.300$) for TD. Those results suggest that GC methods are more suitable to foster the processing of recently acquired information within groups.

Further, the values of both methodological approaches for problem solving were found to decrease ($r \approx -0.300$) with increased personal domain knowledge (*Result 2.7*).

Finally, and probably most important in view of interdisciplinary group problem solving, *Results 2.8* and *2.9* point to significant differences between the methodological approaches regarding the support of intra-group communication when knowledge differences among the team members are high. Whereas GC's capacity to foster group communication is strongly positively related to differences in terms of expertise within groups ($r>0.400$), the correlation is moderately negative ($r \approx -0.300$) *for* TD. Even though those results reflect the subjective perception of the participants and somewhat contrast with other findings like *Results 1.11* and *1.14* (see below), they point at least to some drawbacks of TRIZ and its derivatives in respect to the facilitation of problem solving in interdisciplinary teams.

The fact that participants in the TD condition, prior to problem preparation, considered their knowledge with respect to the problem domain as more sparse than did participants trained in GC (*Result 1.4*) can also be interpreted against an information processing background. One can argue that the use of TD methodology leads to the identification of aspects of the problem setting, of which the participants did not possess any knowledge. That identification of previously unknown problem aspects can then impact the value perception of personally held knowledge. However, it shall be noted that the discussed statistical effect is only marginal ($p=0.061$) and that the explanation given here should be tested elsewhere.

4.2.4.2.3 Discussion of Results with Respect to Hypothesis 2c

An impact of methodological support on quantitative aspects of the generated concepts and solutions was stated in *Hypothesis 2c*.

The experimental results are less clear with regard to this proposition. For most of the criteria for creativity outlined in Paragraph 4.2.3.1, no significant relationship could be found between method and outcome. In this sense, the present experiment confirms the findings of Chulvi *et al.* [2013], who could not detect significant differences in terms of usefulness between ideas which had been generated using TRIZ and those developed using intuitive creativity methods.

However, *Results 1.11* and *1.14* are of interest. They provide support for *Hypothesis 2c* if one takes into account the composition of the teams. As can be seen in Figure 51 and Figure 52, GC and TD exert a significant influence on the originality of both generated concepts (*Result 1.11;* Figure 51) and solutions (*Result 1.14;* Figure 52) depending on whether the composition of the applying groups is monodisciplinary (LS) or interdisciplinary (L2M). Whereas GC is advantageous in LS teams, the opposite is true for L2M groups.

Further, *Result 1.12* points to a significant positive relationship between the use of GC methods and the depth of generated concepts. One possible explanation for this phenomenon could be that participants of the GC condition stated to possess more problem relevant knowledge prior to the experimental procedure (*Result 1.4*).

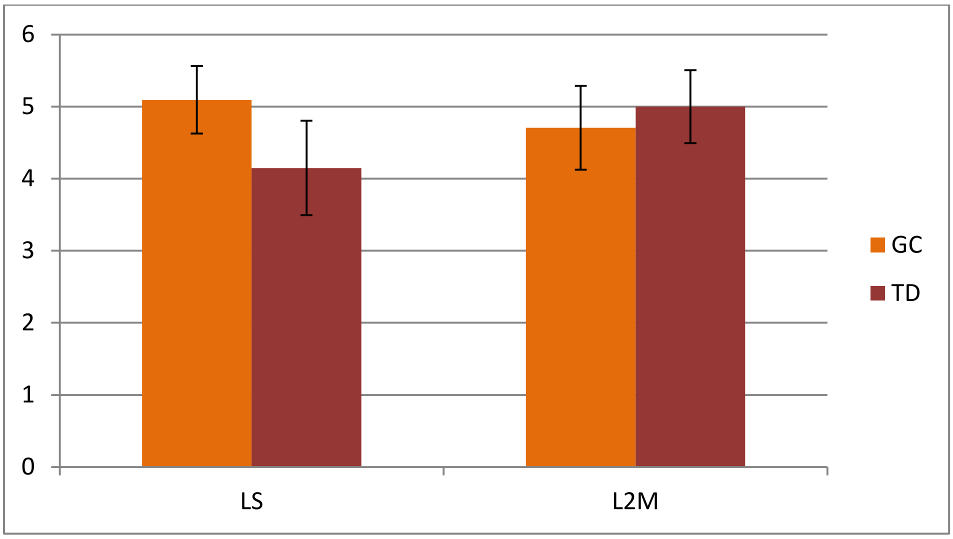


Figure 51: Influence of applied method on originality of generated concepts

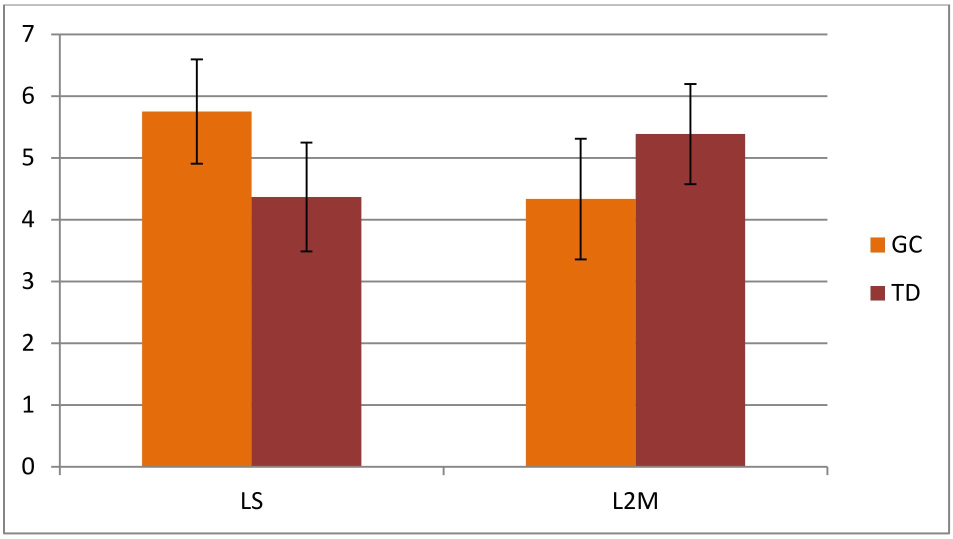


Figure 52: Influence of applied method on originality of generated solutions

4.2.4.2.4 Discussion of Results with Respect to Hypothesis 1d

Finally, *Hypothesis 2d* postulates an impact of applied methods on qualitative characteristics of the process outcome.

Results 4.6 to *4.9* indicate significant differences between the GC and TD conditions in terms of tackled sub problem (*Result 4.6*), systemic level (*Result 4.7*) as well as object of interaction (*Result 4.8*). Especially the focus on the organism-level put by groups working in the TD condition compared to no such trend at GC teams shall be highlighted here.

Concerning the point in time when the generated concepts interact with the problem setting, *Results 3.4* and *4.10* might seem contradictory. Among the most creative concepts, all ideas generated under the TD condition except for two tackle the problem at early process stages. However, the calculated attraction rates indicate a trend of TD groups to generate concepts which intervene later in the infection process. One way to interpret these results would be to argue that TD's capacity to generate high quality concepts is a function of certain dimensions of the concept space like systemic or temporal aspects.

4.2.4.3 Discussion of Further Results

Several results which cannot be interpreted with respect to any of the hypotheses are discussed separately in this paragraph.

Result 1.3 indicates that TD is of more value regarding problem understanding for monodisciplinary groups than it is in the L2M condition. The fact that this result was not replicated in the second questionnaire could lead to the conjecture that the value of TD for problem understanding in teams depends on the problem type, i.e. its level of complexity, ill-structuredness and so on. Another possible explanation would be that the participants in the L2M condition, who met for the first time shortly before the problem solving session, due to unfamiliarity with the other group members, had difficulties to implement TD in the given short time frame (Paragraph 4.2.2.1.4).

The *Results 2.10* and *2.11* confirm findings about the relationship between problem analysis, information sharing, and problem solving which have been reported elsewhere (cf. Chapters 2.4 and 2.5). Whereas *Result 2.10* indicates a correlation between the value of a given method for problem understanding and its value for problem solving, *Result 2.11* draws a link between methodological support for intra-group communication and problem solving.

Finally, the documentation sheets (PIS, PSS, CS and SS) show the participants' ability to apply methods and heuristics of TD with some success even after a very short training. Especially the concept of Ideality and the Closed World model were used very frequently (*Result 3.2*), confirming empirical findings of Ilevbare *et al.* [2013], who identify the concept of Ideality and Function Analysis as problem analysis tools, which are most often used in industry. Further, the presence of participants with a ME background seems to foster the understanding and use of TD methods by the teams (*Results 1.2*, *1.7* and *3.1*). That finding has both pedagogical and managerial implications (cf. Chapter 6.2).

4.2.4.4 Summary of Discussion

In total, the results of the presented experimentation validate both Hypothesis 1 and Hypothesis 2. Figure 53 and Table 45 sum up the result of the experiment as well as the full or validation of the hypotheses and sub hypotheses. Figure 53 shows a model of the problem solving process adapted from Nakagawa [2005] (cf. Paragraph 2.5.2.2.8). The spaces on different layers represent the stages of the problem solving process: the *specific ill-defined problem* with the initial problem setting (PSE), the *specific well-defined problem* with the identified problem (IP) documented by problem identification sheets (PIS), the *problem model* documented by problem structuring sheets (PSS), the *solution model* (not documented), the *divergent idea generation* with concepts documented by concepts sheets (CS), and finally, the *convergent idea generation* with solutions documented by solution sheets (SS).

Table 45 sums up which of the experimental results have been used in order to validate or reject the sub-hypotheses and which of the variables (orange boxes in Figure 53) have been analyzed for each result.

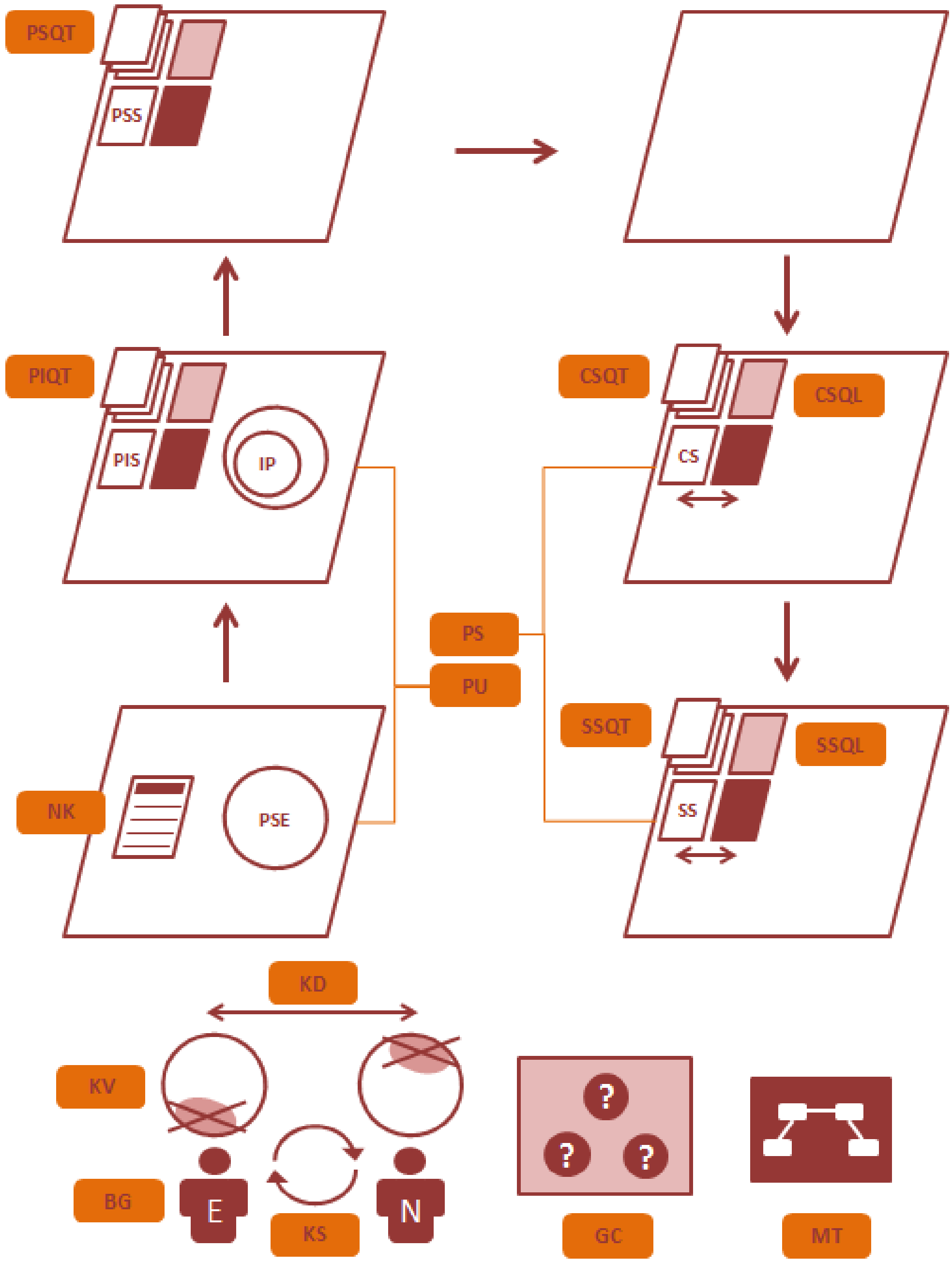


Figure 53: Schematic representation of the collaborative problem solving process investigated in Experiment[13]

[13] GC: **g**roup **c**omposition; BG: participant **b**ack**g**round; PISQL: **p**roblem **i**dentification **s**heets (**q**ua**l**itative aspects); MT: **m**e**t**hod; KV: perceived **v**alue of personal **k**nowledge; SSQT: **s**olution **s**heets (**q**ua**nt**itative aspects); KD: **k**nowledge **d**istance among participants; SSQL: **s**olution **s**heets (**q**ualitative **a**spects); PU: **p**roblem **u**nderstanding; PISQT: **p**roblem **i**dentification **s**heets (**q**ua**nt**itative aspects); PSSQT: **p**roblem **s**tructuring sheets (qua**nt**itative aspects); NK: **n**ew **k**nowledge; PS: **p**roblem **s**olving; KS: **k**nowledge **s**haring; CSQT: **c**oncept **s**heets (**q**uantitative aspects); CSQL: **c**oncept **s**heets (**q**ualitative **a**spects)

Table 45: Overview of hypotheses and results

Hyp.	Val.	Result	GC	BR	PIS QL	MT	KV	SS QT	KD	SSQ L	PU	PIS QT	PSS QT	NK	PS	KS	CS QT	CS QL
H1A	PV	1.15	X	X	X	X												
		1.2		X		X												
		1.7	X			X												
H1B	PV	1.1	X	X			X											
H1C	V	1.13	X					X										
		2.3					X	X	X									
H1D	V	3.1	X							X								
		4.1 - 4.5	X							X								
H2A	V	1.8				X					X							
		1.9				X						X						
		1.10				X							X					
H2B	?	1.4				X	X											
		2.4				X					X			X				
		2.5				X								X	X			
		2.6				X								X		X		
		2.7				X	X								X			
		2.8				X			X							X		
		2.9				X			X							X		
H2C	PV	1.11	X			X											X	
		1.12				X											X	
		1.14	X			X		X										
H2D	V	3.2				X												X
		4.6 – 4.10				X												X

4.2.4.4.1 Hypothesis 1

Sub Hypotheses 1a and *1b* are *partially validated*. Group composition and disciplinary background of the team members were found to have some impact on the way groups use TD methods for both problem identification and problem analysis. Further, some results indicate influence of group composition on knowledge processing in a team. Because those results are either indirect or their effect is considered marginal, those questions require further investigation. Sub *Hypotheses 1b* and *1c obtain support* by the results. Group composition is found to impact some of the quantitative and, to a larger extent, the qualitative aspects of the creative products. Depending on the applied methodology, the influence of group composition is even amplified. Based on these experimental results, *Hypothesis 1* is *validated*.

4.2.4.4.2 Hypothesis 2

The *results validate Sub Hypothesis 2a* as they indicate differences in terms of problem identification and problem structuring between groups which used GC methodology and those which followed the TD approach. Regarding *Sub Hypothesis 2b*, the *results* of the experiment *are mixed*. Whereas the analysis of the outcome of the creative process points towards a positive influence of TD on knowledge processing in interdisciplinary teams, the participant’s perception is another. Therefore, *Sub Hypothesis 2b* can be *neither validated nor clearly rejected*. The impact of the methodological approach on quantitative aspects of the products of the creative, which is suggested by *Sub Hypothesis 2c,* is *partially validated*. As explained in the previous paragraph, significant methodological influence on creative characteristics of the generated concepts and solutions were shown to be a function of the group composition. Finally, *Sub Hypothesis 2d is supported* by the experiment. The results indicate a relationship between the methodology which a group applied and the type of output which the group produced. Taking into account the results of the different sub hypotheses, *Hypothesis 2* is considered as validated by the experiment.

4.2.4.5 Limitations of Experiment

The experiment described in this chapter features several limitations. The most important ones relate to the participants, the methodological training, conditions of the problem solving session as well as to the documentation of the same.

The participants of the experiment were chosen according to two characteristics: disciplinary background and availability. In order to carry out an experiment which satisfies statistical criteria, it was necessary to recruit a large number of participants. Therefore it was decided to use students of ENSAM and EBI as participants, who had the following two drawbacks. First, even though they had obtained education focused on life sciences, the EBI participants are formally members of an engineering school, where they are also taught aspects of product design. Therefore it could be argued that the required difference in terms of disciplinary background between the LS and ME participants was not given. However, *Results 1.5* and *1.6* contradict that argument indicating that the knowledge difference between the two conditions with regard to the problem to treat was perceived to be rather high. Second, the question arises whether graduate students can be considered representative of scientists and engineers who are employed in industry and who engage in problem solving attempts under real conditions. Interestingly, the evaluating experts found that the creative output of the conducted problem solving session mostly represents the state of the art of R&D in the domain, which underlines a certain similarity between students and 'real life' agents. However, it could be interesting to perform similar experiments under more realistic conditions.

Following a similar logic, one could criticize the mode of the methodological training, especially in TRIZ and its derivatives. Scholars and consultants largely agree [TRIZ-France, 2012], that a 4.5 h – training combined with a pedagogical case study of two hours is far too short to ensure the participants will be capable of applying TRIZ methodology. In view of this aspect, it could be replied that the training length corresponds to the duration of trainings which, except for some rare cases, are offered to professionals by scholars and consultants. In addition, it should be noted that the training which the participants obtained contained only some of the most important theories, methods and heuristics of TD, for which the given time frame can be considered sufficient.

Further critique could arise from the fact that the participants were given only 3.5 hours for the entire problem solving process ranging from problem definition to solution generation. Considering the highly complex and knowledge-intensive nature of the problem at hand, this time frame seems extremely short. Even though the latter corresponds to some extent to the conditions under which interdisciplinary problem solving sessions are held in industry, it could be interesting to carry out a similar experiment without such time constraints.

Taking into account the experimental drawbacks with regard to the duration of the training and the problem solving session, the full potential of the investigated methods, especially of TRIZ and, in this case, USIT might not have been detected by the experiment as it is outlined here. Especially the elsewhere – and under different conditions – detected value of TRIZ for changing an expert's view on a problem could not be tested under the given constraints.

A further limitation of the experimental procedure relates to the way in which the problem solving session was documented. Documentation of the complete problem solving process in each group by using audio and video devices may have yielded further insights into the impact of group composition and methodological approach on group information processing. Such an approach is suggested for further research in this area.

The limited number of available participants with an educational background of mechanical engineering allowed building not more than two monodisciplinary groups composed of only those group members. Consequences of that drawback for the experimental setup are statistical uncertainties associated to certain results like e.g. *Result 1.1*. A greater number of groups composed

of only engineers or engineering students for an experimental setup would allow removing that incertitude.
Finally, until further research can test the general validity of the findings obtained by the present experiment, its results should be limited to the domain of medical problem solving as one instance of knowledge-intensive domains.

4.2.4 Conclusion of Experiment

To the best of the author's knowledge, the experiment presented in this chapter is the first one to investigate combined impacts of disciplinary team composition and application of creativity methods under laboratory conditions and with large sample sizes. It provides insight into the processes of collaborative creative interdisciplinary problem solving in knowledge intensive domains – in the case of the present experiment, in medical problem solving. To a certain degree, implications of disciplinary group composition and different knowledge sets in a team as well as of the methodological framework on early concept development could be highlighted. Especially the impact of methods originating from TRIZ and derivatives on problem solving in interdisciplinary groups are of interest in the area of New Product and Process Development (NPPD). Further, it could be shown that basic principles of rational design methodologies, which are considered very complex, can be applied to a reasonable degree after a rather short training. However, there seems to be a need for the presence of individuals originating from the domain of design in order to apply these techniques to other domains of expertise. Nevertheless, some results also indicate the participants' perception of drawbacks of TD methodology when it comes to the application and communication of knowledge. Therefore a need to develop a methodological approach which unifies the advantages of both methodological concepts is identified. The capacity to facilitate problem analysis and problem understanding of TD as well as the freedom to follow personal reasoning and problem solving strategies and to communicate these, which are provided by GC should be features of that new approach.
However, the *Experiment* mainly covers the early idea generation stage of the development process. Hence it only provides answers to parts of the *Research Question*, namely to the aspects of how to support the search and – to some degree – the evaluation of knowledge and technologies from knowledge-intensive domains for problem solving. Nevertheless, the *Experiment* does not give answers to the question of how to evaluate solution concepts which imply the application of distant domain technology. Nor does it investigate how problems related to the integration of such technologies can be solved. The *Case Study* is sought to provide some answers to those questions, which are important especially for later stages of the NPPD process.
The *Case Study* will be described in detail in the following chapters.

4.3 Industrial Case Study

4.3.1 Introduction

From the literature review two ways can be identified in which (design) problem solvers can profit from other problem solvers in other domains.

The first strategy consists of using perspectives on problems and problem solving strategies coming from those domains. The integration of such more abstract principles into the design problem solving process is referred to as knowledge transfer. The second way is to use products of the activity of other experts such as artifacts and discoveries – e.g. technologies or physical effects – in order to solve specific design problems. That approach is called technology transfer.

The experiment which is presented in the previous chapter has investigated multidisciplinary cooperative problem solving without any explicit distinction between those two approaches. However, the question remains of how solution propositions which are expressed at early NPPD stages and which are based on the application of extra-domain technologies – e.g. the implantation of a miniature mechanic injection system into the patient's body – can be developed.

Hypothesis 3 and the Case Study, which was set up to provide an initial test to that hypothesis, are sought to provide answers to that question.

Hypothesis 3 postulates the appropriateness of certain axioms and methods from the TRIZ complex to build a meta-model for the integration of knowledge-intensive technologies to given application settings. From the literature review and from the *Experiment* five requirements related to that approach can be deduced.

- It should be capable of facilitating a technology transfer process from the identification of the problem, to the identification of technologies which bear the potential to solve that problem, to the inventive integration of those technologies into the target product or process [Grant, 1996; Alavi and Leidner, 2001] (cf. Paragraph 2.2.4.2.2) [Albers *et al.*, 2014] (cf. Paragraph 2.2.7).

  The first two aspects of that process, i.e. problem identification and identification of potential technologies, are well supported by design theory and methodology [e.g. Savransky, 2000; Suh, 2001; Cross, 2008] (cf. Chapter 2.5.3.3) [e.g. Bhatta and Goel, 1996; Vincent *et al.*, 2005; Verhaegen *et al.*, 2011] (cf. Chapter 2.5.6.3). The third aspect, i.e. the resolution of problems which impede the integration of those technologies, has not been subject of methodological support [Gericke and Blessing, 2011; Chulvi *et al.*, 2013] until now. However, this aspect has been found to be among the most important reasons for the incapacity to perform technology transfer successfully [Albers *et al.*, 2014].
- The approach should combine
  - advantages of general creativity methods like
    - Intuitiveness [Shah *et al.*, 2000] and
    - General applicability [Ilevbare *et al.*, 2013; Gonçalves *et al.*, 2014]

  as well as
  - concepts of TRIZ and its derivatives which are the most widely accepted and have proven useful like
    - the concept of Ideality [Ilevbare *et al.*, 2013] (Paragraph 4.2.4.3),
    - Dialectical Principles [Moehrle, 2005] (cf. Paragraph 2.5.3.3.1.2) and
  - problem modeling tools (e.g. the Closed World approach and the Magic Particles method).

- Another requirement is the facilitation of problem solving processes with participation of several interacting experts by overcoming existing drawbacks of methods like e.g. Brainstorming [Taylor *et al.*, 1958; Diehl and Stroebe, 1987] (cf. Paragraph 2.3.4.3.1).
- Further, the required approach should satisfy a set of criteria like simplicity, adaptability to available resources in terms of time and expertise knowledge, as well as limited time requirements for the learning of the approach [Geis *et al.*, 2008; Ilevbare *et al.*, 2013] (cf. Chapter 2.5.7).
- Finally, it should present a framework which is sufficiently open to allow the application of models and methods which have proved their value for specific problems under specific conditions [e.g. Bender and Blessing, 2003, Tomiyama *et al.*, 2009] (cf. Chapter 2.5).

In the present chapter, a meta-model for the support of technology integration processes will be introduced which allows the integration and application of various existing problem modeling and problem solving methods. Further, the testing of that meta-model, the associated methods and thus of *Hypothesis 3* by the *Case Study* will be reported. After the introduction of the technology integration meta-model and its exemplary application onto a technology integration case, another application in the *Case Study* will be detailed. Then, a first testing of *Hypothesis 3* by comparing the applied model to existing approaches will be reported. The subsection concludes by highlighting the limitations of the present test setup.

4.3.2 Meta-Model Presentation

In the course of this Ph.D. research, an approach, consisting of a meta-model which serves as framework for the integration of several methodological tools, has been designed. That approach, which is sought to satisfy the above mentioned requirements, will be described in the following paragraphs.

4.3.2.1 Application and Technology / Problem and Potential Solution

The meta-model which shall be presented in this report is composed of two spaces. These are the Problem or *Application Space* and the Solution or *Technology Space*. The modeling of technology integration processes on those two spaces is based on problem solving theory (cf. Chapter 2.5.2.1.1) and thus allows an abstract and generic description of that process. The Problem or *Application Environment*, which is a subset of the Application Space, describes the domain constraints of the specific problem to solve. The Problem or *Application Setting*, finally, is defined as a subset of the Application Environment. It is composed of physical and non-physical elements as well as interactions and interdependencies between these elements, which describe the problem to solve exhaustively.

Solution- or *Technology Space*, *Technology Environment* and *Technology Setting* are defined analogously. The Solution Space is a vast continuum which covers all potential solutions to a given problem. The Solution Environment, as a subset of the Solution Space, contains all of the relevant knowledge and constraints in respect to a specific Solution Setting. The latter, in turn, is defined as the set of physical and non-physical elements and interactions between these elements, which describe a solution in its initial domain of application exhaustively (Figure 54).

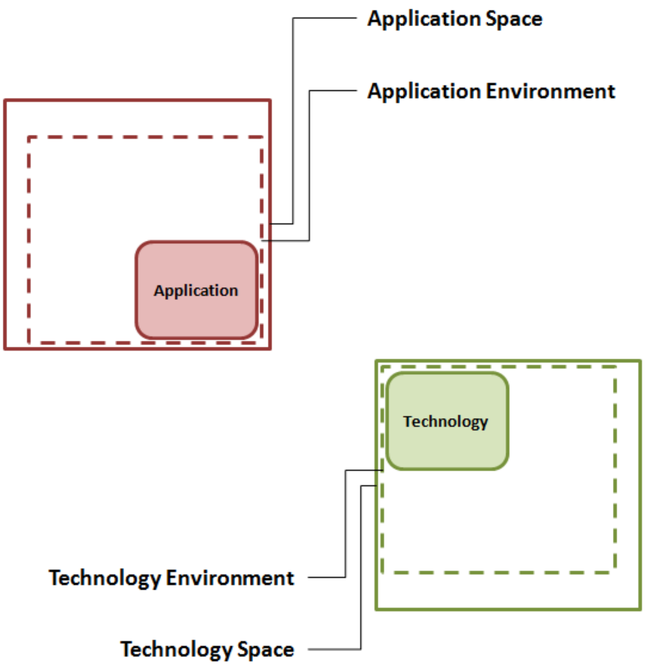


Figure 54: Schematic description of the Application, the Technology as well as of their close environments and the abstract spaces they are situated in

4.3.2.2 Desired and Undesired Interactions

The integration of a Technology into a given Application has the purpose of satisfying certain needs. The modeling of these needs as well as other interactions between Technology and Application is performed using functional modeling principles like those used e.g. in Functional Analysis, TRIZ and USIT (cf. Chapter 2.5.3.1).

According to the meta-model, four types of interactions are possible between the Application and the Technology. First of all, the Technology performs a number of *Desired Interactions* or functions on the Application. Those functions are the reason for the choice of a specific Technology. However, in most of the imaginable cases the Technology also performs a set of undesired side effects or *Undesired Interactions* on the Application.

Likewise, the Application must perform a number of Desired Interactions on the Technology. Those can take the form of e.g. the provision of resources like material, energy or information, or infrastructure. Finally, and analogously to the Technology, it often happens that the Application performs Undesired Interactions on the Technology. Those unwanted effects can reduce or eliminate the functioning of the Technology or they can either affect or even destroy the Technology (Figure 55).

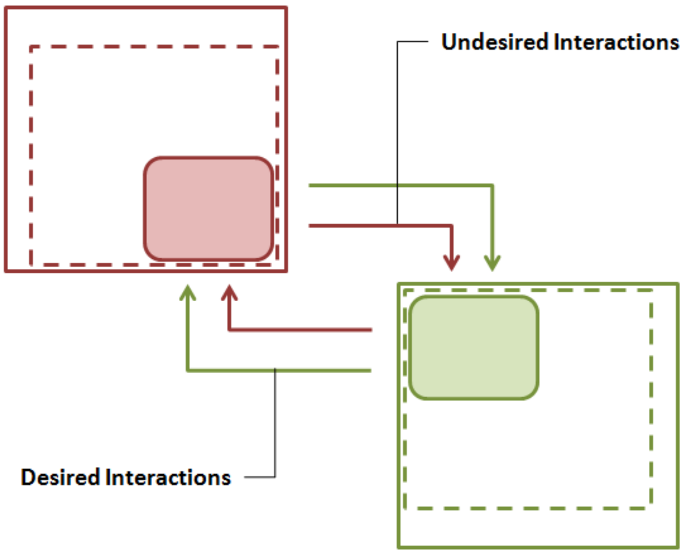


Figure 55: Schematic description of Desired and Undesired Interactions between Technology and Application

4.3.2.3 Potentials, Risks, Needs and Protections

According to the meta-model, both the Application and the Technology possess sets of *Properties* which influence mutual Interactions. These Properties are called *Potential*, *Risk*, *Need* and *Resistance* (Figure 56) and read as follows:

Technology Properties:

- *Function Potential* (P_T): This Property indicates the qualitative and quantitative capacity of the Technology to perform the Desired Interactions on the Application.
- *Risk of Affecting Application* (A_T): This Property describes the risk of exerting Undesired Interactions on the Application
- *Resource Need* (N_T): This Property points to the requirements of the Technology in order to properly carry out its functions
- *Application Side Effect Resistance* (R_T): This Property refers to the robustness of a Technology regarding possible detrimental conditions at the Application or the Application Environment.

Application Properties:

- *Resource Potential* (P_A): This Property indicates the Application's capacity to provide the necessary resources in order to assure a proper functioning of the Technology.
- *Risk of Affecting Technology* (A_A): This Property refers to the risk of exerting Undesired Interactions on the Technology.
- *Function Need* (N_A): This Property describes the Application's functional requirements.
- *Technology Side Effect Resistance* (R_A): This Property points to the robustness of an Application and its constituents regarding detrimental side effects of the Technology.

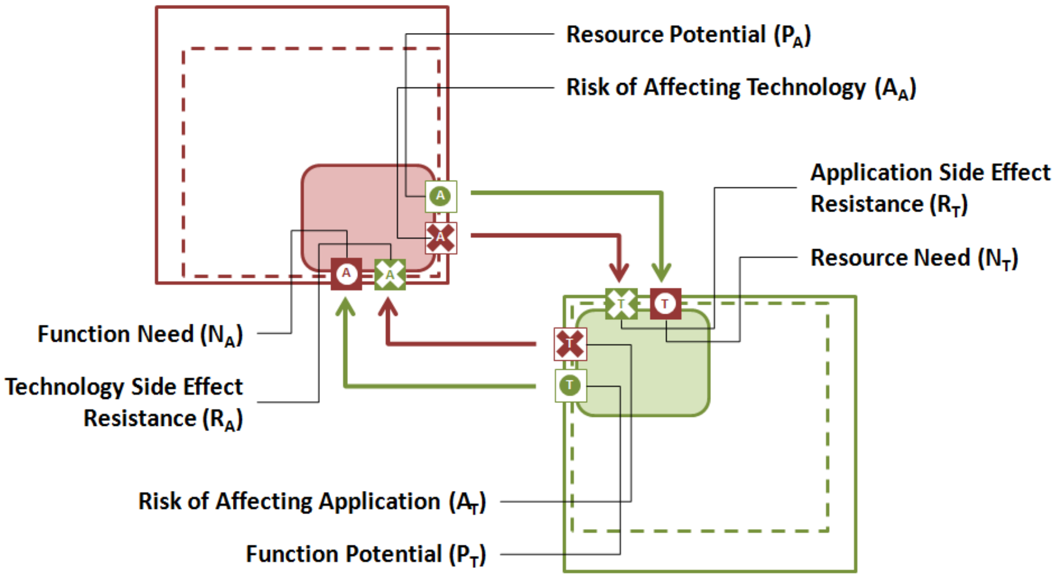


Figure 56: Schematic description of Properties of both the Application and the Technology

4.3.2.4 Ideality

The concept of Ideality (Paragraph 2.5.3.1.1.2) is one of the most important features of TRIZ and its derivatives. It is sought to guide the search for solutions once the problem has been defined. In addition, the modeling of the ideal solution was among the concepts of TRIZ and its derivatives which were most frequently used by the participants during the Experiment.

Based on the meta-model presented in the previous paragraphs, two types of Idealities can be defined. First, the *Ideal Technology*, from an Application perspective, facilitates the search for technologies which could solve a given problem. Second, the *Ideal Application*, from a Technology perspective, allows the search for new applications to a given solution.

Referring to these two perspectives of ideality, two ideal generic scenarios can be drawn. Those scenarios are named *Partial Idealities* and are described as follows (Figure 57).

The Ideal Technology (I_T), from an Application perspective, possesses the following properties (cf. also Formula 3):

- High Function Potential: The functions which the Technology performs correspond in quality and quantity to the Function Need of the Application.
- High Application Side Effect Resistance: The Technology is resistant against specific negative interactions which could arise from the conditions in the Application Setting.
- Low Risk of Affecting Application: The risk that elements or function principles of the Technology affect those of the Application is low.
- Low Resource Need: The Technology requires either few or no resources in order to function properly.

$$I_T = \lim_{\substack{P_T, R_T \to \infty \\ A_T, N_T \to 0}} \frac{P_T + R_T}{A_T + N_T} \qquad (3)$$

In the same way, the Ideal Application (I_A), from a Technology perspective, features the following properties (cf. also Formula 4):

- High Resource Potential: The resources which are available in the Application Setting correspond to the requirements of the Technology in order to function properly.

- High Technology Side Effect Resistance: The Application is resistant against specific negative interactions which could arise from the conditions in the Technology Setting.
- Low Risk of Affecting Technology: The risk that elements or function principles of the Application affect those of the Technology is low.
- Low Function Need: The functional requirements of the Application correspond exactly to the functions the Technology is able to perform in qualitative as well as quantitative terms.

$$I_A = \lim_{\substack{P_A, R_{A \to \infty} \\ A_A, N_{A \to 0}}} \frac{P_A + R_A}{A_A + N_A} \qquad (4)$$

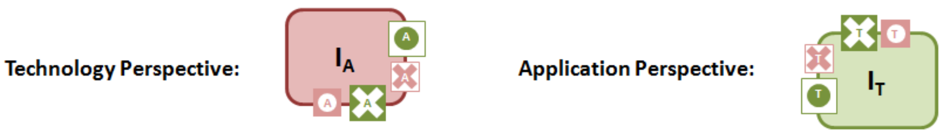


Figure 57: Schematic description of the Ideal Application and the Ideal Technology

4.3.2.5 Problem Modeling

The presented meta-model also allows the modeling and categorization of problems which occur once a technology has been selected to be integrated into a given application. Further, *Generic Strategies* to overcome the integration problems can be identified. These Generic Strategies, in turn, point to specific sub problems which can be assigned to concrete domains of expertise in which the problem solving can take place. This systematic categorization of *Technology Integration Problems* into a finite set of sub-problems can be compared to the Method of Factorization, which follows similar principles [Pahl *et al.*, 2007].

Four types of Technology Integration Problems exist:

- *Insufficient Technology Interactions* (*ITI*): The desired Interactions which the Technology is sought to perform on the Application do not correspond to the requirements.
- *Detrimental Technology Side Effects* (*DTS*): The Technology exerts a negative influence on the Application.
- *Insufficient Resources for Technology Functioning* (*IRF*):The resources which are provided by the Application are not sufficient for a proper functioning of the Technology.
- *Detrimental Application Side Effects* (*DAS*): The Application exerts a negative influence on the Technology.

For each type of Technology Integration Problem, two *Generic Strategies* can be identified (Figure 58):

- Insufficient Technology Interactions (ITI): Problem solving attempts can focus on the improvement of the Technology's Functional Potential (P_T) or on the reduction of the Application's Function Need (N_A).
- Detrimental Technology Side Effects (DTS): The problem solvers can either work on the improvement of the Application's Technology Side Effect Resistance (R_A) or on the reduction of the Technology's Risk of Affecting Application (A_T).
- Insufficient Resources for Technology Functioning (IRF): In this case, the Generic Strategies are improvement of the Application's Resource Potential (P_A) and the reduction of the Technology's Resource Need (N_T).

- Detrimental Application Side Effects (AAS): In order to solve this integration problem, either the Technology's Application Side Effect Resistance (R_T) can be increased or the Application's Risk of Affecting Technology (A_A) can be reduced.

The subdivision of often complex Technology Integration Problems into domain-specific Generic Strategies allows both creative problem solving in monodisciplinary teams and joint problem solving in interdisciplinary groups. As the problems are subdivided into several sub problems, the application of group creativity techniques like e.g. Dialectical Inquiry, Brainwriting, Method 635 or Gallery Method (cf. Chapters 2.3 and 2.5) is possible.

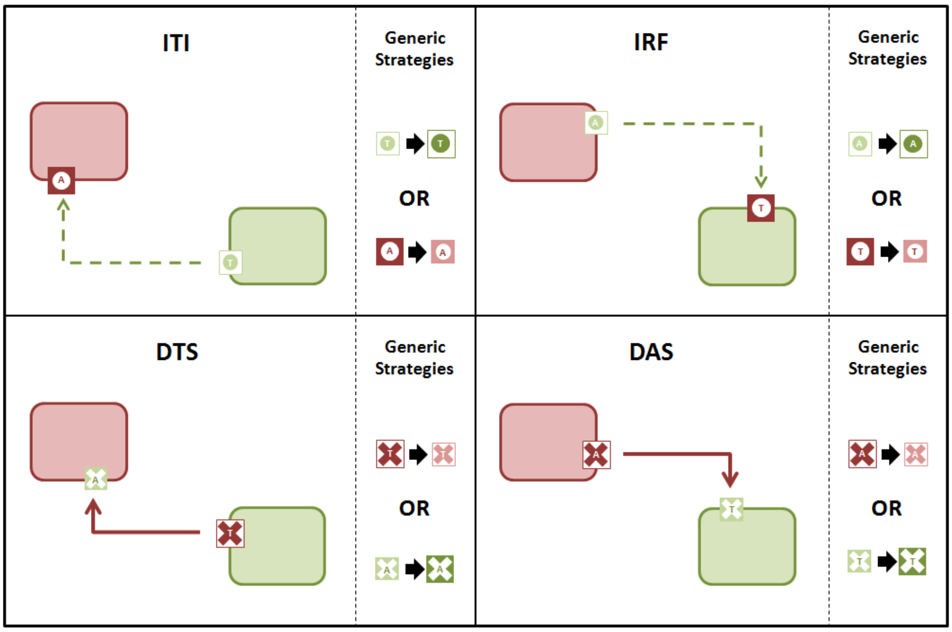


Figure 58: Schematic description of the four types of Technology Integration Problems (TIP) and the Generic Strategies for TIP resolution

4.3.2.6 *Example: Integration of Hydrogen Combustion Technology in Automotive Industry*

In order to further clarify the introduced meta-model, we shall use it in order to model the integration of hydrogen combustion technology into cars [White *et al.*, 2006; Verhelst and Wallner, 2009, Korakianitis *et al.*, 2010; Wikipedia, 2014]. This specific case was chosen because of its timeliness – even though some of the presented issues have been solved decades ago –, its complexity and because it covers a rather large spectrum of knowledge fields. Nevertheless, the example does not take into account all of the existing issues of hydrogen combustion in cars. If that were the case, it would result into a too detailed and complex analysis which would exceed the scope of the present report.

4.3.2.6.1 Application, Required Interactions and Technology

The Application is a *passenger car including passenger cell, chassis and combustion engine*. From the Application Environment arises the need for a technology which is capable of stocking and transforming chemical energy into mechanical power in an internal combustion engine with a low 'station-to-wheel' carbon footprint and low dust particle emissions. Further, an engine performance which is comparable to state of the art gasoline or gasoil engines is required. Finally, the used fuel should be highly available in the Application Environment. The mentioned requirements lead the developers to hydrogen combustion technology. The Technology *hydrogen combustion and hydrogen storage* comprises the concept of ignition of a mixture of hydrogen and oxygen in order to provide mechanical power as well as storage systems for the said hydrogen. Some basic characteristics of hydrogen combustion technology are listed in Table 46. Besides other disciplines, the primary involved knowledge domains are mechanical engineering (ME), materials science (MS), process engineering (PE), physics (PH), and chemistry (CH) (Figure 59).

Table 46 : Technological Characteristics of H_2-Technology (extract)

No.	Technology Characteristics (Tech. Ch.)
1	H_2 features a low 'station-to-wheel' CO_2 impact.
2	H_2 combustion does not emit any dust particles.
3	H-atoms exist abundantly in bound forms (e.g. water)
4	H_2 has a low boiling temperature.
5	H_2 is a very small molecule.
6	H_2 has a low energy density.
7	H_2 burns to surface of combustion chambers.
8	H_2 reacts with other materials.
9	H_2 has a high autoignition temperature.
10	H_2 burns at hot temperatures.

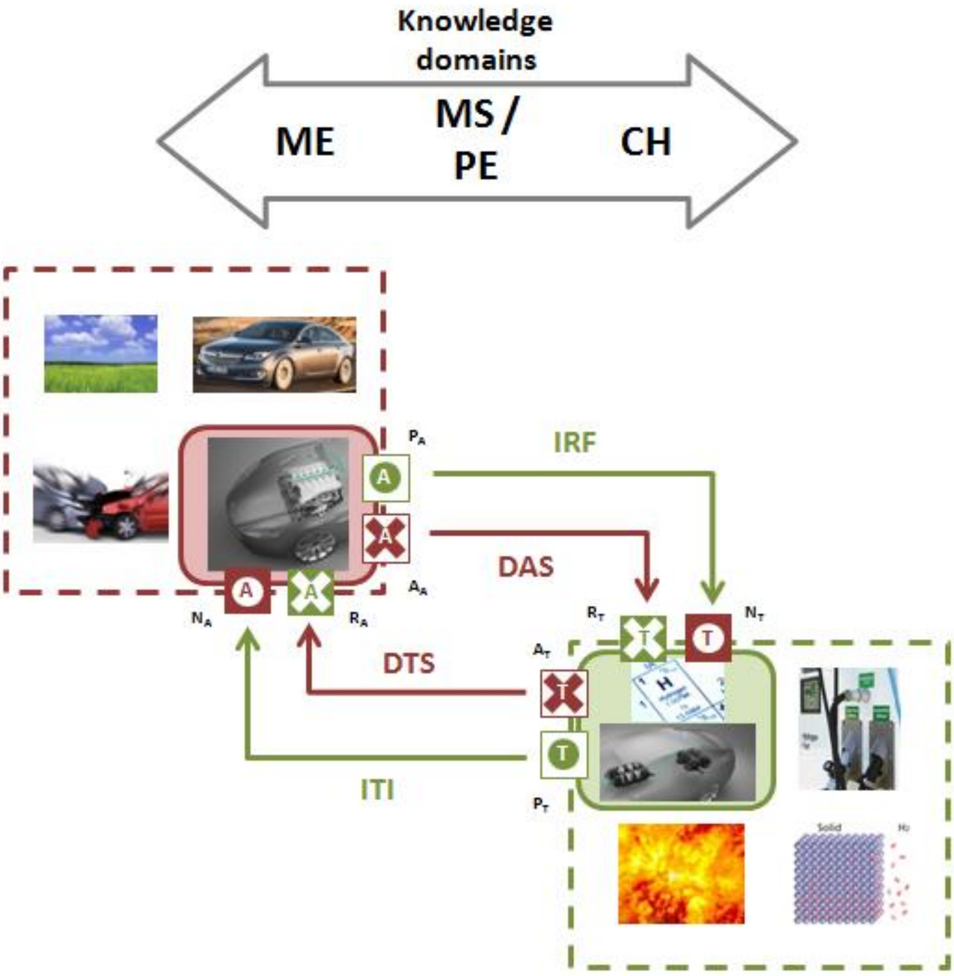


Figure 59: Schema of the integration of hydrogen combustion technology into passenger cars

4.3.2.6.2 Technology Integration Problems

From the task aiming at the integration of the Technology 'hydrogen combustion and hydrogen storage' into the Application 'passenger car including passenger cell, chassis and combustion engine' arise several Technology Integration Problems. Some examples are given in Table 47.

Table 47: List of Technology Integration Problems to solve

Letter	TIP Type	Description	Rel. Tech. Ch.	Knowledge domain
A	ITI	Lower filling ratio in combustion chamber using multipoint injection	4	CH/ME
B	ITI	H_2 diffuses from tank	5	CH/MS
C	ITI	Stocking of sufficient amount of H_2 difficult	4	CH
D	ITI	Stocking of sufficient amount of H_2 difficult	6	CH
E	DTS	H_2 combustion affects lubricant in combustion chamber	7	CH
F	DTS	H_2 causes hydrogenation of lubricant	8	CH
G	DTS	H_2 causes embrittlement of steel used for tanks	8	MS/CH
H	IRF	Ignition of H_2 in compression ignition engines difficult	9	CH
I	DAS	High temperatures at e.g. outlet valves cause engine knocking	10	ME/CH

4.3.2.6.3 Generic Strategies

For each of the Technology Integration Problems described in Table 47, three problem solving variants exist. Hydrogen combustion technology experts can try to solve the problem on the Technology side. Therefore they can use their specific expertise in terms of process engineering, chemistry and material science, which corresponds to the Generic Strategies $\uparrow P_T$, $\downarrow A_T$, $\downarrow N_T$ or $\uparrow R_T$. Alternatively, automotive experts can use their specific knowledge related to mechanical engineering and material science in order to solve the problem on the Application side, which corresponds to the Generic Strategies $\uparrow P_A$, $\downarrow A_A$, $\downarrow N_A$ or $\uparrow R_A$. Of course, there are also solutions which require both Application and Technology expertise. Those solutions are classified as P_T/N_A, A_T/R_A, N_T/P_A, R_T/A_A.

Table 48 gives examples for solutions to the different Technology Integration Problems, lists related, classifies them according to the three Generic Strategies and lists related knowledge domains.

Table 48: Overview of solutions used in order to solve Technology Integration Problems and corresponding Generic Strategies

TIP	Generic Strategy	Solution	Knowledge domain
A	P_T/N_A	High pressure direct injection of gaseous H_2 into the combustion chamber improves filling ratio and overall efficiency.	ME/CH
B	P_T/N_A	Use of very dense materials reduces diffusion of H_2 out of the tank	CH/MS/ME
	$\uparrow P_T$	Chemical H_2 storage in form of metal hydrids or use metal organic frameworks (MOF), which adsorb H_2 improve storage capacity	CH
C/D	$\uparrow P_T$	High pressure storage of H_2 increases energy content per volume unit	PE/MS/CH
	$\uparrow P_T$	Liquefaction of H_2 increases energy content per volume unit	PE/MS/CH
	$\downarrow N_A$	New car architectures or variations of application systems (e.g. coach) provide more space for fuel storage	ME
E/F	$\uparrow R_A$	Use of ceramic surfaces in the combustion chambers can replace lubricants	ME/MS
G	$\downarrow A_T$	Use of alternative storage technologies can replace mechanical storage and thus solve problem of tank material embrittlement.	MS/CH
H	$\uparrow P_A$	Use of small amounts of diesel in order to start the combustion of H_2 (pilot ignition)	ME
I	$\uparrow P_A$	Use of rotary combustion engines (e.g. Wankel engine) can replace engine systems with e.g. outlet valves	ME

4.3.3 Phases of the Technology Search and Integration Process

The meta-model which was presented in the previous chapters is of both descriptive and prescriptive nature. It allows describing the search for technological solutions and the integration of the same into a given problem setting in a generic way. But it also builds a framework for the application of several well-established methods and heuristics to a somewhat prescriptive technology integration process.

In the following paragraphs, a technology integration process is presented which allows the application of a large set of well-established problem modeling and problem solving methods as well as of problem solving heuristics in seven phases. The methods, tools and heuristics which are listed in the different phases of the process represent a non-exhaustive subset of approaches. The user of the process which is presented below is encouraged to choose between the given approaches or to apply others in a pragmatic way. The presented process will be subject of testing in Chapter 4.3.4.

4.3.3.1 Phase 1: Definition of Application Environment

The goal of this phase is to identify the business- and technological environment of the Application and to identify which customer value the Application shall generate.

4.3.3.1.1 Input of Phase 1

Various types of information, e.g. previously defined company strategies, associated business goals and market studies, can be used as input for Phase 1. Moreover stakeholder analyses, Personas or other business- or user-related tools can provide valuable insight. When the Application is situated in a technical environment, technical information of different degree of detail can be used to describe the conditions outside the Application's system boundaries.

4.3.3.1.2 Methods and Tools Applicable during Phase 1

Examples for the methods and tools which can be applied during Phase 1 are given in Table 49. Those are taken either from methodologies of the TRIZ complex (RELEvent, Multi-Screen

Approach), from quality management (QFD, FMEA) or from engineering design (external Functional Analysis). Like in the subsequent phases, the listed methods and their rules of application shall be applied in a pragmatic and goal oriented way.

Table 49: Exemplary list of methods and tools applicable during Phase 1

Method/Tool	Description
RELEvent	Method to describe the use of a product or service by a customer in a procedural way. First the ideal usage scenario is described. Then potential problems interfering with the ideal product or service usage are identified. After this, obvious solutions to those problems and associated secondary problems are listed. Linking the problems, solutions and secondary problems provides a cause-effect network which helps identifying crucial problems to solve [Yezersky, 2006, 2008].
Multi-Screen Approach	Cf. Paragraph 2.5.3.3.3.3
Quality Function Deployment (HoQ1)	Cf. Paragraph 2.5.3.3.2.2; The HoQ for the mapping between Customer Requirements (CR) and Key Product Characteristics (KPC) (HoQ1) can be applied during the present phase.
Failure Mode and Effect Analysis (FMEA)	Method to identify potential failure modes of a product or process and to classify every potential failure mode according to its severity, probability of occurrence and probability of detection before its occurrence [McDermott *et al.*, 2009].
External Functional Analysis	First step of the Functional Analysis as described in Paragraph 2.5.3.3.2.1 in order to define the required functions which the system or process has to perform in its environment.

4.3.3.1.3 Output of Phase 1

The Output of Phase 1 is a description of the business- as well as technical environment of the Application. The description should contain the Application's key interactions with the environment and Key Performance Parameters / Key Product Characteristics.

4.3.3.2 Phase 2: Definition of the Application and of Problems to Solve

The goal of this phase is to define and analyze the Application, i.e. the system or process into which a Technology shall be integrated, as well as the problems to which the Technology shall provide a solution.

4.3.3.2.1 Input of Phase 2

The output of the previous phase and the technical documentation of the Application as it is defined today serve as input for the present phase. Depending on the development state of the Application system that input can range from preliminary layouts (cf. Paragraph 2.5.2.2.4) to already established technical plans and parts lists.

4.3.3.2.2 Methods and Tools Applicable During Phase 2

During the present phase, methods and tools for the modeling of problems within systems can be applied. The identification of those problems can take place during Phase 2 or can be carried out based on the output of Phase 1, e.g. an FMEA. Some tools which are applicable during the present phase are given in Table 50.

Table 50: Exemplary list of methods and tools applicable during Phase 2

Method/Tool	Description
Technical Contradictions	Cf. Paragraph 2.5.3.3.3.4
Physical Contradictions	Cf. Paragraph 2.5.3.3.3.4
Closed World Method	Cf. Paragraph 2.5.3.3.3.5

4.3.3.2.3 Output of Phase 2

The output of Phase 2 is a description of the technical system or process as well as a description and modeling of the problem for which a Technology transfer shall provide a solution. A description of the Application system's components combined with a description of the Application's interaction with its environment (cf. Phase 1) can be used for Technology Integration Problem solving at later process steps (cf. Phase 7).

4.3.3.3 Phase 3: Definition of Application Properties

The goal of this phase the identification of the qualitative and quantitative Application Properties, i.e., the Application's

- Function Need (N_A)
- Potential Technology Side Effect Resistance (R_A)
- Resource Potential (P_A) and
- Risk of Affecting Technology (A_A).

4.3.3.3.1 Input of Phase 3

The inputs of Phase 3 are the descriptions and models of the technological problems which shall be solved by the technology integration. Those problems can take the form of e.g. a specific functional requirement or the solving of a contradiction (in terms of TRIZ).

4.3.3.3.2 Methods and Tools Applicable During Phase 3

The methods and tools which can be applied during this step are based on models and ontologies which help translating and mapping functional requirements into physical behavior and finally into concrete structures or effects (cf. Paragraphs 2.5.2.2.3, 2.5.3.3.2.2, 2.5.3.1.3.6 and 2.5.6.2.1). Whereas the origins of some of those methods lie in TRIZ and its derivatives (Smart Little Dwarves, Magic Particles Approach), others do not (Idea-Inspire [Chakrabarti *et al.* 2005], Quality Function Deployment HoQ2). Some of those methods and tools are listed in Table 51.

Table 51: Exemplary list of methods and tools applicable during Phase 3

Method/Tool	Description
Smart Little Dwarves/ Magic Particles	Cf. Paragraph 2.5.3.3.3.6
Quality Function Deployment (HoQ2)	Cf. Paragraph 2.5.3.3.2.2; The HoQ for the mapping between Key Product Characteristics (KPC) and Functional Requirements (FR) (HoQ2) can be applied during the present phase.
Idea Inspire	Computational tool based on the SAPPhire Model [Chakrabarti *et al.*, 2005] which models causal links between actions of a system, state (changes), physical phenomena, physical effects and organs.

4.3.3.3.3 Output of Phase 3

A list of qualitatively and quantitatively documented Application Properties represents the output of Phase 3. The documentation includes the Application's functional requirements and, depending on the applied method and underlying model, the required effects which could eventually lead to the satisfaction of the functional requirements. Furthermore, the available resources within the Application which could be used in order to realize the integration of a Technology are listed. The documentation also includes information about physical conditions within the Application and its environment which could interfere with the functioning of a Technology. Finally the Application's resistance against eventual harmful physical effects is documented qualitatively and quantitatively.

4.3.3.4 Phase 4: Identification of Potential Technologies

The goal of this phase is the identification of Technologies which bear the potential to solve the previously identified problems (Phase 2) and which fit best the Application Properties which were identified in Phase 3. The search should take into account all technologies irrespective of their domain of origin.

4.3.3.4.1 Input of Phase 4

The input of Phase 4 is the qualitative and quantitative documentation of the Application Properties. The search for Technologies *a priori* capable of solving the problem which was identified in Phase 2 is principally carried out based on the Function Need which were identified in Phase 3. In a similar logic, the remaining Application Properties Potential Technology Side Effect Resistance, Resource Potential and Risk of Affecting Technology can also be used during the search process.

4.3.3.4.2 Methods and Tools Applicable During Phase 4

Various approaches exist for supporting the identification of *a priori* suitable Technologies. Whereas some approaches are based on TRIZ and implement certain associated models [e.g. Yan *et al.*, 2014] others have no direct link to the TRIZ complex. In any case, the usage of methods or tools based on TRIZ models during Phase 4 is not mandatory as already the list of the Application Properties was established using TRIZ axioms. Some of the approaches which are applicable here are implemented in software tools. A small subset of those tools is listed in Table 52.

Table 52: Exemplary list of tools applicable during Phase 4

Method/Tool	Description
AskNature	Online database storing around 1,800 principles which are found to work in living organisms. Those principles can be used to infer solutions to design and engineering problems. The database consists of chapters in which a biological principle is presented in its application context. The different principles can be retrieved using a function-oriented inquiry [Deldin and Schuknecht, 2014].
Expernova™	Search engine mining around 40,000,000 patents and 30,000,000 research works filed in Europe, North America and Asia. The search engine accesses databases of e.g. research institutes, national research associations, universities and patent offices. In contrast to AskNature, the content of the recommended documents is not further processed [Expernova, 2014].
KOMPAT™	Tool for the automatic generation of inquiries for the Wipo patent database. The tool, which is based on the KOM [Montecchi and Russo, 2012] and hence implements contradiction-modeling, combines semantic analysis with a thesaurus and thus allows the automatic identification of *synonyms*, *hyponyms*, *hypernyms*, *meronyms*, *holonyms* and *troponyms* while generating search inquiries. The verb-object-optional-object ontology supports function based patent mining.

4.3.3.4.3 Output of Phase 4

The output of this phase is a list of potential Technologies, physical effects or working principles which are *a priori* capable of satisfying the Application's Function Need (N_A) as it was identified in Phase 3 (and eventually also fit the remaining Application Properties). The list shall contain the specific Function Need to which the Technology relates, its domain of origin as well as boundary conditions applicable in that domain. It is nevertheless suggested to reformulate the description of the Technology, its useful effect and the boundary conditions in generic terms in order to remove communication barriers which are suspected to interfere with successful technology transfer (cf. Paragraph 2.2.7).

4.3.3.5 Phase 5: Evaluation and Selection of Potential Technologies

The goal of Phase 5 is to obtain a short list of Technologies which are considered to have the highest potential to solve the Application Problem identified in Phase 2. The potential of the Technologies is a function of the accordance between Technology Properties and Application Properties. That means that a Technology has a high potential to solve the Application Problem if

- Its Function Potential is likely to satisfy the Application's Function Need ($P_T \geq N_A$)
- The Application is likely to resist the Technology's negative side effects ($A_T \leq R_A$)
- The Technology is likely to function properly by using the resources available at the Application ($N_T \leq R_A$)
- The Technology is likely to resist the negative side effects present in the Application ($R_T \geq A_A$).

4.3.3.5.1 Input of Phase 5

The input of this phase is the previously identified Application Problem as well as the list of potential Technologies which were identified in Phase 4.

4.3.3.5.2 Methods and Tools Applicable During Phase 5

Basically, different metrics can be applied in order to evaluate the suitability of potential Technologies to solve the Application Problem. However, a score which combines the accordance between the respective Technology and the Application seems most appropriate and opportunist. The following Ideality Score S_I is one suggestion for such a combination.
The formula to calculate the *Ideality Score* S_I[14] reads as follows:

$$S_I = C_{ITI} * (C_{ATS} + C_{IRF} + C_{AAS}) \qquad (5)$$

$$C_{ITI} = C_F * C_O \qquad (6)$$

$$C_{ATS}, C_{IRF}, C_{AAS}, C_F, C_O \in \{0,1,2\}$$

[14] C_{ITI} describes the degree to which the Technology's P_T corresponds to the Application's N_A. The term is a product of C_F, i.e. the correspondence between the action performed by the Technology and the action required by the Application, and C_O, i.e. the correspondence between the object of the action required by the Application and the object of the action normally performed by the Technology. Similarly, C_{ITI} refers to the correspondence between the Technology's A_T and the Application's R_A, C_{IRF} relates to the correspondence between the Technology's N_T and the Application's P_A and finally C_{AAS} points to the correspondence between the Technology's R_T and the Application's A_A. The values which the different terms can accept range from *0*, if there is no correspondence, to *2*, if there is a strong correspondence.

4.3.3.5.3 Output of Phase 5

The output of Phase 5 is a short list of Technologies the integration of which would most suitably solve the Application Problem which was identified in Phase 2. For each Technology, a Technology Sheet can be established which contains the respective Technology Properties, i.e. the Technology's

- Function Potential (P_T)
- Risk of Affecting the Application (A_T)
- Resource Need to Function Properly (N_T)
- Application Side Effect Resistance (R_T).

4.3.3.6 Phase 6: Identification of Technology Integration Problems

The systematic identification of Technology Integration Problems (TIP) is the goal of Phase 6. Problems which avoid the resolution of the Application Problem by a specific Technology or which avoid the Integration of the Technology into the Application are examples for TIPs.

4.3.3.6.1 Input of Phase 6

The input of this phase consists of the qualitative and quantitative description of the Application Properties as established during Phase 3. Further, the short list of the most suitable Technologies and the corresponding Technology Sheets is used for this phase. Depending on the available time and financial constraints, additional input can be generated by interviews of experts in the domain of the respective Technologies, detailed literature review, domain conferences, etc.

4.3.3.6.2 Methods and Tools Applicable During Phase 6

Different problem identification, problem analysis and modeling methods and tools are applicable during this phase. An exemplary subset of those methods is given in Table 53. However, the present meta-model provides a specific framework for the identification and categorization of Technology Integration Problems (cf. Paragraph 4.3.2.5). This framework consists of four types of problems which all can be modeled as a misalignment between Application Properties and Technology Properties:

- Insufficient Technology Interactions (ITI) consist of a misalignment between the Application's Function Need (N_A) and the Technology's Function Potential (P_T).
- Detrimental Technology Side Effects (DTS) relate to a misalignment between the Application's capacity to resist Technology side effects (R_A) and the risk that the Technology will cause those side effects (A_T).
- Insufficient Resources for Technology functioning (IRF) point toward a misalignment between the Application's potential to provide resources in terms of space, time, material, energy, etc. (P_A) and the Technology's requirements in this regard in order to function properly (N_T).
- Detrimental Application Side Effects (DAS) cover misalignments between negative side effects generated at the Application (A_A) and the capacity of the Technology to resist those effects (R_T).

Table 53: Exemplary list of methods and tools applicable during Phase 6

Method/Tool	Description
Technical Contradictions	Cf. Paragraph 2.5.3.3.3.4
Physical Contradictions	Cf. Paragraph 2.5.3.3.3.4
Su-Field Analysis	Cf. Paragraph 2.5.3.3.3.5
Closed World Method	Cf. Paragraph 2.5.3.3.3.5

4.3.3.6.3 Output of Phase 6

The output of Phase 6 is a list of Technology Integration Problems for each analyzed Technology. In those lists, the TIPs are categorized according to the above mentioned classification. Moreover, depending on the applied problem modeling techniques, a set of further problem models can be an additional output.

4.3.3.7 Phase 7: Technology Integration Problem Solving

The goal of the last phase is the generation of solution concepts to the Technology Integration Problems which were identified during Phase 6. According to the Technology Integration Meta-Model presented previously, solutions can be generated following two Generic Strategies:

- The Technology and consequently the Technology Properties are modified in order to better fit the Application Properties.
- The Application and consequently the Application Properties are modified in order to better fit the Technology Properties.

In addition, both Generic Strategies can be applied jointly. That means that both the Technology and the Application are modified in order to align Technology and Application Properties.

4.3.3.7.1 Input of Phase 7

All the previously generated outputs serve as inputs for the present phase. The Technology Integration Problems which are subject of Phase 7 are taken from Phase 6. Eventual modifications of the Application require the Outputs of Phases 1 to 3. Likewise, eventual modifications of the respective Technologies require the Outputs of Phases 4 to 5. Moreover, input from experts in the domains in which the Technologies are rooted is desirable.

4.3.3.7.2 Methods and Tools Applicable During Phase 7

A large set of problem solving techniques and tools is applicable during Phase 7. Depending on the Generic Strategies followed at that phase, the problem solving methods have their origins in different disciplines. As the set of techniques used in different natural science disciplines is as large as it is diverse, no examples for those approaches are given here. Hence, Table 54 gives only examples for methods or heuristics (the latter of which should be used as a function of previously established problem models) which have been briefly introduced in Chapter 2.5. It shall be emphasized that the problem solving process can also be carried out using intuitive problem solving techniques like Brainstorming, provided that relevant domain knowledge is available.

Table 54: Exemplary list of methods and tools applicable during Phase 7

Method/Tool	Description
Brainstorming	Cf. Paragraph 2.5.3.2.1
Morphological Analysis	Cf. Paragraph 2.5.3.2.2
Method 635	Cf. Paragraph 2.5.3.2.3
Physical Contradictions	Cf. Paragraph 2.5.3.3.3.4
Su-Field Analysis	Cf. Paragraph 2.5.3.3.3.5
Closed World Approach	Cf. Paragraph 2.5.3.3.3.5
Separation Principles	Cf. Paragraph 2.5.4.2.1
Standard Solutions	Cf. Paragraph 2.5.4.2.2
Solution Operators	Cf. Paragraph 2.5.4.2

4.3.3.7.3 Using the Dyadic Logic of the Presented Approach

The dyadic nature of the presented approach leads to a representation of each Technology Integration Problem as a misalignment between a specific Application Property and a corresponding Technology Property. Besides the integration of the dialectical principles of TRIZ, such a representation offers three main approaches towards the solution of the respective modeled integration problem (cf. Paragraph 4.3.3.7).

First, experts in the domain of origin of the Technology can attempt to solve the problem of modifying the specific Technology Property (P_T, A_T, N_T, R_T). In order to do so they can apply problem solving methods and heuristics which have proven successful in their domain. From an Application point of view, such an approach should be carried out first. The reason for this is that the resolution of the TIP by modifying only the Technology and keeping the Application invariant approaches the Technology to the Ideal Technology (I_T) (cf. Paragraph 4.3.2.4) and hence satisfies the second Evolution Law of TRIZ.

If the modification of the Technology in order to fit the Application's Properties is not successful – or cannot be carried out – an attempt can be made to solve the TIP by modifying the Application Properties (N_A, R_A, P_A, A_A) in order to make them fit the current Technology Properties. Modifications of the latter properties bear the risk of alterations of the Application's Key Performance Parameters or Key Product Characteristics. This is why the second approach satisfies the second TRIZ Evolution Law only from a Technology perspective but not from an Application perspective.

The third approach consists of aligning Technology Properties and Application Properties in a joint problem solving process. Such a process can be performed during multidisciplinary creative problem solving sessions (cf. Case Study). During those sessions, in which experts of the Application- as well as of the Technology domain should participate, the application of progressive creativity methods (cf. Paragraph 2.5.3.2.3) seems appropriate. Those methods were found to give the problem solvers of both domains the opportunity to apply domain specific strategies without being exposed to immediate criticism from other participants (cf. Paragraph 2.3.4.3.1).

4.3.3.7.4 Output of Phase 7

The output of Phase 7 and thus of the Technology Search and Integration Process is a list of inventive solution concepts to a previously established list of Technology Integration Problems. The concepts are categorized into either

- Modifications of the Technology to integrate into the Application
- Modifications of the Application in order to make the integration of the Technology successful or
- Joint modifications of both the Technology and the Application.

For each solution concept generated during Phase 7, eventually associated secondary problems as well as required knowledge are documented.
The output of Phase 7 serves as input for further product or process development stages which are described elsewhere in the literature [e.g. Suh, 2001; Pahl *et al.*, 2007].

4.3.4 Meta-Model Application

The presented meta-model for the integration of a technology into a specific application (cf. Paragraph 4.3.2) and the associated process (cf. Paragraph 4.3.3) have been tested in an industrial field study. This study will be presented in the following chapter. Because of reasons of confidentiality, the exact topic of the study as well as the exact results cannot be revealed. Instead, generic terms will be used whenever possible and specific terms will be mentioned only when necessary.

4.3.4.1 Industrial Context

The industrial partner for this field study was SKF (Svenska Kullagerfabriken) AB, a Swedish-based manufacturer of roller bearings in the premium segment. The partner department was the unit which is responsible for standard deep groove ball bearings (DGBB) and self-aligning ball bearings (SABB) for industrial applications at Saint Cyr (France).
SKF has been applying several product development and quality management methodologies since 1990. Especially the *Six Sigma* and *Design for Six Sigma* (*DFSS*) toolsets [see Staudter *et al.*, 2013 for an overview] have being applied on more than 1000 projects by more than 20 ‘Master Black Belts’, 400 ‘Black Belts’ and 2100 ‘Green Belts’ as of 2011 [Johnstone, 2011].
The field study has been performed in cooperation with a DFSS Black Belt innovation manager and a DFSS Green Belt project manager (SKF development engineers), who had obtained a three-day training in creativity methods as well as in TRIZ and its derivatives. In the respective paragraphs will be highlighted which of the following actions were performed by the SKF development engineers and which were carried out by the author.

4.3.4.2 NCD/NPPD Context

The industrial field study relates to specific phases of an NPD process. This process was the result of a Front End Innovation (cf. Paragraph 2.5.2.2.5) study performed by A.I.M. on the topic of *innovation potential of DGBBs in the industrial sector* (cf. Project 3A in Chapter 5.3). Regarding the NPD process, the identification of Customer Attributes, the listing of Functional Requirements as well as, to a certain degree, the identification of Design Parameters are covered by the field study (Figure 60).

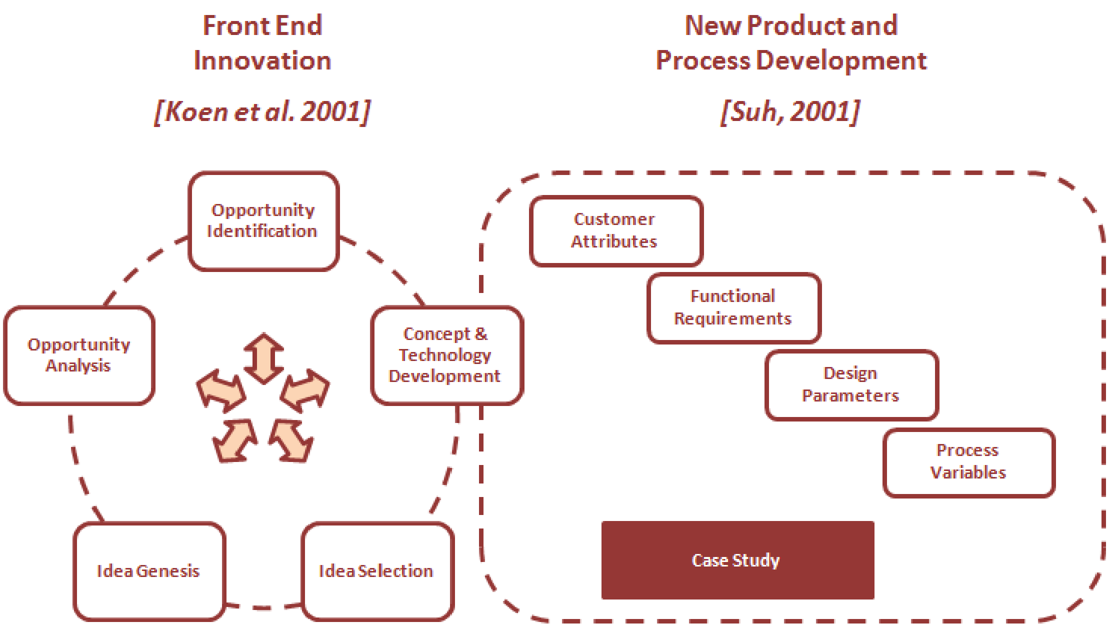


Figure 60: New Concept Development / New Product/Process Development context of Case Study

4.3.4.3 Technology Integration Process

4.3.4.3.1 Definition of Application Setting and Application Environment

The starting point of the study was the concept of a new *business model* (*BM*). It was the result of the previously mentioned Front End Innovation study and earlier considerations of SKF managers which have been confirmed by that study. The BM consists of a *value proposition* to the customer which is based on the *documentation of a set of physical parameters during several steps of the DGBB product life cycle*.

In order to identify key Customer Attributes (cf. Paragraph 2.5.2.2.3) and to further define the desired value proposition (1), a *RELEvent Analysis* (2) [Yezersky, 2006, 2008] has been performed. That analysis, which combines aspects of life cycle analyses, product use analyses, and product/process FMEAs, provided further insight into the Customer Attributes to satisfy.

Finally, the Application Setting and its constraints were defined using the Closed-World Approach (3) [Sickafus, 1997; cf. Paragraph 2.5.3.1.3.5].

Figure 61 sums up the Application Setting and Application Environment Definition step of the process.

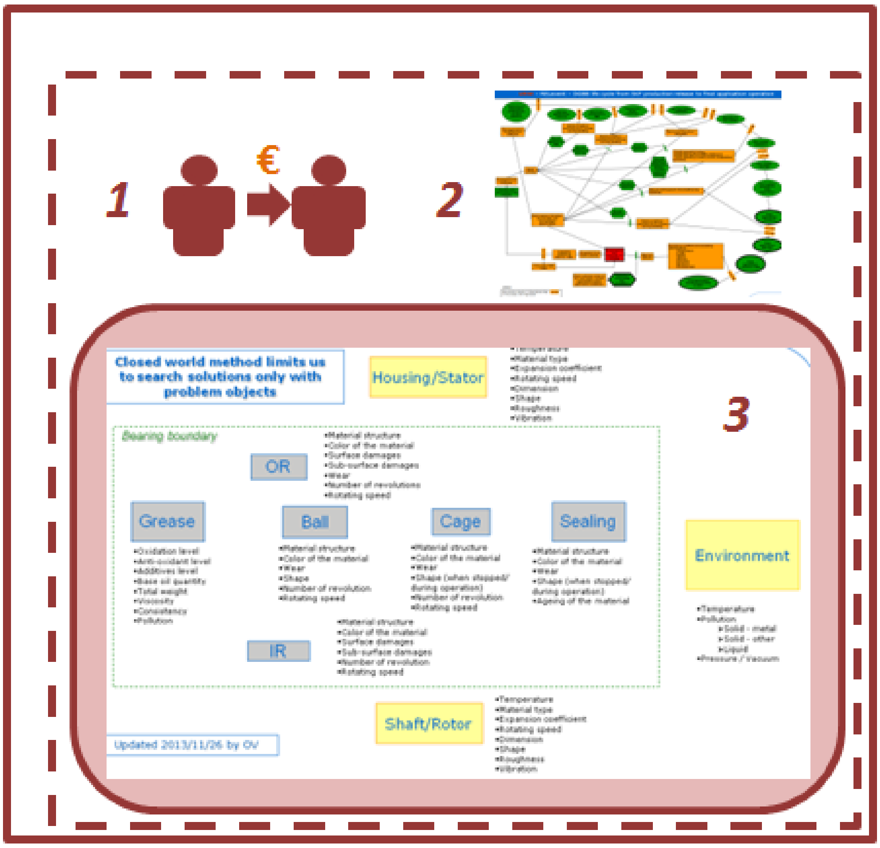


Figure 61: Schema of the definition of the Application Setting and -Environment

4.3.4.3.2 Definition of Application Properties N_A, R_A, P_A and A_A

The Customer Attributes obtained during the previous steps were further mapped onto Functional Requirements using the Magic-Particles Approach (4, 5) [Sickafus, 1997; cf. Paragraph 2.5.3.1.3.6] and, in a second step, the House of Quality of Quality Function Deployment (6) [Prasad, 1997; cf. Paragraph 2.5.3.1.2.2]. The Customer Attribute-Functional Requirement mapping was completed by data obtained from interviews with 12 SKF experts and partner experts. Once a list of Functional Requirements representing the Function Need of the Application (N_A) was established, the Application's Technology Side Effect Resistance (R_A), its Resource Potential (P_A) as well as its Risk of Affecting Technology (A_A) were defined in both qualitative and quantitative terms.

Figure 62 sums up the Attribute Property Definition step and Figure 63 schematizes the established lists of Application Properties.

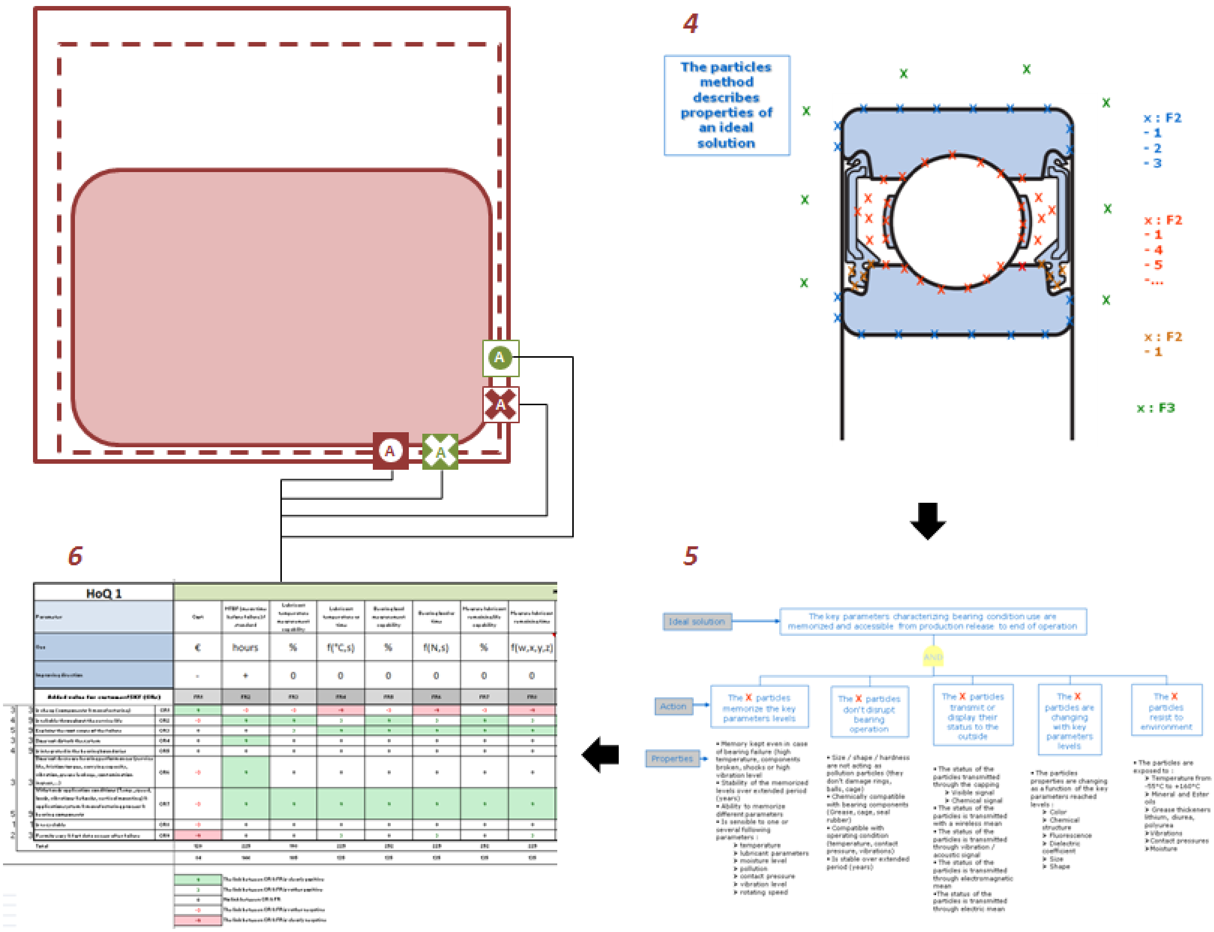


Figure 62: Schema of the definition of the Application Properties using Magic Particles Approach and Quality Function Deployment

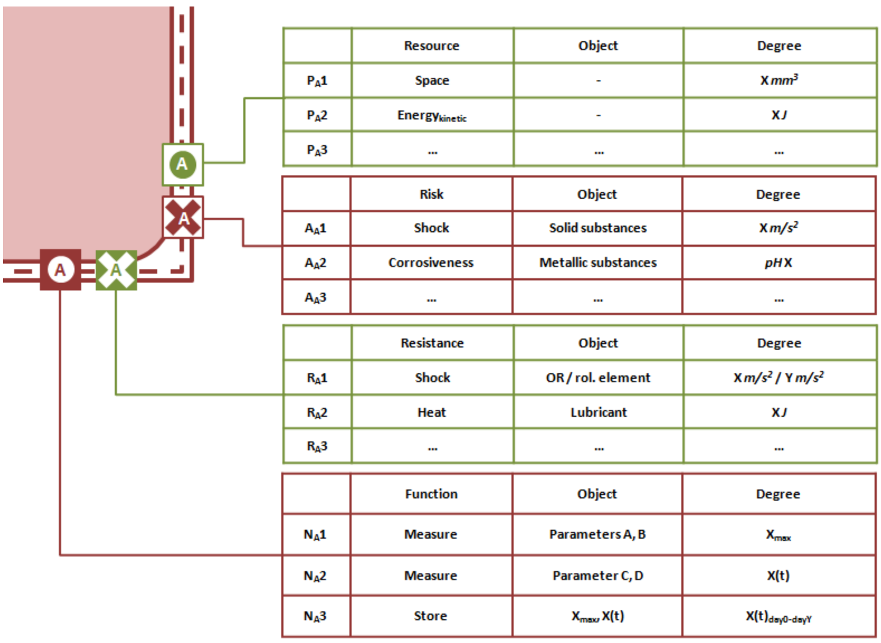


Figure 63: Schema of identified Application Properties

4.3.4.3.3 Identification of Potential Technologies

Based on the Function Need (N_A) of the Application, the author performed both a classical internet search and a thesaurus-based patent-, publication- and expert review using two types of software:

- The KOMPAT™ software was used in order to search for patents for technologies which could possibly satisfy the identified Function Need. The software uses a thesaurus [cf. Aufaure *et al.*, 2006 for a discussion] in order to generate homonyms to existing search terms and is supposed facilitate information retrieval also in distant knowledge domains. KOMPAT™ uses the taxonomy *Verb*Object(*Optional Object)* for the search process (Figure 64).
- The Expernova™ software was used in order to search for companies and research entities which bear potentially valuable knowledge for the satisfaction of the identified Function Need. The taxonomy *Verb*Object* was used for the search process in a database of scientific publications and patents (Figure 65).

The search performed in this manner yielded a total of 156 potential Technologies the Technology Fields of which ranged from mechanical engineering to medical technology, to geology and marine research. Figure 66 sums up the Potential Technology Identification step.

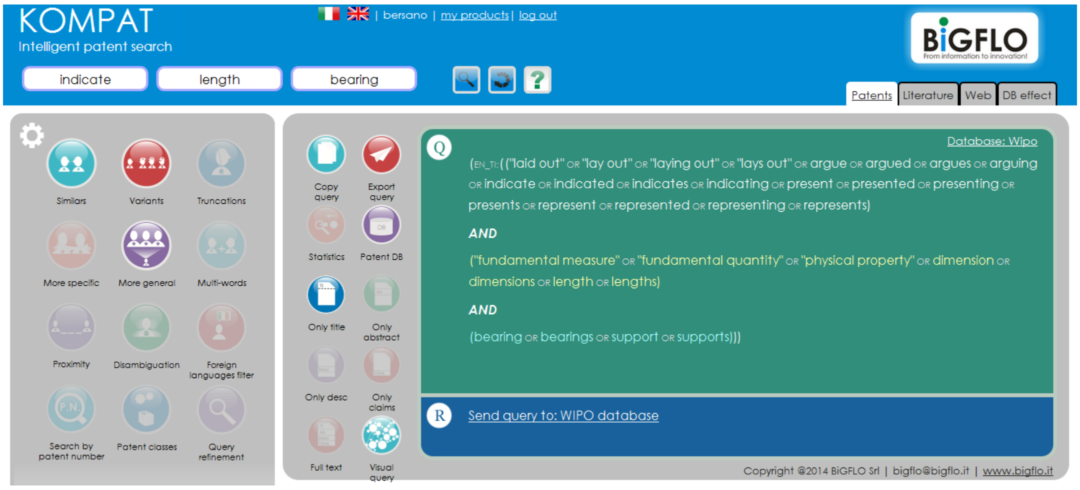


Figure 64: Graphic interface of KOMPAT™ software

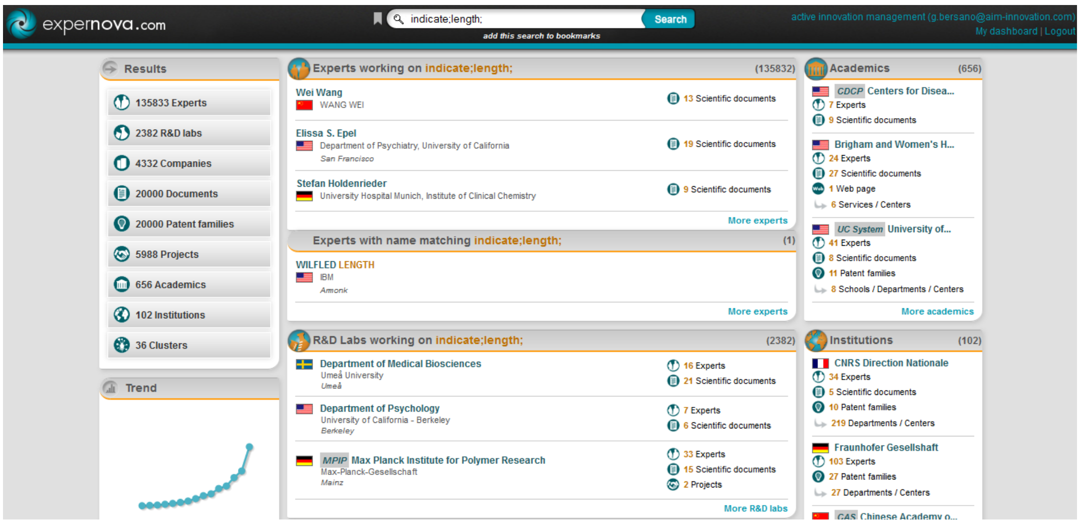


Figure 65: Graphic interface of Expernova™ software

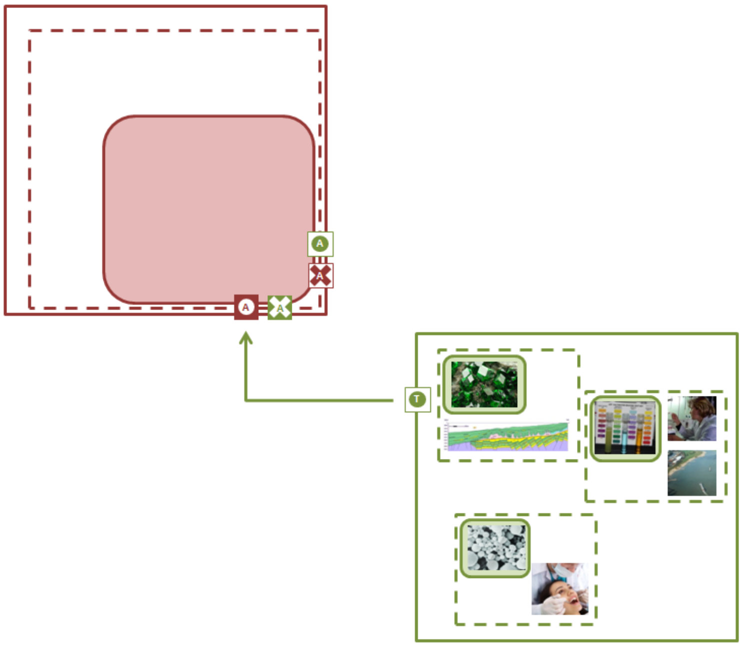


Figure 66: Schematic description of the set of candidate Technologies and their respective Technology environment

4.3.4.3.4 Evaluation and of Potential Technologies and Technology Selection

The 156 potential Technologies were then evaluated with regard to the degree to which they *a priori* suit the Application, i.e., the extent to which the Technologies correspond to the Ideal Technology (I_T) from the Application's perspective and vice versa (cf. Paragraph 4.3.2.4). The evaluation was performed based on the *Ideality Score* S_I presented in Paragraph 4.3.3.5.2.

The 57 technologies which reached a score of at least 12 where selected and presented to the product development engineers (Figure 67). The engineers selected 36 of the 57 Technologies for further investigation. Figure 68 sums up the Potential Technology Evaluation and Selection step.

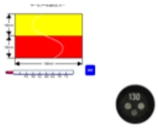
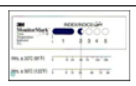
Search		Knowledge / Technology											
		Description						Proximity					
								UE					
Fct.	Obj.	Condit.	Reference	Knowledge Bearer	Typ.	Comments	Figures	F	O	R	H	N	F x O x (R+H+N)
F1	IR/OR/cage	-	www.bradyid.com: Temperature indicating labels	e.g. Brady	Co	< 180 °C		2	2	1	2	2	20
F1	IR/OR/cage	-	www.thermolabel.eu: Two stage reversible temperature indicating tape: P-5.7	e.g. Thermolabel	Co	activation temperature: < 130 °C		2	2	1	2	2	20
F1I	IR/OR/cage	low temperature	solutions.3m.com: time temperature indicating labels	e.g. 3M	Co	activation temperature: < 34 °C recoding time: 2 weeks		2	2	1	2	2	20
F2.1 F2.2 F2.3	grease	low temperature?	www.omega.com: Water quality test strips - pH - Iron - Copper - ...	e.g. Omega	Co	- test strips - low temperature applications - what components of grease indicate oxidation/grease quality		2	2	1	2	2	20

Figure 67: Extract of the presentation of the 57 technologies which was used for technology evaluation and choice (functions are replaced by generic terms for secrecy reasons)

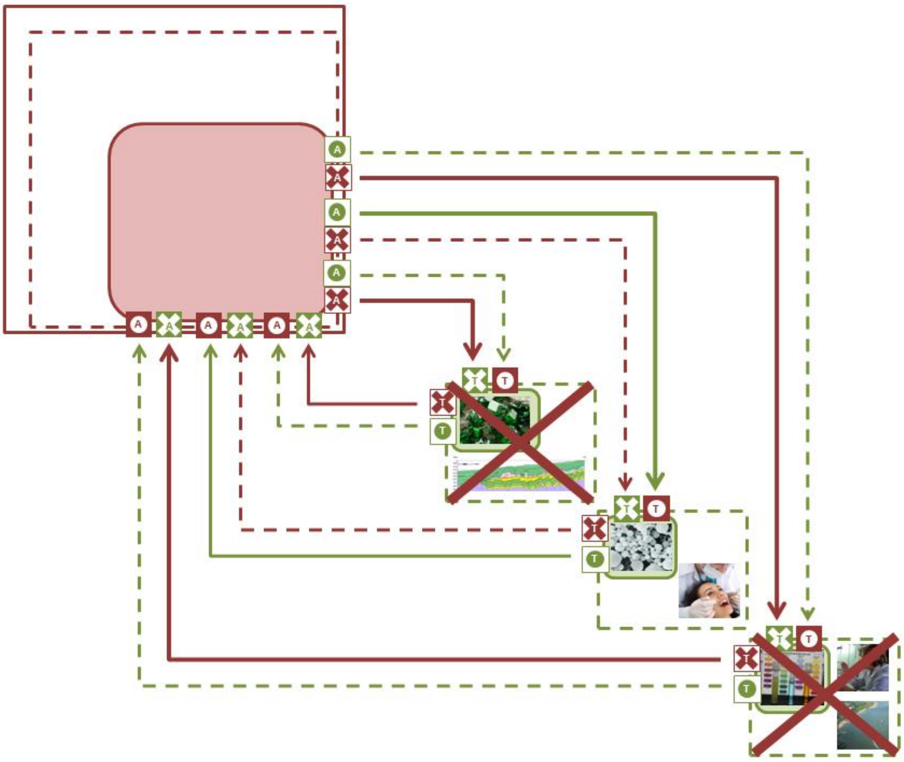


Figure 68: Schematic description of the process of Technology evaluation and choice depending on the correspondence between Technology and Application Properties

4.3.4.3.5 Technology Integration Problem Solving

The author then performed a literature review in order to obtain more detailed information about the Technologies which had been selected in the previous process step. A focus was set on the Technology Attributes in both qualitative and quantitative terms. It was also tried to contact experts in the respective Technology Environments. However, from 16 attempts to contact experts only four contacts could be established, which made direct information gathering impossible.

The results of the literature review were *Technology Sheets* which synthesize the Properties of every investigated Technology. Figure 69 gives some examples of the established Technology Sheets.

In order to integrate the identified Technology into the Application setting while assuring that the resulting system satisfies the highest amount of Functional Requirements and thus Customer Attributes, two group Technology Integration Problem Solving sessions were held. The processes and outcomes of these sessions will be discussed in the following paragraphs.

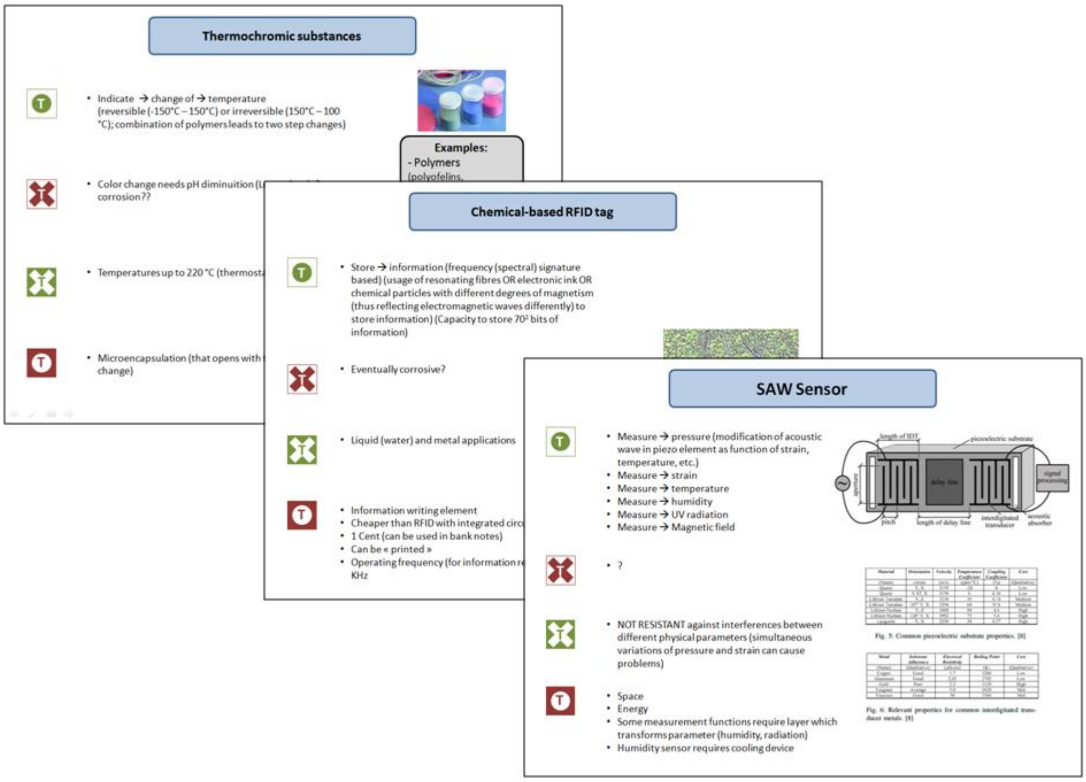


Figure 69: Examples of Technology Sheets for Technology Integration Problem solving

4.3.4.3.5.1 Brainstorming Workshop

The first Technology Integration workshop was a classical brainstorming session. It was facilitated by the two SKF development engineers and primarily used *Lateral Thinking* techniques like *Random Input* [De Bono, 1977] to stimulate creative outcome. Participants were SKF employees from several departments such as product design, manufacturing, application engineering, etc. Before the actual Brainstorming session, the facilitators introduced the project topic and the work which had been done so far without specifically introducing the *Technology Integration Meta-Model*. Then they presented the chosen potential Technologies. The Brainstorming workshop (BS) took 3.5 hours and dealt with the following three problems (Pb):

- BSPb1: How to satisfy N_A4: How to realize *Function 1* for all required *Parameters*?
- BSPb2: How to satisfy N_A5: How to realize *Function 1* for peak values and integrals of *f(t) over time* of *Parameter C*?
- BSPb2: How to satisfy N_A1-N_A5 using Technology *α:* How to realize *Functions 1* to *4* for *Parameters A* to *D* using *Technology α*?

4.3.4.3.5.2 Workshop on Technology Integration Problems

Contrary to the previous session, the second workshop explicitly took into account the *Technology Integration Meta-Model* and the resulting *Technology Integration Problem* Model. The participants of that workshop, which took two hours and which was facilitated by the author, were the two SKF development engineers. The session concentrated on how to satisfy all functional requirements which had been established beforehand using Technology α by overcoming the previously identified Technology Integration Problems. Hence, the problem statement read as follows:

TIPb: *How to solve the remaining Technology Integration Problems related to the Integration of Technology α into the Application System DGBB?*

During the problem solving session, each Technology Integration Problem (TIP) (1) was modeled using cardboard sheets. Figure 70 exemplifies the modeling of the TIP “How to realize the performance of Function 1 with respect to the Parameter A as function of time using Technology α?” (2). Then the Generic Strategies (3) were applied in order to solve each TIP. In order to support this inventive problem solving process, the participants were provided with three types of cardboard sheets. The first sheet represented the elements of the Application Setting as it had been modeled by the Closed World Method (cf. Paragraph 4.3.3.3.1) (4). The second sheet – the Technology Sheet for Technology α – presented some general information about that Technology as well as its Technology Attributes (5). The last set of sheets presented *Problem Solving Heuristics* which are used in TRIZ and derived methodology in order to solve such types of problems (6).

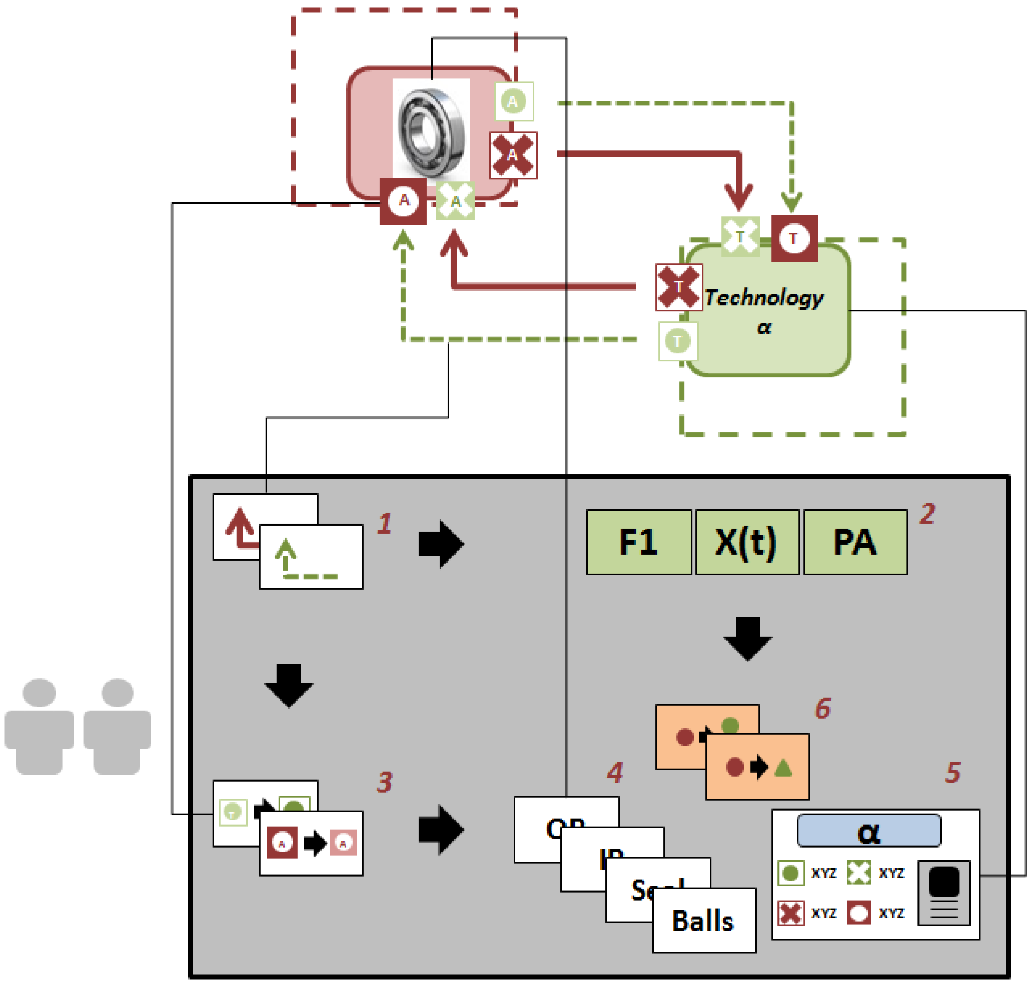


Figure 70: Schema of the Workshop on Technology Integration Problems and the provided methodological support

The products of the Technology Integration Problem solving session were documented on sticky notes. Distinction was made between Technology Integration Problems, suggested solutions to these TIPs, further knowledge which is required to better understand the problem or build on suggested solutions as well as problems emerging from those solutions. Figure 71 shows the production of the reasoning related to the solution of TIP *Insufficient Technology Interactions* (*ITI*) and *Insufficient Resources for Technology Functioning* (*IRF*).

Figure 71: One of the sheets which were used to document the products of the workshop on the solution of Technology Integration Problems and explanation of the different sticky notes; (a): TIPs; (b): solution concepts for TIPs; (c): required but missing knowledge; (d): subsequent problems associated to solution suggestions

4.3.5 Meta-Model Evaluation

In order to compare the presented meta-model for technology integration with existing methodological approaches, the participants of the Case Study, i.e. the SKF development engineers, were asked to evaluate the performance of the process and the associated tools against processes suggested and facilitated by DFSS. That evaluation will be discussed in the present chapter.

4.3.5.1 Evaluation Criteria

In order to evaluate the overall applied approach, the two participating engineers were asked to compare the performance of the approach with the performance of currently used methods on seven-point Likert-type scales in terms of the criteria. Those criteria, which are based on the work of Thiebaud [2003], are listed in Table 55.

The evaluation criteria are classified into four groups. The first group features two performance aspects which relate to the capacity of the approach to point to and deal with knowledge originating from other domains. The second evaluation class lists performance criteria which concern the diversity, originality and quality of the generated process outcome. The last two classes contain two respectively three criteria and relate to acceptability aspects of methods (cf. Chapter 2.5.7) like required resources for deployment or necessary effort for method understanding.

Table 55: Evaluation criteria and evaluation classes (based on [Thiebaud, 2003])

No.	Criterion	Abbreviation	Description	Evaluation class
1	Mechanism for quitting of domain of expertise	QDE	Does the method help the designer to consider other solutions than those linked to his/her domain of expertise?	Knowledge transfer related
2	Indication of missing knowledge	IMK	Does the method help to identify information/knowledge/capabilities which should be obtained in order to continue the development of the idea/solution?	
3	Originality of generated concepts	OGC	Does the method foster the generation of ideas which have not been generated before?	Concept quality related
4	Diversity of generated concepts	DGC	Does the method allow the generation of ideas which implement different know-how (or expertise) within the given boundaries of the problem (given application / given function to realize / given technology to use)?	
5	Elaboration level of generated concepts	ELGC	Does the method foster the combination of several solutions (or technologies) in order to come up with more sophisticated/improved ideas/solutions?	
6	Exploitability of generated concepts	EXGC	Are the generated solutions estimated to be worth further exploration and do they seem exploitable? / How big is the ratio of explorable and or exploitable ideas?	
7	Ease of workshop session preparation	EWP	How much time and what means are necessary in order to prepare a working session?	Resources related
8	Fluidity of concept generation	FCG	Does the method allow the quick generation of multiple ideas with respect to one topic (technology)?	
9	Process structure	PS	Does the method feature a process, an explicit logic for implementation?	Learning related
10	Ease of implementation	EI	Does the implementation of the method require sophisticated techniques?	
11	Ease of learning	EL	Does the initial understanding of the method require rather a few hours or rather several months?	

4.3.5.2 *Performance of Suggested Process*

The results of the evaluation are shown in Figure 72.

The presented approach was judged to be superior to current approaches in terms of knowledge transfer-related performance characteristics. The difference of the mean score in both criteria (QDE and IMK) was at least 2.5 points.

When it comes to the performance criteria related to the quality of the generated concepts, the results are somewhat mixed. The presented approach yields better results with regard to originality (OGC) and diversity (DGC) of generated concepts. However, the explorability of the concepts generated (EXGC) by the presented approach is only slightly better than the concept explorability which is normally provided by currently used approaches. In terms of concept elaboration level (ELGC), currently used approaches (the Hybridization of Pugh Matrix [cf. also Staudter *et al.*, 2013] was mentioned) were judged to provide slightly better results.

Already established approaches were estimated to require fewer resources in terms of time and auxiliary means for the preparation of creative problem solving workshops (EWP) than does the presented approach. The amount of time which is required for concept generation during the workshop (FCG) was estimated the same for both approaches.

Finally, the presented approach obtained slightly higher scores in learning related criteria. Compared to currently used methods, it was estimated to feature a more explicit logic and structure (PS). Further, the participating engineers found the applied approach to require less sophisticated tools or techniques than do currently used processes (EI). The time which is necessary in order to be able to successfully apply the method (EL) was considered to be equal for both approaches.

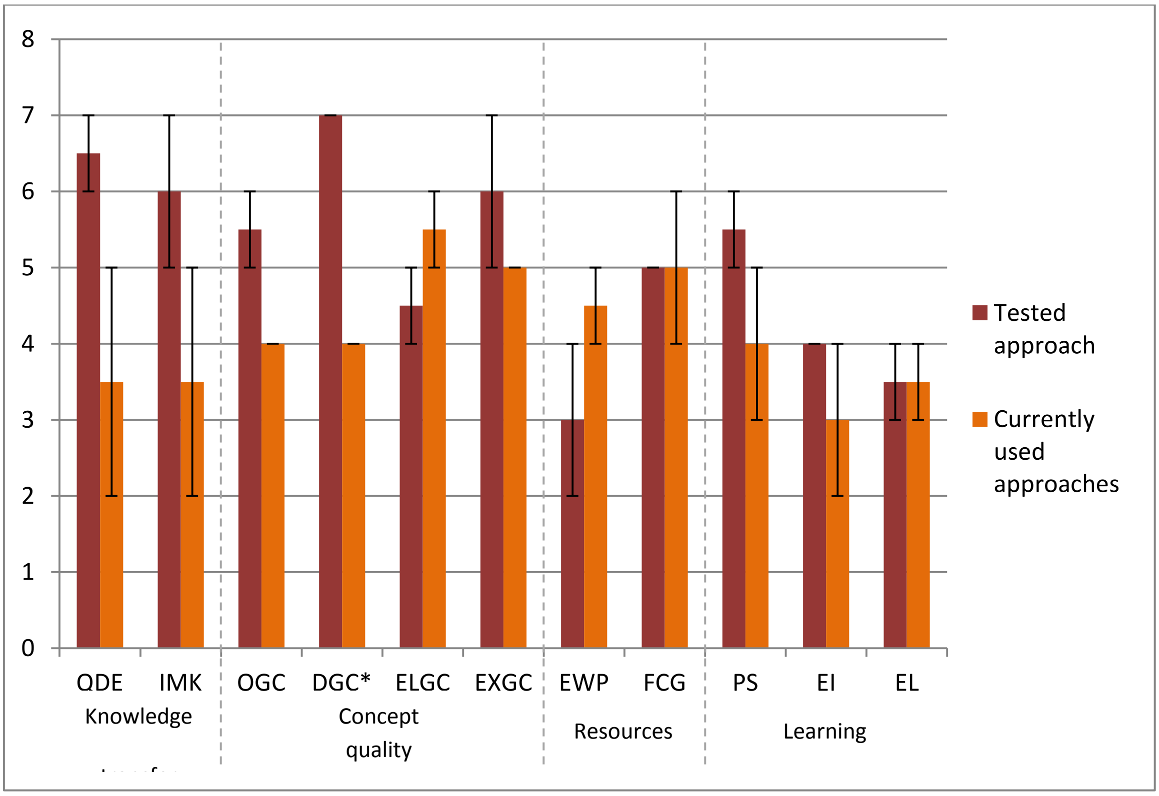


Figure 72: Comparison of tested and currently used approaches (DFSS); *: evaluation by DFSS Black Belt only

4.3.6 Discussion

The results of the *Case Study* will be discussed both with regard to Hypothesis 3 in particular and in more general terms in this chapter.

4.3.6.1 Discussion with Respect to Hypothesis 3

Hypothesis 3 postulates a value of the axioms and methods of TRIZ and its derivatives for the evaluation and the integration of knowledge intensive technologies in order to solve problems in industrial NPPD processes.

In order to test that hypothesis, those axioms and methods of TRIZ and its derivatives which have been found to be the most accepted and applied during the Experiment were integrated into a meta-model for technology search and integration. That meta-model was then tested in an industrial case study.

Against the background of *Hypothesis 3*, especially the knowledge transfer related and concept quality related performance criteria are of interest.

The former indicate to what degree the presented approach and the implemented TRIZ-based elements lead to the consideration of distant knowledge spaces and to reasoning within those spaces. The latter provide, to some extent, insight into the effectiveness of the TRIZ axioms and methods when it comes to the integration of knowledge into problem solving concepts.

As mentioned in Paragraph 4.3.3.4.2, the presented approach was found to exhibit advantages with regard to knowledge transfer-related criteria. Further the tested approach was found to lead to more original and diversified concepts than do currently used approaches, whereas the performance of both approaches is somewhat comparable in terms of concept elaboration level and concept explorability.

Those results provide first indications that the presented meta-model and the associated methods might actually represent a useful approach for supporting the search and the evaluation of knowledge-intensive technologies as well as for the integration of the latter in order to solve NPPD problems.

However, due to several limitations of the case study setup – the approach could be tested in only one industrial case study and only two participants evaluated the approach – *Hypothesis 3* cannot be validated with statistical certitude. In order to do so, more quantitative studies which should cover a broader spectrum of application domains should be conducted.

4.3.6.2 Further Discussion

During the development of the presented meta-model and the associated process, a focus was set on the simplicity and adaptability of the approach as well as on limited time requirements for the participants in order to be able to successfully apply the approach.

The participating engineers estimated the preparation of a problem solving session in the presented approach to require more effort (EWP) than in the case of currently used approaches. It could be argued that the additional effort was due to another, only indirectly approach-related aspect. In fact, the inquiries which had to be performed in order to obtain missing information and knowledge – which, in turn, had been identified during the process (cf. Paragraph 4.3.3.3.4) – were time consuming. In that sense, the additional effort would be a price to pay in order to present and deal with more and more distant domain knowledge during the problem solving sessions.

Further, the tested process was judged to be more structured than currently used approaches and to provide a more explicit logic which improves the chance of a correct implementation. That result is interpreted as an indication that the presented approach, at least to some degree, represents a step forward towards more pedagogical knowledge integration strategies.

4.3.7 Limitations of the Case Study

The presented case study has several limitations, most of which are due to the chosen test method. While an industrial case study has several advantages such as

- *Real world problems* and *topics* which are treated against the background of *real industrial projects*;
- *Participation of experts* – in the case of this case study expert project and innovation managers with considerable methodological experience – and;
- *Time* and *financial resources* which largely exceed those of laboratory experiments,

that method also has drawbacks which translate into

- *Limitation of the number of analyzable processes* to $n = 1$, which makes statistical comparisons impossible: The case study featured only one single industrial NPD process and tested the presented approach against the background of that one project only. In order to provide more reliable results, further case studies and/or laboratory experiments with a higher number of participants are necessary.
- *Limited number of participants* ($n = 2$), which makes statistically significant comparisons difficult: As only two engineers were involved in the conduction of the project, only those two participants were capable of giving reliable feedback on methodological performance. Laboratory experiments or larger industrial case studies are necessary in order to compare two well defined sets of methods and in order to assess in more detail advantages and drawbacks of those methodological sets.
- *Participants who do not satisfy all requirements*: On the one hand the methodological training of the participating engineers was important in order to ensure a qualified and quick execution of the project. Further, their methodological background allowed them to compare the tested approach to a wider set of methods which are currently applied at SKF for similar purposes. On the other hand, however, the present case study does not provide any evidence into the appropriateness of the presented approach for an application by less trained and thus less inclined engineers.
- *Lack of participants with distant domain expertise*: Even though it was initially planned to integrate experts in the domain of origin of the candidate technologies in the creative problem solving process, such integration was not possible. As reasons for that can be mentioned issues related to intellectual property and lack of interest from the expert side.
- *Secrecy agreements, which prohibit the presentation of sensible results such as detailed information on investigated technologies and generated concepts*: As the case study investigated a project which is sought to generate customer value in a highly competitive industrial domain, unfortunately no detailed information can be given on the investigated technologies and knowledge domains, on the functions which those technologies shall perform as well as on the output of the investigated process in terms of concepts and perspectives. As a consequence, the presented meta-model of knowledge integration cannot be compared to usual approaches by a detailed comparison of generated concepts and ideas.
- *Project time frames which make an evaluation of results impossible both in managerial as well as in economic terms*: At the moment of writing this report, the investigated project is not finished yet. As further conduction of this project is associated with major costs, which are also due to the knowledge-intensive nature of the treated technologies, such decision making is not supposed to take place in near future. Hence, even though two non-disclosure agreements have been signed with to potential technology providers following

this case study, no additional information on the industrial and economic success of the investigated project can be given in the medium term.

Especially the limited numbers of analyzed processes and of participants reduce significantly the statistical value of the presented case study and have as consequence that Hypothesis 3 cannot be validated today.

4.3.8 Conclusion of Case Study

The case study presented in this chapter investigated the value of certain axioms and methods of TRIZ and its derivatives for the process of technology search evaluation and integration. It tested a descriptive and prescriptive meta-model and the associated process which cover the above-mentioned activities in a New Product Development context in the roller bearing industry.

The tested process was applied by two engineers and with support of the author in order to identify customer needs, to establish a value proposition, to translate this value proposition into customer requirements, and further into Functional Requirements. Then the meta-model was used in order to identify candidate technologies which are able to perform the required functions, while at the same time satisfying other criteria like e.g. limited resource requirements. Finally, the meta-model and the associated methodology were used in order to solve remaining problems related to the integration of chosen candidate technologies in creative problem solving sessions. The tested process and the associated methods were then evaluated against processes and methods which are normally used in the participating company.

The analysis of the case study points towards advantages of the tested approach when it comes to processing and integration of distant domain knowledge and technologies and to diversity and originality of generated concepts. However, the tested approach obtained slightly inferior evaluation scores with regard to necessary effort for workshop preparation.

The industrial case study and hence the application of the *Technology Integration Meta-Model* induced further open innovation related activities at SKF, which can be considered as indicator for the success of the project. Nevertheless, in order to statistically confirm the results of the *Case Study* and thus to be able to validate *Hypothesis 3*, further research is required.

4.4 Conclusion of Hypotheses Testing

The experiments reported in this subsection were designed in order to investigate the research question: How to support the process of search for as well as evaluation and integration of knowledge and technologies originating from knowledge-intensive and science-related domains in the context of NCD and NPPD processes? From this research question were derived three hypotheses.

Hypothesis 1 postulated an impact of disciplinary group composition on the creative group problem solving process and its outcome. *Hypothesis 2* suggested that the methods chosen to support interdisciplinary group problem solving also had significant influence on the problem solving process and its outcome. In order to test those hypotheses, an *Experiment* compared the problem solving attempts of monodisciplinary groups with those of interdisciplinary teams. Further, the experiment measured the differences which arise from the use of pragmatic intuitive methods like Brainstorming compared to hierarchical analytical approaches like TRIZ and USIT. Besides the partial validation of both hypotheses, the experiment provided detailed insight into the advantages and drawbacks of the different methodological approaches for mono- and interdisciplinary group problem solving.

Hypothesis 3 postulated the possibility to integrate main concepts of TRIZ and USIT theory and methodology into a meta-model for the integration of a technology into a given problem setting. The given meta-model, which is presented in this subsection was tested in an industrial *Case Study* and evaluated against existing approaches by methodologically experienced engineers. The results of the evaluation point towards benefits of the presented meta-model in terms of both knowledge transfer facilitation and concept quality. As the *Case Study* represents one singular test, a validation of the *Technology Integration Meta-Model* and thus of *Hypothesis 3* still requires further and more quantitative analyses.

5 Contributions

Academic as well as industrial contributions which are the result of the performed research and development activities within the framework of this research will be discussed in the present subsection.

5.1 Overview of Academic and Industrial Contributions

Both academic and industrial contributions are reported in the present section. The former refer to insight into creative processes in groups, to the development of a meta-model for the search and integration of technologies in NCD/NPPD processes, as well as to the application of existing design methods on non-technical systems. As such, academic contributions are the result of the *Experiment*, the *Case Study* (Figure 73) and other, mainly project-related, activities (e.g. MoNTS).

Industrial contributions consist in methodological approaches combining existing design and management methods for the support of industrial NCD/NPPD processes (Projects 1, 2, 3A, 3B of Figure 73). A further contribution is the development of a process and training for problem modeling and problem formulation in order to foster Open Innovation processes in the pharmaceutical industry (Project 4 of Figure 73).

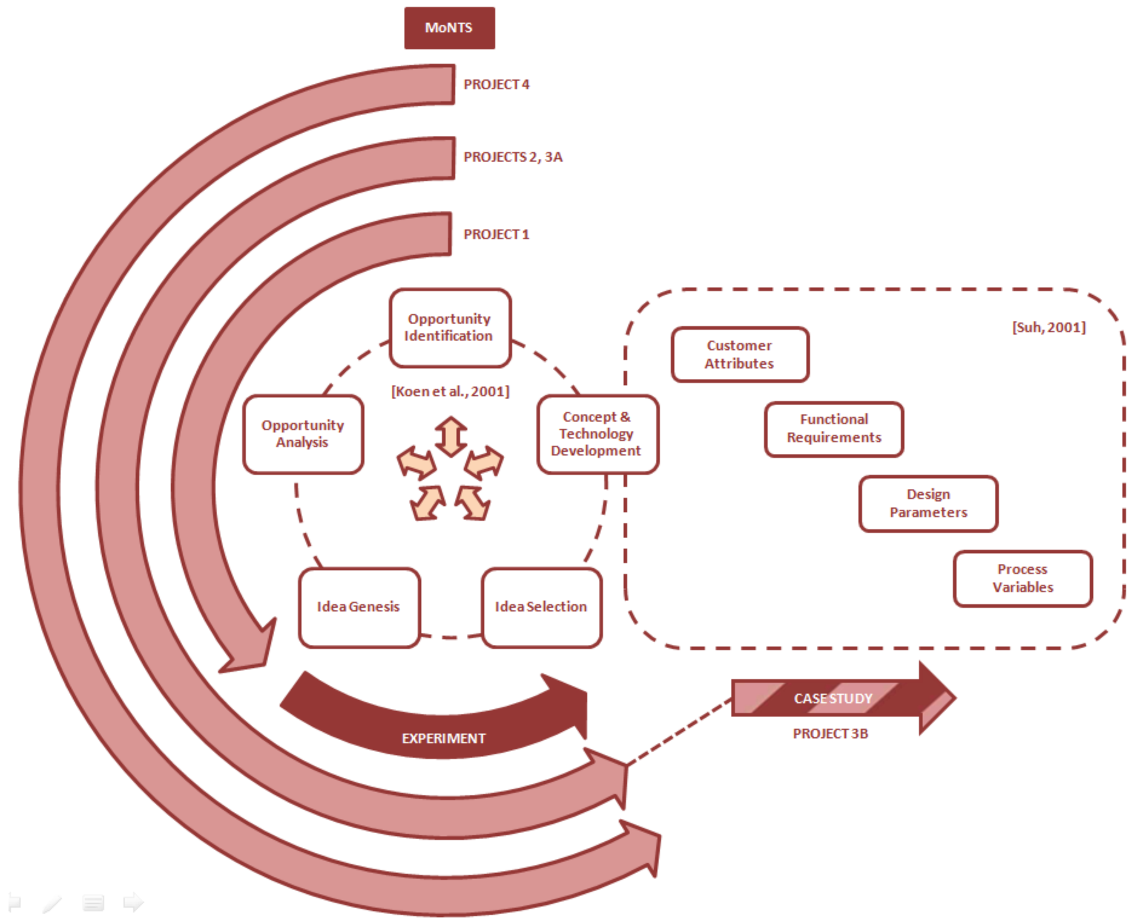


Figure 73: Overview of academic and industrial contributions against the background of industrial NCD/NPPD processes

5.2 Academic Contributions

The academic contributions are essentially results of the *Experiment* and the *Case Study* and will be summed up in this chapter (cf. also Figure 74). Those contributions relate to

- The impact of group composition and methods on group creativity (cf. Chapter 5.2.1)
- The comparison of methodological approaches (cf. Chapter 5.2.2)
- The meta-model and related methods for technology search and integration (cf. Chapter 5.2.3)
- The modeling of activity in natural science and of non-technical systems using design theory (cf. Chapter 5.2.4)

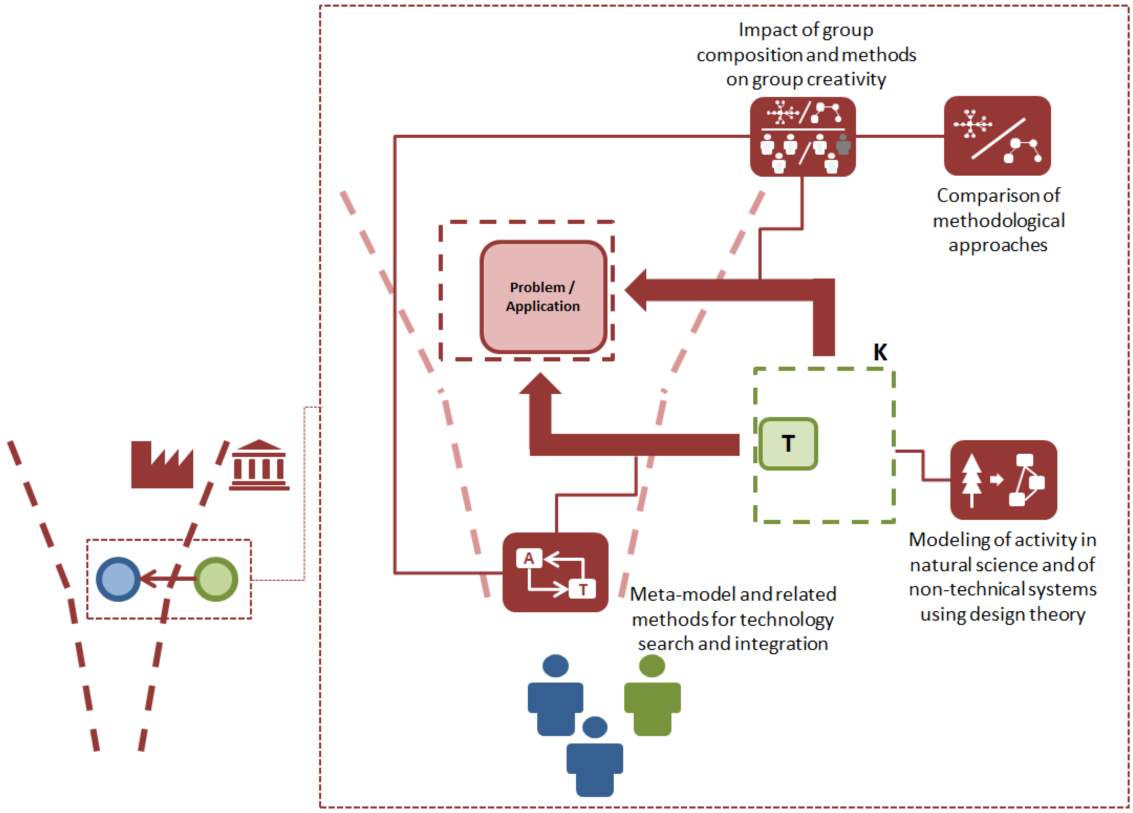


Figure 74: Academic contributions in the context of knowledge- and technology transfer

5.2.1 Impact of Group Composition and Methods on Group Creativity

The *Experiment* provides insight into the impact of disciplinary (engineering design – life science) group composition and of methodological support on the process of creative group problem solving in NCD/NPPD. Further the experiment generated knowledge about the impact of group composition and applied methods on the results of as well as on information processing during this process. Comparing groups with mono and interdisciplinary group composition and groups using more pragmatic (GC) approaches with groups using more hierarchical methods (TD), the following can be stated (cf. also Table 56) [cf. also Schoefer *et al.*, 2013a, 2013b]:

- Disciplinary group composition, by impacting the value perception of personally held knowledge, seems to affect information sharing and thus group information processing during group problem solving. Further it impacts the way in which products of the problem solving process are documented as well as qualitative aspects of these products in terms of related strategies and goals.

- The choice of either more pragmatic general creativity methods (GC) or hierarchical analytical approaches (TD) during problem analysis, problem modeling and solution generation impact the creative problem solving process in terms of identified sub problems and problem models. Further, the applied methodology, similarly to group composition, exerts an impact on qualitative aspects of the creative products.
- Maybe most important, although not explicitly inquired by *Hypotheses 1* and *2*, are combined effects of disciplinary group composition and methodological choice. It could be shown that group composition, as a function of the applied method, impacts method application during the problem solving process, communication and thus group information processing, as well as quantitative and qualitative aspects of the problem solving output.

Table 56: Observed impact of disciplinary group composition and applied methods on creative group problem solving

	Disciplinary group composition	**Applied Methods**	**Combination of group composition and applied methods**
Problem solving process		X	X
Information processing	X		X
Quantitative aspects of results	X		X
Qualitative aspects of results	X	X	X

5.2.2 Comparison of Methodological Approaches

Further, the results of the *Experiment* provide information about specific advantages and drawbacks, as well as trends of methodological performance under certain conditions in creative problem solving in groups. Table 57 provides an overview of the relative performance of general creativity methods (GC) compared to hierarchical approaches like TRIZ and its derivatives (TD).

Table 57: Comparison of methodological performance in general and under specific conditions; +: comparably higher performance; -: comparably lower performance; ↑: increasing performance; ↓: decreasing performance; /: no trend

Performance criterion	Condition	TD	GC
Facilitating problem understanding	-	+	-
Leading to diversity of identified sub problems	-	-	+
Leading to diversity of established problem models	-	+	-
Leading to concentration of concepts on certain systemic levels	-	+	-
Leading to concept depth	-	-	+
Leading to concept and solution originality	In interdisciplinary groups	+	-
Leading to concept and solution originality	In monodisciplinary groups	-	+
Facilitating concept generation	With increasing domain knowledge in a group	/	↑
Facilitating communication	With increasing domain knowledge differences in a group	↓	↑

5.2.3 Meta-Model and Related Methods for Technology Search and Integration

The meta-model of technology search and integration (Figure 75), which has been introduced in Chapter 4.3.2 and tested in the *Case Study*, serves three purposes.

First, it describes the process of the search for potential technological solutions to a given problem in the NCD/NPPD process as well as potential problems which must be overcome in order to successfully integrate these technologies into a given application setting.

Second, the meta-model transforms the somewhat unilateral TRIZ concept of ideality into a bi- or multilateral model of several idealities, which are established from at least two perspectives, the application perspective (*Ideal Technology*) and the technology perspective (*Ideal Application*). In this way, the meta-model and the associated process allow the identification of *Technology Integration Problems*, which can be solved in three ways. First, the *Technology*, i.e. its properties P_T, A_T, N_T and R_T can be modified in order to fit the *Application's* requirements. Second, the *Application*, i. e. its properties P_A, A_A, N_A and R_A, can be changed in order to satisfy conditions which allow the integration of the *Technology*. Each of these two activities of Technology Integration Problem solving can be carried out by monodisciplinary teams of experts of either the Technology domain or the Application domain using specific domain knowledge. A third way to solve each Technology Integration Problem are interdisciplinary problem solving workshops during which a well-defined problem is attempted to be solved by groups composed of both Technology and Application domain experts. In addition to the above-mentioned points, the dyadic nature of the meta-model has another advantage. It allows the modeling of Technology Integration Problems in a dialectical way thereby facilitating the application of different sets of TRIZ problem solving heuristics (cf. Chapter 2.5.4.2).

Third, as could be shown in the *Case Study*, the meta-model allows the application of different sets of methods and tools in order identify the *Application*, its *Environment* and *Properties*, in order to search for *Technology* candidates and to model the *Properties* of the latter and, finally, in order to solve remaining Technology Integration Problems in a creative way. This latter characteristic of the presented meta-model allows the user to follow either pragmatic or hierarchical goal oriented strategies in order to obtain his or her goals – a criterion for good methodological support.

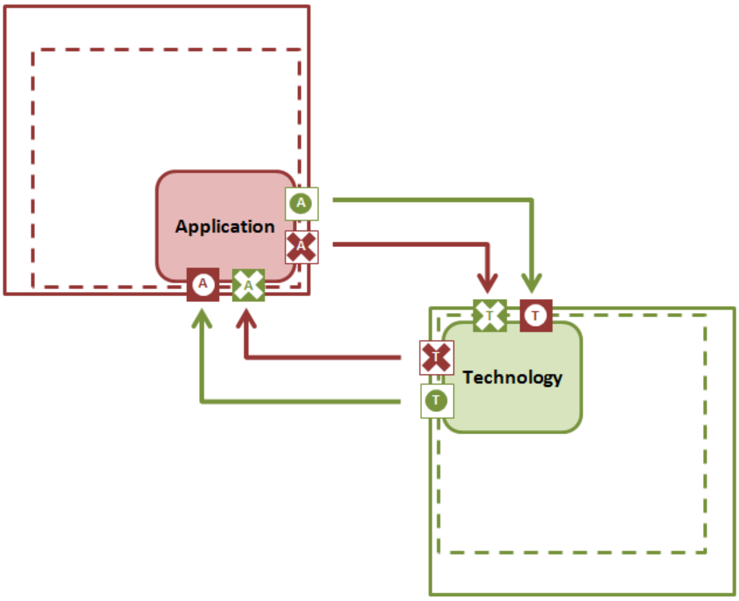


Figure 75: Presented meta-model for technology search and integration

5.2.4 Modeling of Activity in Natural Science and of Non-Technical Systems Using Design Theory

Further academic contributions relate to the modeling of activities in natural science as well as of non-technical systems using models originating from design theory (*MoNTS* in Figure 73).

More specifically, knowledge creation in natural science as well as the application of design theory knowledge in order support that knowledge creation process has been modeled using C-K Theory (cf. Paragraph 2.5.2.2.9). Further, complex biological organisms (Figure 76) as well as pathophysiological processes have been modeled using axioms and methods of TRIZ and its derivatives [Schoefer *et al.*, 2012]. The thus obtained system and problem models are essential elements for a training module which was designed in order to teach basic concepts of TRIZ and USIT to a multidisciplinary class of students, thus responding to a request formulated by Ilevbare *et al.* [2013].

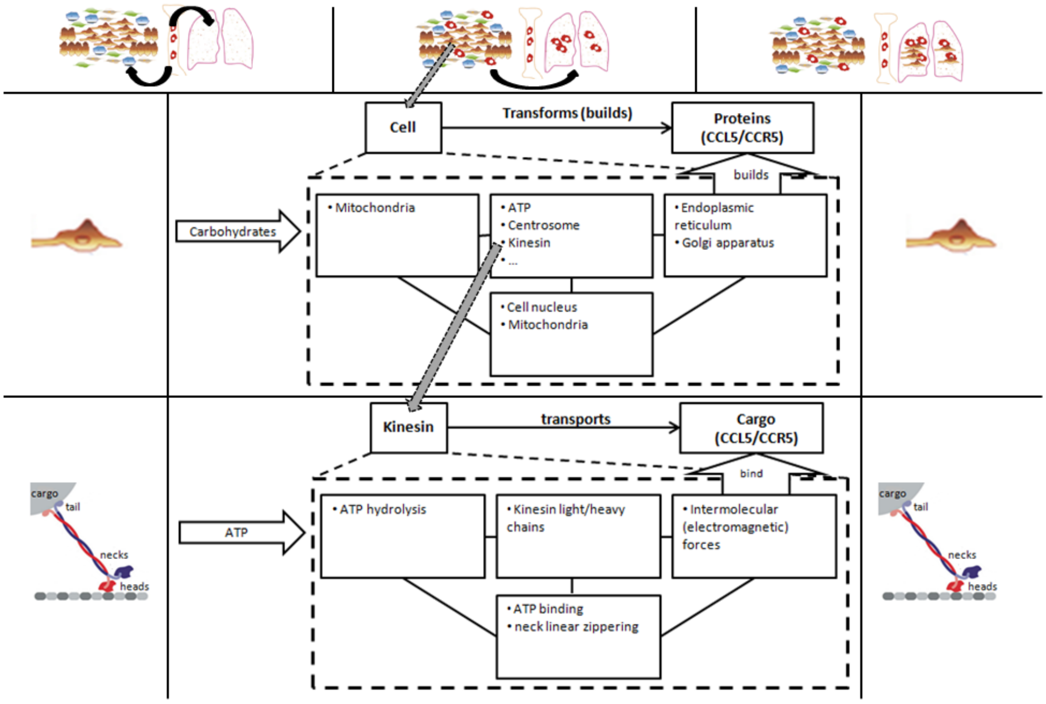


Figure 76: Modeling of cancer cells and kinesin-based cargo transport within these cells using TRIZ axioms and methods [Schoefer *et al.*, 2012]

5.3 Industrial Contributions

In this chapter are presented industrial contributions related to applications of design and management methods to industrial development projects and to the management of Open Innovation Processes.

5.3.1 Overview

Table 58 gives an overview of the performed projects, their industrial and theoretical context, problems engaged during the projects, applied methods and tools as well as the output of each project. The methodological approach which was applied with minor adaptations on *Projects 1, 2* and *3A* shall be described in more detail in the following paragraph.

Table 58: Overview of industrial projects and the output of these projects

Project	Indust. context	Theoret. context	Application system	Problem to solve	Methods, models and tools	Project output
1	Manufacturer of postage meters and mailroom equipment (MoPMME)	NCD	Postage meter- and mailroom equipment related knowledge and technology	Identification of opportunities for value propositions which satisfy future needs based on current knowledge and technologies	• Synectics • Multi-Screen Tool (TRIZ) • Evolution Laws (TRIZ) • Smic Prob-Expert [Godet, 2006] • RELEvent • Brainstorming	List of future scenarios with associated opportunities which relate to the MoPMME's technologies and knowledge
2	Manufacturer of bearing solutions for automotive industry (MoBSAI)	NCD	Car steering systems and related technology	• Identification of steering systems which best solve future problems • Identification of technological problems within these systems • Generation of solutions based on MoBSAI's current knowledge and technologies	• Synectics • Multi-Screen Tool (TRIZ) • Evolution Laws (TRIZ) • RELEvent • Role Playing • Closed World Method (USIT) • Magic Particles Method (USIT) • Problem Solving Operators (USIT)	• Prioritized list of technological problems associated to steering system technologies • List of potential solutions to these problems • List of important R&D questions to answer • Technology roadmap
3A	Manufacturer of standard Deep Groove Ball Bearings (MoDGBB)	NCD	• Electric motors • Conveyor systems • Electric pumps	• Identification of solutions which best solve future problems • Identification of technological problems within these solutions • Generation of solutions based on MoDGBB's current knowledge and technologies	• Synectics • Multi-Screen Tool (TRIZ) • Evolution Laws (TRIZ) • RELEvent • Role Playing • Closed World Method (USIT) • Magic Particles Method (USIT) • Problem Solving Operators (USIT)	• Prioritized list of technological problems associated to electric motor, conveyer system and pump technologies • List of potential solutions to these problems • List of important R&D questions to answer • Project lead to *Project 3B*
3B	Manufacturer of standard Deep Groove Ball Bearings (MoDGBB)	NCD/NPD	Deep Groove Ball Bearing	Cf. Chapter 4.3.3	Cf. Chapter 4.3.3	• Prioritized list of candidate technologies • List of solution concepts for technology integration • Non-disclosure agreements signed with two technology providers
4	Large pharmaceutical company	Open Innovation Processes	• Drugs • Health care services	Application and communication of Design Theory and Methodology to non-design experts	• Multi-Screen Tool (TRIZ) • Evolution Laws (TRIZ) • RELEvent • Closed World Method (USIT) • Magic Particles Method (USIT) • FBS-Model • Technology Search and Integration Meta-Model • …	Process for • Problem modeling and • Problem formulation in order to foster Open Innovation processes and development of training in related methods, models and tools

5.3.2 Approach Used for NCD in Projects 1, 2 and 3A

The methodological approach which was used in the *Projects 1*, *2* and *3A* with minor modifications is depicted in Figure 77. Table 59 synthesizes the *Process Stages 1* to *6*, which are carried out during the NCD phases Opportunity Identification, Opportunity Analysis, Idea Genesis and Idea Selection [cf. Koen *et al.*, 2001]. Figure 78 shows how the *Process Stages 1* to *4* are synthesized in a file which is based on the TRIZ Multi-Screen tool and which serves as Knowledge Management support at SKF.

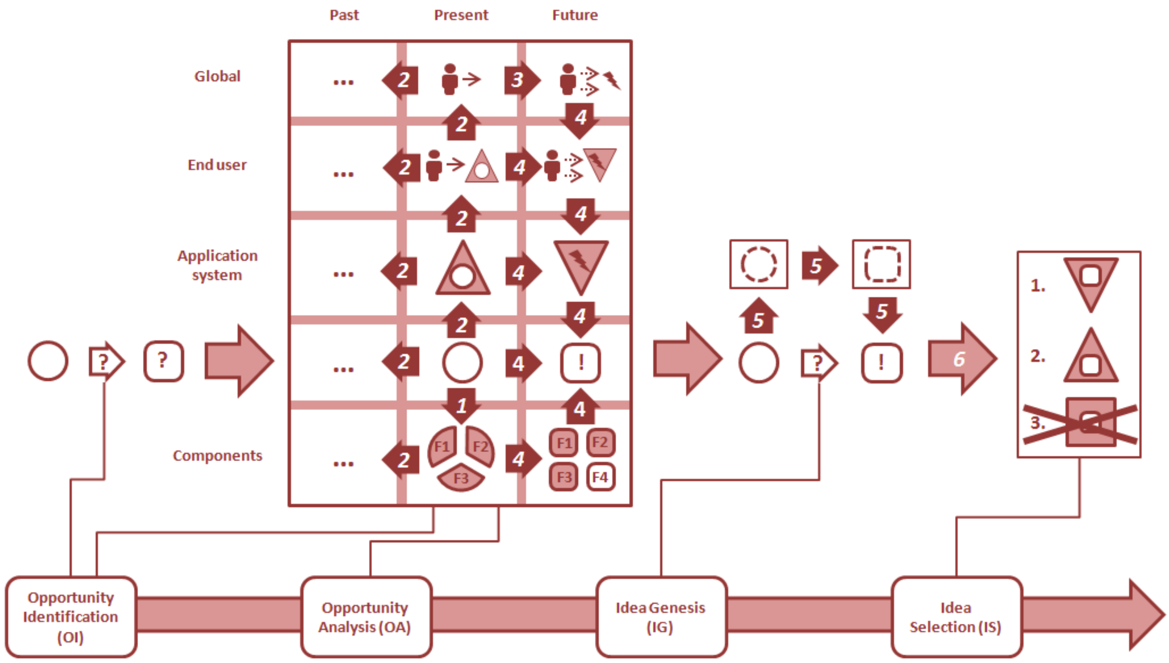


Figure 77: Schematic description of the methodological approach carried out in Projects 1, 2 and 3A

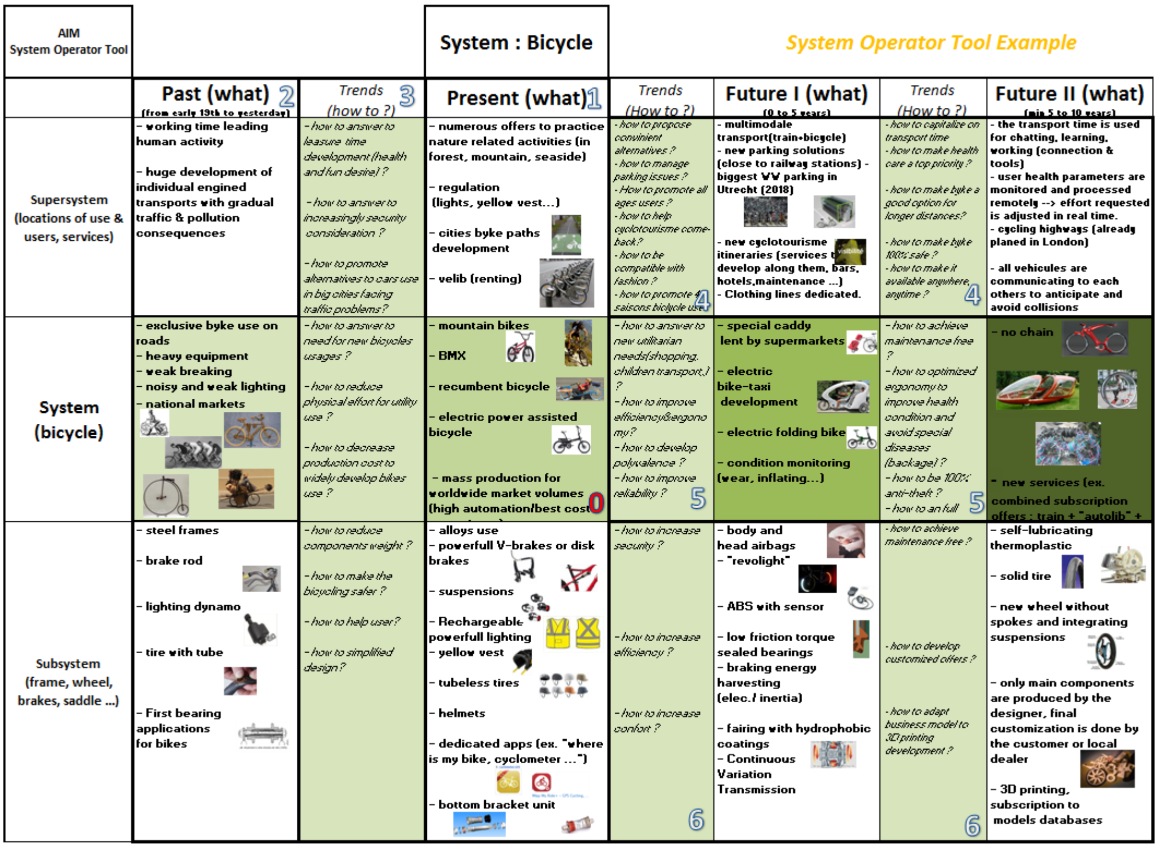


Figure 78: TRIZ Multi-Screen Tool used as Knowledge Management tool at SKF

Table 59: Stages (St.) of the methodology applied in *Projects 1*, *2* and *3A* and corresponding NCD-Phases (NCD-Ph.) Opportunity Identification (OI), Opportunity Analysis (OA), Idea Generation (IG), and Ideas Selection (IS)

NCD-Ph.	St.	Goal	Input	Activity/tools/ resources	Output
OI	0	• Identification of business problem to solve • Identification of target system	Fuzzy business environment	Responsible manager asks questions of a questionnaire based on *Synectics*.	Definition of target system (i.e., subject of NCD process) and its application systems
	1	Analysis of the target system, its purpose and functions	• Documentation about the system • Development- and application engineer experience	• Development- and application engineers are interviewed • Analysis of target system against the background of *TRIZ Evolution Laws*.	• Definition of system components and system functions • Identification of system consumption in terms of energy, material, space
	2	Identification of system environment at different systemic levels (application system, user interaction, super trends) in the present and the past	• Definition of system components and functions (output of Stage 1) • Literature review • Development- and application engineer experience	• Literature review • Interviews with internal and external experts • Workshops with development and application engineers • Documentation of results in *TRIZ Multi-Screen Tool*	Documentation of the development of the system and its environment on different levels as well as advantages and drawbacks of that development (updatable Multi-Screen database cf. Figure 78)
	3	Identification of future global scenarios	• Multi-Screen database (output of Stage 2) • Socio-economic super trends	• Identification of relevant super trends by expert group (futures study experts) • Scenario planning by futures study experts and science-fiction authors using *Smic Prob-Expert* Tool	List of scenarios combining most probable super trends
OA	4	• Identification of future usage scenarios, future systems which best perform in these scenarios and future functional requirements • Identification of future problems at these systemic levels	• List of scenarios (output of Stage 3) • Multi-Screen database (output of Stage 2) • Development-, application engineer and sales employee knowledge	• Deduction of development of different systemic levels from *TRIZ Evolution laws* • Top-down deduction of future user interaction, application systems and associated problems using *RELEvent* analysis and *Role Playing* as well as expert interviews	• List of future problems on different systemic levels (based on output of Stage 3) • List of systems and technologies which best solve these problems
IG	5	• Generation of concepts of technical solutions to the problems identified in Stage 4 • Identification of key information/ knowledge to obtain	• List of future problems on different systemic levels (output of Stage 4) • List of systems and technologies which best solve those problems (output of Stage 4)	• Problem solving workshops facilitated by *methodology of TRIZ and derivatives* (participants: development and application engineers, sales employees,…) • Systematic identification and documentation of missing knowledge	• List of problems and solutions related to specific application systems, end user scenarios, global scenarios and key knowledge to obtain
IS	6	• Identification of most important problems, solutions and missing knowledge	• List of problems, solutions and knowledge (output of Stage 5)	• Prioritization of items in list according to consistency with *Evolution Laws* and scenario probability	• Prioritized list of problems and solution concepts for entry into NPPD process and establishment of technology roadmap

5.4 Summary of Contributions

The academic contributions, which are the result of the *Experiment*, the *Case Study* and of the application of design methodology on non-technical systems, provide some insight into interdisciplinary problem solving. Furthermore, they provide support for the integration of knowledge-intensive technologies in the course of industrial New Concept Development and New Product/Process Design processes.

The industrial contributions essentially relate to propositions and executions of New Concept Development processes which are characterized by new combinations of existing design and management methods. Further, Design Theory and Methodology has been implemented into a process for problem modeling and problem communication which is sought to foster Open Innovation in the pharmaceutical industry.

In the final section of this dissertation, the work which was performed within the framework of the presented research will be summed up and related research perspectives will be discussed.

6 Conclusion and Perspectives

6.1 Conclusion

The research which is presented in this dissertation is thought to treat the question of how to support methodologically the search for and evaluation and integration of knowledge and technologies originating from knowledge-intensive and natural science-related domains in product- and process design processes. It gives answers to that question by providing insight into the process of interdisciplinary creative problem solving within NCD/NPPD. Further it sheds light on the value of certain concepts of design methodology for the integration of knowledge-intensive technologies in the context of design problem solving. Especially the impact of group composition in combination with method choice on the problem solving process, as well as quantitative and qualitative aspects of its creative output could be shown in a large scale laboratory experiment. Further, advantages and drawbacks of more pragmatic approaches compared to more analytical and hierarchical methods have been identified. Finally, a meta-model dedicated to the description and prescription of the process of search and integration of knowledge-intensive technologies has been introduced and tested. The most important findings of this research are the following:

- Disciplinary group composition in terms of group members with design-related and science-related background affects both information processing during problem solving and the products of the creative process in groups in terms of quality and type.
- The applied methodological approach influences the problem solving process as well as the type of generated ideas.
- Monodisciplinary groups of domain experts using pragmatic general creativity methods engage in problem solving processes which differ in all four investigated aspects from those of interdisciplinary groups using hierarchical and analytical methods: the process itself, information processing during the process, creative output quality, and creative output type.
- The reasons for those differences are suspected to be of several kinds. First, the participation of novices in a given domain leads to more intensive and extensive discussion of existing and missing problem-related knowledge. Second, the methodological approaches impact the integration of domain-specific ideas into generated concepts and solutions. Third, the presence of group members stemming from the same discipline than the applied method fosters both understanding and application of this method within the group.
- First indications were found that an approach integrating concepts and strategies of both methodological approaches bears benefits for the creative integration of technologies during NCD/NPPD.
- The modeling of natural science-related knowledge and systems using models and axioms of TRIZ and its derivatives is possible, valuable and it can lead to the identification of problem solving strategies originating from external domains.

In addition, those findings have significant implications and open several perspectives for research.

6.2 Implications and Perspectives

First of all, the results of the *Experiment* have implications for R&D management. The findings confirm and extend theories which suggest an important impact of disciplinary group composition and applied methods on group problem solving in early design process stages [e.g. Plattner *et al.*, 2010]. As a consequence, R&D management should consider the implication of more distant disciplinary perspectives as soon as possible during the problem identification and problem analysis process. Further, the results of that experiment indicate a need for adaptation of the applied methodological approaches to group composition and vice versa. Methods which are suitable for monodisciplinary group problem solving processes at where the participants possess similar knowledge and essentially speak the same language may not satisfy the requirements of interdisciplinary groups. Conversely, the successful application of more 'sophisticated' methodological approaches might require the participation of individuals who feature a certain familiarity with those approaches. On the one hand, if one considers for example the application of engineering design methods for problem solving in medicine, the participation of designers might be indicated. On the other hand – and against the background of engineering design more important – the integration of methods and solutions originating from natural science might require a very early implication of scientific experts.

The latter aspect is of interest especially for approaches like bio-inspired design where designers search for solutions to design problems among living organisms. In order to optimize the search for and integration of biological knowledge and solutions, an implication of biological experts as early as in the problem identification stage is considered important. This specific issue is subject to research which is currently undertaken at LCPI [Fayemi *et al.*, 2014].

Also with regard to the Open Innovation paradigm [Chesbrough, 2003], the results of the *Experiment* and the *Case Study* are relevant. The findings may lead to the conclusion that the mechanisms like open innovation platforms [e.g. NineSigma, 2013; InnoCentive, 2014], which companies use in order to foster inbound as well as outbound innovation projects, might be improved to some extent. Here especially the processes of problem identification and formulation, which are carried out in a company before a problem description leaves the organizational boundaries, might be modified according to the findings of this Ph.D. research. In this sense, AIM recently engaged in collaborations with major actors of the pharmaceutical industry in order to develop new problem identification and problem modeling approaches which are based on the work described here.

In addition, the present research also indicates potential lines of inquiry. First of all, the impact of the methodological approach on information processing during group problem solving could not be determined by the investigations which are reported here. Yet, further research in this respect could lead to valuable insight with regard to methodological choice as a function of specific group and problem settings.

Further, and perhaps more ambitious, this Ph.D. research represents an additional step towards what could be referred to as a unified model of knowledge. The latter, in turn, could lead to the possibility of target group building where the selection of each group member is a function of its accordance with the given problem setting and the required solution type.

Publications

National Conference Paper

Schoefer M., Maranzana N., et al. (2012b). Proposition d'une Démarche pour Structurer les Problèmes Scientifiques et Techniques et Identifier des Pistes de Recherche. Confère 2012. San Servolo.

International Conference Papers

Schoefer M., Maranzana N., et al. (2012a). From Design Research to Research Design - Transfer of Design Theory to Natural Science. International Design Conference - DESIGN 2012. Dubrovnik.

Schoefer M., Maranzana N., et al. (2013a). Testing the Value of TRIZ and Its Derivatives for Knowledge Transfer in Problem Solving Attempts by Multidisciplinary Teams. International Conference on Engineering Design - ICED 13. Seoul.

Schoefer M., Maranzana N., et al. (2013b). The value of TRIZ and its derivatives for interdisciplinary group problem solving. TRIZ Future Conference 2013. Aoussat A., Cavallucci D., Tréla M. and Duflou J. Paris.

Russo D., Schoefer M., et al. (2013). Supporting ECO-Innovation in SMEs by TRIZ Eco-guidelines. TRIZ Future Conference 2013, Paris.

International Journal Article

Schoefer M., Maranzana N., et al. (XXXX). Separate and Combined Effects of Disciplinary Composition and Methodological Support on Design Problem Solving in Groups – A Quantitative Study. Submitted to Design Studies.

Synopsis in French Language

1 Contexte du Travail

La présente section situe le travail de recherche dans un contexte académique. Basé sur ce contexte, une question de recherche est identifiée et est par la suite mise en relation avec trois domaines de recherche et avec les travaux de recherche effectués au Laboratoire CPI.

1.1 Introduction

Les travaux de recherche présentés dans cette dissertation sont liés à la résolution collaborative de problèmes dans le contexte du *New Concept Development* (NCD) ainsi que du *New Product and Process Developemnt* (NPPD). Contrairement aux travaux existants (cf. Chapitre 1.3.3), l'accent est mis sur la collaboration entre individus (ou groupes) avec une formation en sciences naturelles et individus provenant des domaines liés à la conception « classique » en ingénierie. Comme il sera démontré dans les chapitres suivants, le besoin de résoudre des problèmes interdisciplinaires est d'une très grande importance pour la création d'innovations dans les domaines industriel mais aussi scientifique. En plus, nous montrerons que les approches méthodologiques existantes ne traitent pas des problèmes liés à la résolution de problèmes par des équipes interdisciplinaires et que les performances de ce type de résolution de problème n'ont pas encore été investigué.

Après une analyse bibliographique considérable qui couvre les sujets de la conception (d'ingénierie), de la psychologie et des sciences cognitives ainsi que les sciences organisationnelles, deux approches méthodologiques pour la résolution de problèmes ont été choisis. Par la suite, la valeur de ces approches a été testée par une expérimentation utilisant comme exemple un problème ouvert et mal-structuré issu d'un domaine fortement basé sur la connaissance scientifique. Les conclusions de cette expérimentation ont contribué à la conception d'un méta-modèle descriptif, et quelque part prescriptif, qui structure l'intégration de technologie fortement basées sur la connaissance scientifique dans une application donnée. La performance de ce méta-modèle censé intégrer des concepts des deux approches méthodologiques mentionnées auparavant a été testée lors d'une étude de cas industrielle. Les résultats des deux investigations donnent des réponses aux questions de comment soutenir la résolution interdisciplinaire de problèmes et l'intégration de technologies lors des processus de NCD et NPPD. Ces résultats ouvrent des perspectives intéressantes pour de futures recherches dans le domaine de la résolution de problème.

1.2 Contexte de la Recherche

Une part considérable des activités de recherche et développement (R&D) est liée à des domaines fortement basés sur la connaissance qui nécessitent des connaissances issues de différents domaines industriels et scientifiques. De plus, les acteurs de la R&D sont forcés de trouver des solutions créatives et innovantes à de nouveaux problèmes ou de trouver de meilleures solutions à des problèmes déjà résolus afin de réduire coûts, accéder à de nouveaux marchés, attaquer des compétiteurs ou 'simplement' fournir des découvertes.

La recherche présentée dans ce rapport est liée à la question de comment fournir du support méthodologique à la résolution interdisciplinaire de problèmes et à l'intégration de technologies dans des domaines fortement basés sur la connaissance.

La connaissance issue des sciences naturelles joue un rôle important pour la création de valeur et qui sont considérés de nos jours comme essentiels pour la croissance industrielle et humaine. Des exemples connus dans ces domaines sont la nano- et la bio-technologie. La connaissance liée aux sciences naturelles est devenue de plus en plus importante également pour des produits d'ingénierie classique. Dans ce rapport, les termes « basé sur la connaissance » et « interdisciplinaire » font référence aux sciences naturelles et, dans le dernier cas, aux activités à l'interface entre les sciences naturelles et l'ingénierie.

1.2.1 Motivation

En 1996, L'Organisation pour Coopération et le Développement Economique [OECD, 1996] décrivait l'économie de ses pays membres comme étant essentiellement basée sur la connaissance. Ce constat était expliqué par les estimations que plus que 50 pourcent du Produit Intérieur Brut des économies membres majeures sont fortement basés sur la connaissance. La littérature plus récente [OECD, 2004 ; Luintel and Kahn, 2011] fournit aussi la preuve d'une forte relation entre les stocks de connaissance fondamentale (ainsi que appliquée et expérimentale) et la production et productivité domestique des économies industrialisées.
Suivant une analyse de six enjeux technologiques du 21e siècle [Bourgeois and Grou, 2007], qui sont introduits dans Tableau X, on peut conclure que la connaissance fondamentale et appliquée provenant de domaines des sciences naturelles vont continuer à jouer un rôle de plus en grand sur les marchés technologiques.
L'intégration de domaines de connaissance de plus en plus distants dans le design de nouveaux produits et processus mène à des niveaux de complexité plus élevées [Tomiyama, 2006] et à des équipes de recherche et développement de plus en plus interdisciplinaires [Paletz and Schunn, 2010]. Dans ce contexte et compte tenu les problèmes de collaboration toujours existants entre des disciplines proches [Tomiyama et al., 2009], il est curieux que l'inter- et la transdisciplinarité ainsi que la collaboration entre disciplines n'ont été discutées que récemment dans la littérature [Gericke and Blessing, 2011 ; Chulvi et al., 2013].
On peut déduire de ces analyses, un besoin de recherche sur les processus de résolution créative de problème ainsi que sur l'impact des facteurs comme la composition de groupe disciplinaire et le support méthodologique. La modification des approches méthodologiques existantes pourrait aussi être intéressante à explorer afin de mieux les adapter à ces besoins émergents. Finalement, même s'il existe déjà des approches pour la recherche de connaissance et de technologie de domaine distants qui se prêtent a priori à la résolution d'un problème donné, il y a une lacune en ce qui concernent les modèles et méthodes soutenant d'une façon efficace le processus d'intégration de technologie. Ces problèmes, à un certain degré sont traités dans ce travail.
En conclusion, la question de recherche suivante, qui sera détaillé dans Chapitre 3, a été formulée :

Comment soutenir méthodologiquement la recherche, l'évaluation et l'intégration de connaissance et de technologies originaires de domaines fortement basées sur la connaissance et liés aux sciences naturelles dans des processus de conception de produits et de processus ?

Tableau 1

Domaine technologique	Défis	Référence	Disciplines non-ingénierie liées
Problèmes environnementaux	• Amélioration d'efficience de production alimentaire • Réduction d'effet de serre • Réduction de la pollution d'eau, de terre et d'air • Réduction de la consommation de matières premières • Réduction de déchets	[Bourgeois, 2007a]	• Biologie • Médicine vétérinaire • Chimie • Physique
Technologie d'information et de communication	• Miniaturisation d'outils émergente • Développement d'électronique de spin • Développement d'électronique moléculaire	[Bourgeois, 2007b]	• Physique • Chimie • Biologie
Technologie de transport	• Stockage d'énergie électrique • Amélioration et implémentation de la combustion d'hydrogène et des technologies liées à la pile à combustible	[Haouat, 2007]	• Chimie • Physique
Technologie d'énergie	• Réalisation d'un mixe énergétique qui intègre l'énergie solaire, géothermique et de biomasse • Développement de la technologie pour la fusion nucléaire	[Boudin, 2007]	• Physique • Chimie • Biologie
Santé et technologie de santé	• Traitement de maladies cardiovasculaires et neurodégénératives • Développement de nouvelles méthodes d'opération • Amélioration de la délivrance ciblée de médicaments • Amélioration de prothèse 'intelligentes'	[Deregnaucout and haouat, 2007]	• Médicine • Biologie • Nanosciences • Biosciences
Technologie de purification d'eau	• Amélioration de la technologie de distillation • Amélioration de la technologie osmose invertie	[Bourgeois, 2007a]	• Chimie

1.2.2 Recherche liée

Le travail présenté dans ce rapport est essentiellement lié à trois champs de recherche :
La conception de produits, la psychologie et les sciences cognitives ainsi que les sciences de l'organisation, qui couvre entre autres des aspects de spécialités comme la sociologie (Figure 1). Comme chacun de ces champs est discuté d'avantage en Chapitre 2, seulement quelques remarques introductives sont données ici.

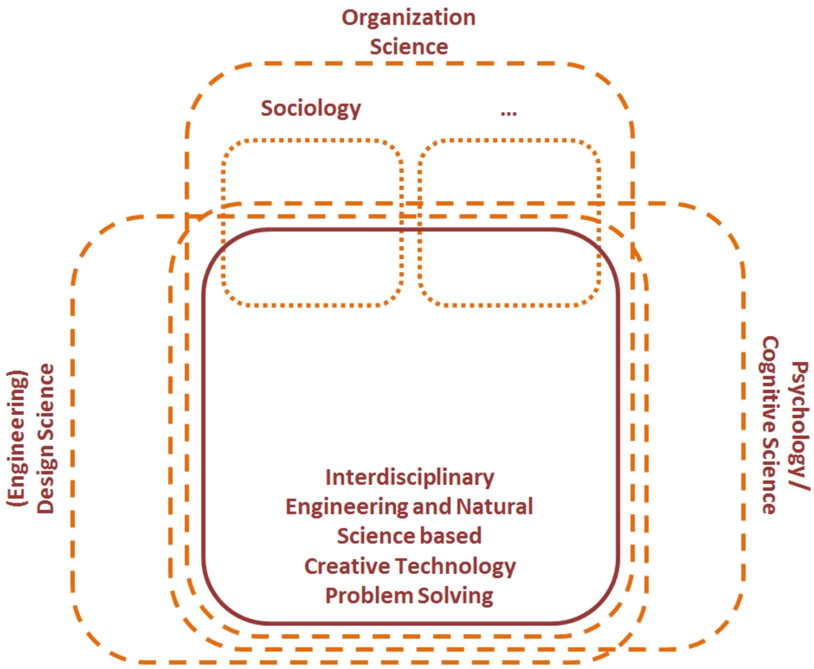


Figure 79

1.2.2.1 Conception de Produits

La conception de produits est une activité qui consiste dans l'application de la connaissance scientifique et de l'ingénierie pour résoudre des problèmes techniques et pour optimiser les solutions obtenues en vue de besoins et contraintes définies auparavant [Pahl et al., 2007]. La science de la conception, qui est considérée comme synonyme de le recherche de la conception dans ce rapport, est définie comme 'un système de connaissance logiquement lié, qui devrait contenir et organiser la connaissance complète pour la conception' [Hubka and Eder, 1996, p. 73]. Dans le cadre de la recherche présentée ici, trois aspects de la conception sont particulièrement intéressants :

- Des modèles descriptifs (et partiellement prescriptifs) du processus de conception global comme présentés par exemple par Pahl et al. [2007] et Suh [2001] ;
- La méthodologie prescriptive, des méthodes et outils pour des phases de conception spécifiques et la résolution de problème en conception [par exemple Cross, 2008 ; Alsthuller and Seljuzksi, 1983] et ;
- Problèmes et aspects théoriques liés à l'interdisciplinarité en conception [par exemple Tomiyama, 2003, 2006]

1.2.2.2 Psychologie et Sciences Cognitives

La psychologie concerne 'l'étude de l'esprit et du comportement' [APA, 2014] et couvre 'tous les aspects de l'expérience humaine.' Les sciences cognitives ont été définies comme un 'effort essentiellement empirique pour répondre […] aux questions empiriques […] liées à la nature de la connaissance, ses composants, ses sources, son développement et son déploiement' [Gardner, 1985, p. 6]. Selon Gardner, les concepts de la représentation mentale ainsi que des ordinateurs électroniques sont essentiels pour décrire l'activité de l'esprit humain dans les sciences cognitives. Etant un domaine de recherche interdisciplinaire, il couvre des sujets comme la philosophie, la psychologie, l'intelligence artificielle, la linguistique et la neuroscience.

Dans le contexte de la recherche présentée ici, les aspects suivant de la psychologie et des sciences cognitives sont importants :

- La théorie de la créativité, y compris les conditions qui favorisent la réussite créative [par exemple Collins et Amabile, 1999], et les modèles de la pensé créative [par exemple Finke et al., 1992] ;
- La description de l'esprit humain comme un processeur d'information [par exemple Simon, 1978] et la modélisation de la pensé créative comme une sorte de résolution problème [Simon, 1985] ;
- L'impact du contexte disciplinaire d'un individuel sur ses préférences cognitives [par exemple Kozhevnikov, 2007] et les stratégies de résolution de problèmes appliqués [Lawson, 1979].

1.2.2.3 Sciences de l'Organisation

La théorie de l'organisation ou la science de l'organisation fait référence à 'l'étude de comment fonctionnent des organisations et comment elles affectent et sont affectées par [leur] environnement' [Jones, 2003, p. 8]. Selon Shenhav [2003], ce 'domaine intellectuel' (p. 183) couvre des aspects de disciplines diverses comme la sociologie, les sciences politiques, la psychologie, l'ingénierie, les sciences du mangement et l'économie.
La recherche présentée ici prend en compte différents aspects de la théorie de l'organisation comme :

- La théorie et la gestion de l'innovation dans un contexte industriel [par exemple Popadiuk et Choo, 2006 ; Chesbrough, 2003] ;
- La théorie de création de connaissance [par exemple Nonaka, 1991] ainsi que les aspects de la gestion et du transfert de la connaissance [par exemple von Krogh, 1998] ;
- La catégorisation de disciplines scientifiques d'un point de vu socio-cognitif [par exemple Becher et Towler, 2001].

1.3 Résumé et Conclusion du Contexte du Travail Présenté

Le travail présenté dans ce rapport est motivé par la tendance industrielle à générer de la valeur en utilisant de la connaissance et des technologies provenant des domaines liés aux sciences naturelles. Cependant la résolution interdisciplinaire des problèmes souffre de lacunes et – à part quelques travaux récents – peu de travaux discutent collaborations inter- et transdisciplinaires en conception. Ces deux aspects indiquent un problème important : Comment fournir du soutien méthodologique pour la résolution interdisciplinaire de problème et pour l'intégration de technologies basées sur les sciences naturelles pendant le processus de la conception ?
La recherche présente, qui est principalement liée à la science de la conception, la psychologie et les sciences cognitives ainsi que aux sciences de l'organisation, peut être décrite comme suivant :

- D'abord une recherche bibliographique extensive a été effectuée afin d'identifier de la théorie et des problèmes importants en vue d'aborder la question de recherche à différents niveaux systémiques (cf. Chapitre 2). Du à la large échelle et le nombre considérable de publications analysées, il n'était pas possible d'accéder à toutes les sources originales. Lorsque ça a été le cas, les sources originales et secondaire sont données à travers de l'intégralité du rapport.

- Ensuite, en prenant compte les résultats de cette recherche bibliographique, une question de recherche ainsi que trois hypothèses ont été formulées (cf. Chapitre 3).
- Ces hypothèses sont finalement testées lors d'une expérimentation et d'une étude de cas industrielle en suivant des méthodes de recherche complémentaires (cf. Chapitre 4).

Les résultats de ces tests et des projets industriels liés sont présentés par la suite (cf. Chapitre 5). Le Chapitre 6 conclue sur cette recherche et indique des perspectives de ce travail pour la recherche et l'industrie.

2 Recherche Bibliographique

Pendant que la première section situait le travail de recherche dans un contexte industriel et académique, la section ci-présente synthétise la recherche bibliographique conduite pendant ce travail. Après une courte introduction sur la structure de cette section, des aspects intéressants du sujet sont étudiés selon cinq niveaux systémiques. La conclusion synthétise les points les plus importants identifiés dans la littérature et fait un lien avec la section suivante.

2.0 Structure de la Recherche Bibliographique

Ce travail de recherche est lié aux problèmes de la résolution de problèmes interdisciplinaires et à l'intégration des technologies basées sur la connaissance scientifique. Dans ce contexte, le rôle du soutien méthodologique pour ces activités est d'un intérêt particulier. Comme mentionné en Chapitre 1, les domaines de recherche associés à cette question peuvent être localisés dans les domaines de la conception et du design, de la psychologie et les sciences cognitives ainsi que dans les sciences de l'organisation. Cependant, la recherche bibliographique présentée n'est pas structurée selon ces domaines. La structure de ce chapitre suit plutôt une logique systémique (Figure 2).

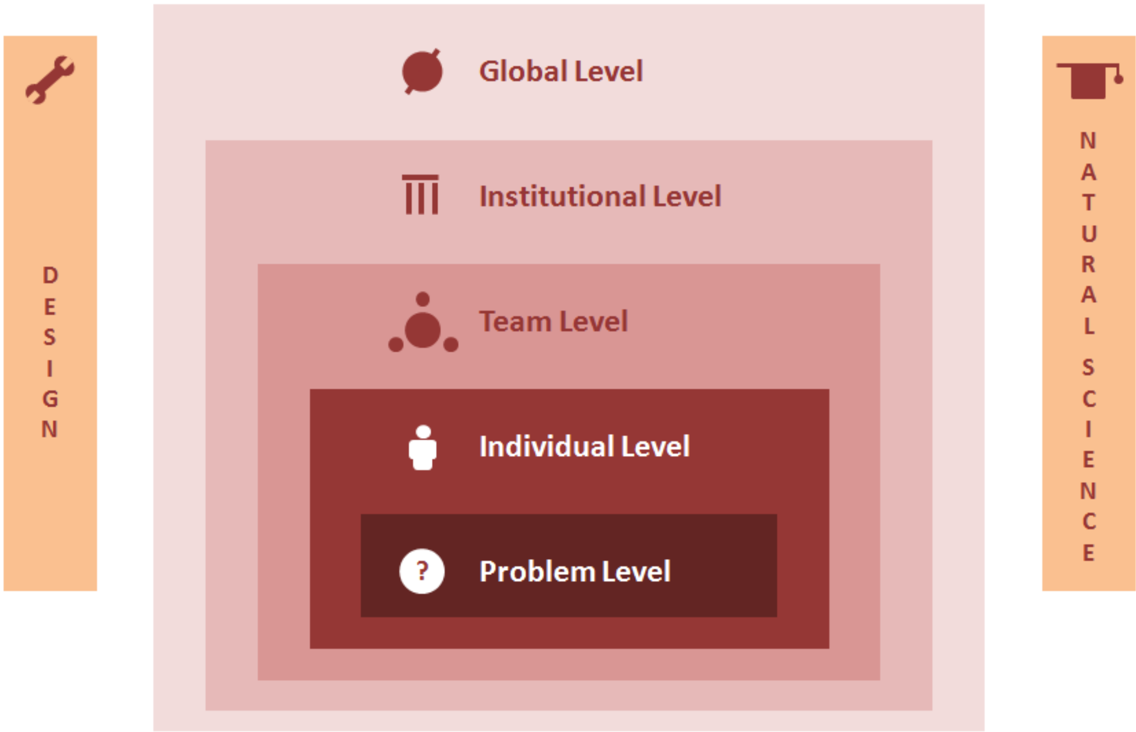


Figure 80

Afin d'investiguer la résolution interdisciplinaire créative de problème (Chapitre 2.5), il est nécessaire de comprendre la théorie et les mécanismes de la créativité et de résolution de problème à l'échelle individuelle (Chapitre 2.4) et en équipe (Chapitre 2.3). De plus, les aspects relatifs à la création de la connaissance et à son transfert à l'intérieur et au-delà des frontières d'une entreprise (Chapitre 2.2) doivent être compris. En début de partie, quelques définitions fondamentales seront données ainsi que quelques informations sur l'impact de la connaissance interdisciplinaire sur la création de valeur en industrie et une définition du terme discipline (Chapitre 2.1).

Le Chapitre 2.6 synthétise les aspects les plus importants des problèmes identifiés. Ces derniers mènent finalement à la formulation de la question de recherche et des hypothèses comme elles sont décrites en Chapitre 3.

2.1 Niveau Global

Le processus d'innovation peut être décrit comme un processus de recombinaison. L'innovation peut recombiner des aspects technologiques et/ou commerciaux nouveaux. La connaissance scientifique exerce un impact quantitativement et qualitativement important sur la génération industrielle de valeurs. La connaissance originaire de disciplines (scientifiques) distantes peuvent en particulier affecter des projets innovants. Les modèles qui décrivent le développement d'innovations dans un contexte de collaboration académique et industrielle ont évolués en même temps que les changements dans la production de la connaissance. La génération de connaissance pour innover est caractérisée par une incertitude augmentée, des temps de collaboration réduits et le besoin d'appliquer les capacités d'une institution à des marchés nouveaux. Cependant, le transfert entre la science et l'industrie aujourd'hui souffre encore de problèmes dus aux différences culturelles entre les partenaires.

2.2 Niveau Institutionnel

Afin d'innover, les organisations doivent altérer entre des processus d'exploration et d'exploitation, qui sont eux, liés à différentes activités de création de connaissance. Ces dernières sont considérées comme étant essentiellement des processus sociaux de conversion de différents types de connaissance. Des exemples importants pour la création de connaissance sont le développement de nouveaux produits et processus et leur ainsi que le transfert de connaissance et de technologie, ces derniers deux concepts étant utilisés comme synonymes ici. Le transfert de connaissance, à l'intérieur d'une entreprise ou au-delà de ses frontières, couvre à la fois le partage de connaissance par la source des connaissances et l'intégration de connaissance par le récepteur (Figure 3).

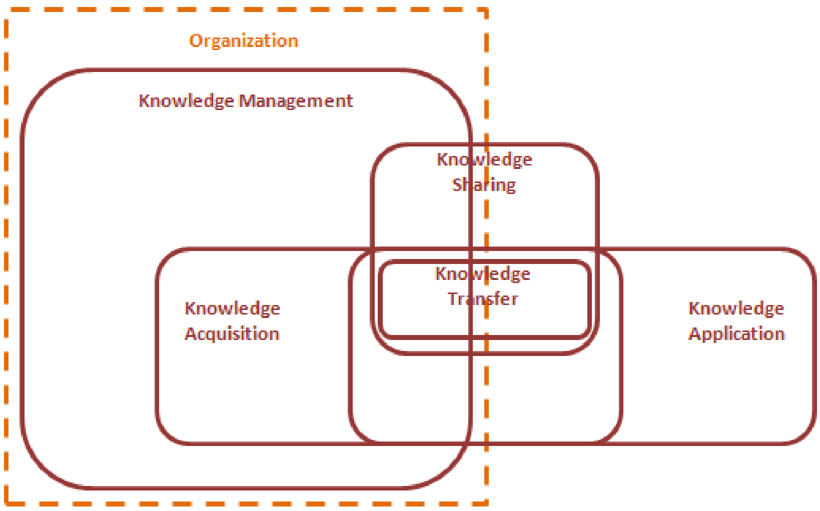


Figure 81

La codification de la connaissance, donc sa transformation en information transmise par symboles, est une des façons les plus importantes de transférer la connaissance. Cependant, elle porte le risque d'une simplification excessive et d'une décontextualisation qui empêche l'application effective à des nouveaux contextes. Par conséquent, les barrières au transfert de connaissance les plus importantes sont le manque de compréhension mutuelle en termes de référence culturelle et de contexte ainsi que les difficultés de communication entre la source et la cible de la connaissance. A ces problèmes, qui sont considérés comme interférant avec la capacité de transférer de la connaissance, on peut ajouter des problèmes techniques liés à l'intégration de technologies dans un produit donné. Finalement, l'aptitude d'une organisation ou d'un individu à identifier de l'information ou de la connaissance de valeur potentielle, de l'assimiler et de l'appliquer afin de créer de la connaissance nouvelle et de créer – par ainsi – de la valeur est nommée « absorptive capacity ». L'amélioration de cette « absorptive capacity » nécessite des capacités de traitement de connaissance intensives et une base de connaissance interdisciplinaire extensive de la part de l'entité cible.

2.3 Niveau d'Equipe

Les groupes d'individus sont souvent utilisés pour traiter des tâches telles que la génération d'idées créatives, la résolution de problème, la prise de décision et la résolution de conflit. Ainsi, les équipes utilisent souvent des stratégies d'une façon plus fiable que des individus isolés. Cependant, les groupes homogènes ainsi que hétérogènes ne produisent pas toujours des résultats supérieures particulièrement en termes de diversité disciplinaires et fonctionnelles. Pour améliorer la performance du travail de groupe, trois stratégies peuvent être identifiées. Premièrement, l'identification et même l'introduction de conflits peut mener à améliorer des processus de groupe, si ces conflits sont bien gérés. Dans un deuxième temps, des modèles mentaux partagés, qui se basent sur un certain nombre de modalités, peuvent mener à la communication et à l'intégration de différentes perspectives. Dans un troisième temps, des approches méthodologiques conçues pour réduire la fixation mentale sur certains concepts ont montré une certaine efficacité. Cependant, les processus de raisonnement qui ont lieu au sein de chaque individu exercent également une influence importante sur la façon dont un groupe exerce des tâches.

2.4 Niveau Individuel

L'homme est capable de générer une variété de produits créatifs, parmi lesquels on peut citer la suppression de contraintes ou barrières dans le processus de raisonnement. Particulièrement en science, la créativité peut aboutir à des produits créatifs et des systèmes technologiques sophistiqués. Afin d'être créatif, il est nécessaire qu'un individu dispose d'une certaine expertise dans le domaine ainsi que de stratégies particulières liées à la créativité.

L'expertise dans le domaine se manifeste dans des quantités importantes de *chunks* de connaissance à la fois structurelle et procédurale. Elle mène à des représentations de problèmes plus approfondies et souvent plus abstraites qui peuvent par la suite être résolues par exemple par analogies. Cependant, même si on considère dans beaucoup de domaines que posséder une expertise et résoudre des problèmes par analogies distantes est plus créatif, elles restent l'exception. Des instructions par rapport à la pensé analogique peuvent avoir un impact positif sur la résolution de problème analogique et trop de familiarités avec un domaine donné peut interférer avec la créativité.

Parmi les capacités de raisonnement créatif, les stratégies méta-cognitifs mènent à une certaine organisation du processus de pensé qui aide à dépasser des limitations comme celles de la capacité de mémoire. En plus, le développement parallèle de concepts opposés ou contradictoires ainsi que leur synthèse est un processus de pensée qui mène souvent à des productions créatives.

Les chercheurs en sciences cognitives et les psychologues décrivent le processus créatif comme la génération et modification de concepts élémentaires parmi lesquels certains sont combinés et développés d'avantage. Avec cette approche, quelques caractéristiques spécifiques de ces concepts élémentaires comme l'ambiguïté et l'incongruence sont censées d'être responsables du produit créatif.
Il a été finalement trouvé qu'il existe des différences individuelles en termes de style cognitif, c'est-à-dire dans la façon dont les individus perçoivent l'information et traitent les problèmes. Certaines de ces préférences sont liées au contexte disciplinaire des individus. En accordance, des différences importantes entre les stratégies de résolution de problème utilisées par les scientifiques et les designers et ingénieurs ont été détectées.

2.5 Niveau du Problème

La résolution créative de problèmes est essentielle pour les activités en conception et en sciences. La conception et la science présentent des aspects distincts et communs dans cette perspective. La littérature et les autres contributions à la résolution de problème en général et dans le contexte de la conception et de la science en particulier peuvent être catégorisées en théories et méthodologies ou méthodes. Ces dernières présentent souvent des heuristiques de résolution de problème. Les méthodes – en conception, en science ou plus génériquement – sont souvent basées sur des aspects théoriques de la résolution de problème comme des processus de recherche dans des espaces à différents niveaux d'abstraction. Des heuristiques explicites ont été identifiées soit par l'induction d'analyses empiriques, soit par la déduction d'axiomes théoriques. Même si plusieurs heuristiques de domaines spécifiques sont des versions spécialisées de leurs contreparties plus génériques, leur puissance semble être négativement corrélée à leur applicabilité générale.
La convergence de technologie constatée dans les activités de R & D actuelles et l'importance de la conception de produits sur contrainte cause des problèmes qui ne peuvent pas être résolus par les théories et méthodes monodisciplinaires existantes. Malheureusement ; la recherche et les approches méthodologiques liées à la facilitation de la résolution interdisciplinaire de problèmes sont toujours rares. Les approches existantes se concentrent sur la modification de solutions existantes dans les mêmes domaines de connaissance, sur l'analyse automatisée de textes ou sur des domaines sources spécifiques comme la biologie. Selon la connaissance de l'auteur, il n'existe pas d'approche méthodologique pour la résolution interdisciplinaire et créative de problèmes et pour l'intégration de technologies. Une telle approche capable de lier et intégrer des méthodes et heuristiques de différents domaines de la conception et de la science porterait probablement le potentiel d'améliorer les processus de recherche et de développement actuels. Figure 4 synthétise Section 2.5.

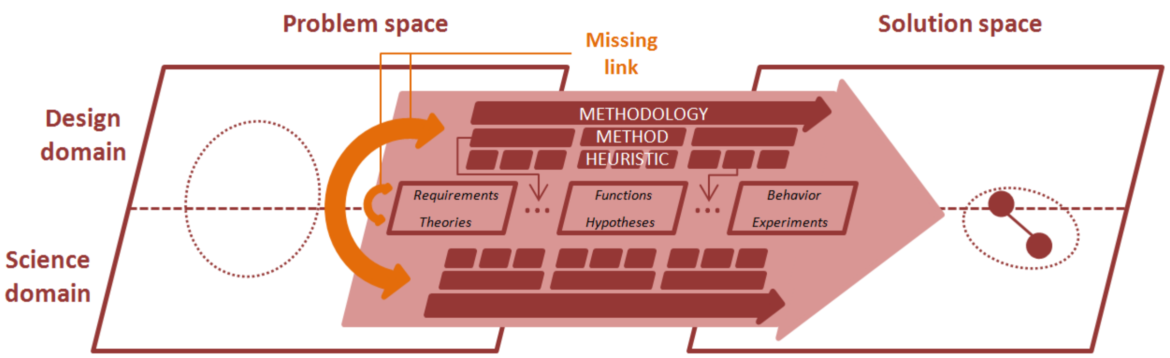


Figure 82

2.6 Sommaire et conclusion de la revue de la littérature

2.6.1 Sommaire de la revue de la littérature

Les Tableaux 2 à 6 synthétisent les problèmes et solutions liées à la résolution interdisciplinaire et collaborative de problèmes et à l'intégration de technologies fortement basées sur la science aux niveaux global, institutionnel, aux niveaux de l'équipe et de l'individu ainsi qu'au niveau du problème.

Tableau 2

Niveau Global		
Faits	**Problèmes**	**Solutions**
Innovations peuvent être décrites comme nouvelles combinaisons d'éléments.		
Combinaisons de connaissance distante effectuent souvent le plus grand impact.		
Les conditions de création de connaissance ont changé vers une incertitude augmentée, des temps de collaboration réduites et la nécessité d'appliquer les capacités des institutions à des nouveaux marchés et applications.		
Les disciplines des sciences naturelles, sociales et d'ingénierie peuvent être classifiées selon des aspects cognitifs mais aussi sociaux.	→ La collaboration souffre de différences culturelles entre partenaires scientifiques et industriels	

Tableau 3

Niveau Institutionnel		
Faits	**Problèmes**	**Solutions**
Pour innover, les institutions doivent alterner entre les processus d'exploration et d'exploitation (de connaissance)		
Exploration et exploitation sont liées à différents types de conversion de connaissance tacite et explicite.		
L'application de connaissance existante peut mener à l'innovation radicale.		
Le transfert de connaissance/technologie consiste dans le partage de connaissance/technologie et son intégration	→ L'intégration de connaissance est difficile à cause du besoin de faire converger des domaines de connaissance différents et du aux problèmes d'adaptation de technologies à des produits spécifiques → Les routines cognitives créent barrières à l'application de connaissance nouvelle. → La codification de connaissance mène souvent à une simplification et une décontextualisation excessive. → Un manque de compréhension mutuelle et des problèmes de communication sont des barrières importantes au transfert de connaissance.	→ Augmenter la Capacité d'Absorption d'une entité améliore sa capacité d'identifier, assimiler et d'appliquer de la connaissance nouvelle MAIS nécessite des capacités de traitement de connaissance intenses ainsi que des bases de connaissance interdisciplinaires extensives.

Tableau 4

Niveau de l’équipe		
Faits	**Problèmes**	**Solutions**
Les Equipes multifonctionnelles peuvent augmenter la Capacité d’Absorption d’une entité et ainsi aider à réduire les délais de production de produits.	→ Les découvertes par rapport à la performance d’équipes comparée à la performance d’individus sont mixtes. → La diversité disciplinaire réduit l’efficacité et l’efficience d’une équipe au court terme. → Les raisons pour cet effet sont : • Pensé de groupe • Influence de la majorité • Partage d’information portée en commune seulement • Schémas d’interprétation incohérents • Conflits non-gérés	→ Les Approches méthodologiques comme Brainstorming ou l’introduction / la simulation de conflits peuvent dépasser ces problèmes. → Les Modèles mentales partagés et → La gestion de conflits peuvent améliorer la performance de groupe.

Tableau 5

Niveau individuel		
Faits	**Problèmes**	**Solutions**
Certaines catégories de productions créatives résultent d'une suppression de barrières et contraintes.		
La créativité scientifique peut résulter d'un raisonnement théorique ou d'une invention technologique.		
L'Expertise et les (méta-)stratégies de raisonnement sont des conditions importantes pour la créativité.		
L'Expertise dans un domaine peut être modélisé comme un large nombre de pièces de connaissance structurelle ainsi que procédurale.		
La connaissance expertise mène à des représentations de problèmes plus abstraites, qui favorisent la résolution de problème analogique plus systématique et qui utilise des analogies plus lointaines.	→ Le développement d'analogies distantes est difficile même pour des experts. → L'expertise peut nuire la performance créative.	→ Les Instructions pour la pensée analogique peuvent aider dans la résolution de problème. → Les Stratégies méta-cognitives aident à dépasser des limites cognitives (p. ex. capacité de mémoire limitée). → Le développement parallèle de concepts opposés et leur synthèse suivante peut mener à des produits créatifs.
La Créativité peut être modélisée comme la génération de concepts élémentaires (souvent ambigus ou incongruents) et la transformation ou synthèse de ces concepts.		
Le contexte disciplinaire individuel est lié aux préférences de style cognitif et aux (méta)stratégies de résolution de problème utilisées.		

Tableau 6

Niveau du problème		
Faits	**Problèmes**	**Solutions**
Les activités de la conception et de la recherche se focalisent sur des buts différents mais parfois intersectés.		
La résolution de problème dans la conception et dans la recherche peut être décrite par une recherche de solutions dans des espaces différents.		
Des processus dans la conception et dans la science sont caractérisés par l'usage de méthodes et heuristiques qui sont – à un certain degré – génériques.	→ Une relation négative entre l'applicabilité générale et la puissance des méthodes a été constatée.	
Les systèmes technologiques deviennent de plus en plus complexes et intègrent d'avantage de connaissance de domaines diverse.	→ Des problèmes de communication et de compréhension empêchent le processus de conception de systèmes technologiques. → Aucune méthode appropriée n'existe pour résoudre ce problème.	
Les méthodes doivent être flexibles et adaptables à la fois aux besoins et aux problèmes auquel elles sont appliquées.	→ Les méthodes existantes ne disposent pas de ces propriétés.	

2.6.2 Conclusion de la Recherche Bibliographique

Avec cette recherche bibliographique on peut voir que des tendances économiques et technologiques actuelles obligent les entreprises ainsi que les institutions de recherche à résoudre des problèmes avec une inter- et transdisciplinarité augmentée afin d'appliquer leur connaissance à des nouveaux marchés et applications. Ces institutions sont de plus obligées d'effectuer des projets de R&D en respectant des délais de plus en plus courts.

Dans ce contexte, les problèmes de communication et le manque de compréhension mutuelle entre acteurs scientifiques et industriels sont parmi les plus importantes raisons d'échec des activités de transfert de connaissance et de technologie. Afin de traiter des enjeux comme la simplification excessive et la décontextualisation de la connaissance, les équipes R&D et leurs entités supérieures doivent développer et augmenter leur capacité absorptive, un processus qui nécessite une vaste base de connaissance interdisciplinaire. La majorité des problèmes liés à l'intégration de connaissance et technologie originaires de domaines de connaissance distantes ne peuvent pas être résolus d'une façon distante. C'est pour ça que des sessions de résolution de problème face-à-face semblent être des aspects importants de projets R&D actuels et futurs et ceci particulièrement dans la conception de produits nouveaux.

Cependant, même si des experts scientifiques et de la conception peuvent tirer avantage de styles cognitifs complémentaires ainsi que des stratégies de résolution de problème et des heuristiques associées, il n'existe pas de cadre méthodologique opérationnel qui soutenant le transfert de cette connaissance. Les éléments requis pour un tel support méthodologique sont une facilité d'appréhension améliorée ainsi qu'une adaptabilité au besoin de l'utilisateur et aux problèmes à résoudre.

3 Question de Recherche et Hypothèses

La recherche présentée dans ce rapport étudie la question de comment améliorer la capacité d'une organisation à développer des solutions créatives pour des problèmes technologiques. Le focus est mis sur l'identification et l'intégration de connaissance provenant de domaines scientifiques distants dans la conception de produits et de processus. Le cadre systémique de recherche est l'équipe R&D, c'est-à-dire un groupe d'individus qui disposent d'un certain degré d'expertise dans une discipline ainsi que les caractéristiques cognitives et culturelles associées. Pour ce faire, des théories, méthodes et outils issues de la psychologie, du management et de la conception ont prouvé une certaine efficacité. Malgré cela il n'existe pas de recherche qui explique comment ces concepts impactent la recherche et l'intégration de connaissance et technologies par des équipes interdisciplinaires – c'est-à-dire des équipes composées d'ingénieurs et designers d'un côté et de scientifiques de l'autre – dans les conceptions de produit et de processus.

Il faut noter que le périmètre de cette recherche se limite à des aspects de créativité et d'inventivité ce qui exclue d'autres aspects aussi importants pour l'application d'une solution au marché, condition nécessaire pour une innovation.

3.1 Question de Recherche

La question de recherche de ce rapport de thèse, qui a été brièvement introduite en Section 1 et dont l'importance a été prouvée en Section 2 de ce rapport, est la suivante :

Comment soutenir méthodologiquement la recherche, l'évaluation et l'intégration de connaissance et technologies provenant de domaines fortement basées sur la connaissance (scientifique) dans les processus de conception de produit et de processus.

3.2 Justification Méthodologique

3.2.1 Choix Méthodologique

Afin de tester l'impact de différentes approches méthodologiques sur la résolution interdisciplinaire de problème et sur l'intégration de connaissance et technologies provenant de domaines fortement basées sur la connaissance (scientifique), Brainstorming et Mindmapping ainsi que TRIZ et ses dérivés ont été choisis. Les approches sélectionnées représentent à un certain degré les deux extrêmes du spectre méthodologique. D'un côté, Brainstorming et Mindmapping comme méthodes de créativité germinales et générales nécessitent peu d'effort afin de devenir apte à leur utilisation. De plus, elles peuvent être catégorisées comme techniques qui favorisent la résolution de problème et les approches de conception opportunistes.

Les méthodes et axiomes de TRIZ et ses dérivés comme USIT peuvent être eux classifiées comme techniques analytiques et empiriques. En utilisant ces méthodes, l'individu qui veut résoudre un problème ou – dans le contexte de cette recherche – l'équipe est censé suivre un processus plus hiérarchique. Dans le cas de TRIZ, ce processus se traduit par l'analyse et la modélisation du problème, la génération de solutions génériques et, finalement, l'implémentation des solutions génériques afin de résoudre le problème initial. Les différentes méthodes et axiomes sous- jacents de TRIZ et ses dérivés nécessitent un effort d'appréhension et un entrainement avant leur application qui est considéré comme considérable. Malgré ces inconvénients les techniques du complexe TRIZ, quatre raisons pour ce choix méthodologique peuvent être listées :

- Les « méthodes faibles », qui sont utilisées implicitement mais extensivement dans la science, à l'exception d'une méthode, correspondent bien aux processus de résolution de problème ainsi qu'aux axiomes et méthodes fournis par TRIZ et USIT (Tableau 7).
- Les concepts des contradictions (TRIZ) et Graphes de Changement Qualitatif (USIT) partagent le même principe dialectique sous-jacent que les processus de raisonnement qui sont importants pour la créativité individuelle [Rothenberg, 1983 ; Simonton 2004 ; Finke et al. 1992] et de groupe [Schwenk, 1990].
- Les méthodes de résolution de problème par analogie de TRIZ et USIT comme l'approche des Particules Magiques correspondent à des concepts qui ont été décrits comme étant utilisés pour la résolution de problème en science naturelle par, par exemple, Demokrit et Maxwell [Savransky, 2000].
- Les outils de modélisation de problème et les heuristiques de résolution de problème, particulièrement d'USIT, présentent une certaine ambigüité [Sickafus, 1997], un concept important pour la résolution créative de problème et pour le *Design Thinking* [Plattner et al., 2010].

Tableau 7

Méthodes faibles en science	Axiomes et concepts de TRIZ/USIT
Générer et Tester	A éviter selon TRIZ
Monter la colline	**TRIZ:** Opérateur Taille-Temps-Coût **USIT:** Changement de Paramètres
Analyse Moyens-Fins	***Détection de différents entre l'état actuel et l'état final:*** **TRIZ:** Résultat Idéal Final; Contradictions; Modélisation Su-Champs; Modèle avec Nains Miniatures **USIT:** Approche des Particules Magiques ***Operateurs:*** **TRIZ:** Principes Inventives; Principes de Séparation; Standards Inventifs **USIT**: Opérateurs de Solution
Planification	Le processus de la méthode 'Planification' correspond bien au processus de résolution de problème de TRIZ et USIT.
Analogie	***Modélisation superficielle:*** **TRIZ:** Lois d'Evaluation de Systèmes Techniques ***Modélisation relationnelle:*** **TRIZ:** Contradictions; Loi de l'Intégralité de Systèmes ***Modélisation Structurelle:*** **TRIZ:** Modèle avec Nains Miniatures

3.2.2 Inconvénients de TRIZ et Ses Dérivés

Malgré le fait que les méthodes provenant de TRIZ et USIT sont parmi les approches les plus structurées pour la résolution de problème dans des domaines technologiques, elles présentent quelques inconvénients considérables vis-à-vis du transfert de connaissance et de technologie :

- Le processus de résolution de problème décrit dans TRIZ est caractérisé par la transformation d'un problème spécifique en des modèles de problème plus génériques (1), le développement de modèles de solution basées sur l'analyse de ces modèles de problème (2), et finalement la transformation de ces solutions génériques en des solutions concrètes et spécifiques (3). Les premières deux étapes sont bien décrites dans la littérature et un grand nombre de méthodes et outils sont disponibles pour soutenir la personne qui doit résoudre le problème. Par contre, pour la troisième étape aucun support méthodologique n'a pu être identifié pendant la recherche bibliographique. Cela signifie que l'intégration de technologies identifiées comme solutions potentielles – une tâche qui a été identifiée comme un problème important dans la littérature – reste un problème pour des individus et équipes qui veulent résoudre des problèmes.

- Le problème d'intégration de technologies est quelque part lié à la perspective unilatérale vis-à-vis des problèmes. Avec TRIZ et les approches liées, le processus de résolution de problème se focalise sur
  - Une – souvent seule – personne qui doit résoudre le problème
  - La description d'un problème dans des limites assez étroites et
  - Une – souvent seule – solution idéale du point de vue de la personne qui doit résoudre le problème.

  Ces focalisations, même si elles favorisent la génération de solutions fortement inventives, interfèrent avec la résolution de problèmes bi- ou multilatéraux. Par contre, ces exactement ces problèmes qui peuvent émerger du besoin d'intégrer des solutions ou technologies spécifiques dans un problème donné.

Adresser ces inconvénients de TRIZ et ses dérivées par rapport aux problèmes de transfert et d'intégration de technologie reste un défi majeur.

3.3 Hypothèses

Dans les chapitres précédents ont été identifiés différents problèmes liés à la question de recherche. Ces problèmes concernent différentes phases du processus de développement de concepts et de produits nouveaux et sont traités dans la présente dissertation par l'exploration de trois hypothèses. Les Hypothèses 1 et 2 sont d'un intérêt particulier pendant le processus de développement de concepts nouveaux, c'est-à-dire le *fuzzy front end*. L'Hypothèse 3 est liée à la dernière étape du développement de concepts nouveaux ainsi qu'au processus plus formalisé de développement de produits ou processus nouveaux.

3.3.1 Hypothèse 1

La première hypothèse concerne l'aspect de la diversité de connaissance émergeant d'une diversité disciplinaire dans la résolution créative de problèmes et son impact sur trois paramètres : le processus de résolution de problème en général, le traitement d'information pendant ce processus et, finalement, ses résultats en termes de productions créatives. Dans le contexte de cette recherche, le concept de multidisciplinarité fait référence à des interactions entre les domaines de la conception et de la science. La recherche présentée se distingue d'autres approches où les interactions entre différentes sous-disciplines au sein du domaine de la conception sont analysées. L'Hypothèse 1, qui concerne la génération d'idées – ainsi que la phase de sélection d'idées du processus NCD, est formulée comme suivant.

H1 : La diversité disciplinaire et en terme de connaissance des groupes a un impact sur

> H1a : le processus de résolution créative de problème dans des domaines fortement basés sur la connaissance et les technologies.
>
> H1b : le traitement de connaissance pendant ce processus.
>
> H1c : des aspects quantitatifs de la production créative.

H1d : des aspects qualitatifs de la production créative.

3.3.2 Hypothèse 2

L'Hypothèse 2 concerne les aspects méthodologiques de la résolution créative de problèmes en équipe et compare deux approches différentes pour la facilitation de la pensée créative. Les méthodes classifiées comme méthodes germinales et générales, qui peuvent être appliquées sans prendre en compte le sujet à traiter, sont testés contre des méthodes rationnelles et basées sur l'histoire provenant de la théorie de la conception. En accordance avec la première hypothèse, Hypothèse 2 se concentre sur le fait que :

H2 : La méthodologie appliquée pendant le processus de résolution de problème en groupe a un impact sur

H2a : le processus de résolution créative de problème dans des domaines fortement basés sur la connaissance et les technologies.

H2b : le traitement de connaissance pendant ce processus.

H2c : des aspects quantitatifs de la production créative.

H2d : des aspects qualitatifs de la production créative.

3.3.3 Hypothèse 3

La troisième hypothèse concerne les inconvénients des approches analytiques du complexe TRIZ, qui ont été identifiés dans les Paragraphes 3.2.1 et 3.2.2. La valeur des méthodes et outils provenant de TRIZ et ses dérivées pour la génération de concepts inventifs à des problèmes technologiques a été prouvé empiriquement (cf. Paragraphe 2.5.7 du Rapport). Ces outils ont également prouvé leur utilité pour l'identification de technologies qui s'appliquent – a priori – a un problème donné. Néanmoins, pour le problème important de l'intégration d'une technologie identifiée à une application technologique et commercial (cf. Paragraphes 2.2.4.2.2, 2.7.7 et 2.5.6.1 du Rapport), aucun support méthodologique significatif n'a pu être identifié dans la littérature. De plus, TRIZ a été évalué comme nécessitant un effort considérable pour être appris et appliqué, ce qui est un facteur qui empêche une dissémination plus importante de cette approche en industrie. La troisième hypothèse suggère une possibilité d'adresser ces inconvénients de TRIZ et de ses méthodes associées. Elle postule que l'intégration de notions basiques de TRIZ dans un méta-modèle conçu pour décrire et prescrire le processus d'intégration de connaissance est possible. Le méta-modèle devrait

- Se baser sur des axiomes de TRIZ comme l'Idéalité et les principes dialectiques (cf. Paragraphe 2.5.3.3.1.2 du Rapport)
- Permettre l'application de différentes méthodes provenant de TRIZ et autres approches largement utilisées en industrie
- Etre essentiellement de nature bilatérale, c'est-à-dire adresser des problèmes d'intégration de technologie de la perspective de l'application pour laquelle la technologie fournit une solution mais aussi de perspective de la technologie elle-même.

L'Hypothèse trois considère que :

H3 : Les axiomes et méthodes de TRIZ et ses dérivées peuvent fournir un cadre utile pour la recherche et l'évaluation a priori de technologies fortement basées sur la connaissance ainsi que pour l'intégration de ces dernières pour le but de résoudre des problèmes de développement de produits et processus nouveaux industriels

3.4 Sommaire de la Question de Recherche et des Hypothèses

La validation ou infirmation de ces trois hypothèses est devrait illuminer la question de comment des processus de R&D industriels en général et plus particulièrement les processus de développement de concepts nouveaux et de produits et processus nouveaux peuvent profiter de la multidisciplinarité. La valeur de connaissance et de technologies complémentaires, styles cognitifs et stratégies de résolution de problème qui sont censés se trouver dans les différents domaines, sera particulièrement testée (Hypothèse 1). De plus, deux approches représentant deux extrêmes du spectre méthodologique seront comparées en termes d'avantages et inconvénients possibles par rapport à la facilitation de processus interdisciplinaires (Hypothèse 2). Un troisième aspect de ce travail de recherche est la possibilité d'extraire des notions centrales de TRIZ et ses dérivées pour construire un méta-modèle pragmatique censé structurer le processus interdisciplinaire d'intégration de technologies afin de résoudre des problèmes de conception donnés (Hypothèse 3).
Ces hypothèses (cf. Tableau 8 pour une synthèse) seront testées dans une expérimentation et une étude de cas industrielle, qui seront décrites en Chapitre 4.

Tableau 8

	La composition de groupe impacte…	La méthodologie impacte…	TRIZ et ses dérivées représentent une valeur pour la recherche, l'évaluation et l'intégration de technologies fortement basées sur la connaissance afin de résoudre des problèmes de NPPD.
…le processus de la résolution créative de problème.	H1a	H2a	
…le traitement de connaissance.	H1b	H2b	
…la production créative quantitativement.	H1c	H2c	
…la production créative qualitativement.	H1d	H2d	
			H3

4 Test des Hypothèses

Dans ce chapitre sont présentés les tests qui ont été effectués afin de tester les hypothèses développés en Chapitre 3.

4.1 Aperçu

Pendant les travaux de recherche, deux tests, qui sont par la suite évoqués comme *Expérimentation* et *Etude de Cas*, ont été effectués. Ces tests diffèrent selon deux critères. Le premier critère concerne les étapes des processus de NCD et NPPD couverts et le second est lié à la typologie expérimentale (Figure 5).

L'Expérimentation analyse différents aspects de processus de groupe pendant les phases de la *Génération d'Idées* et la *Sélection d'Idées* du processus de NCD dans des domaines fortement basés sur la connaissance dans des conditions quasi-laboratoires. L'Etude de Cas est lié aux Phases de *Sélection d'Idées* jusqu'au *Développement de Concept et de Technologie* des Processus NCD et NPPD dans l'industrie.

Ces tests permettent de mettre en lumière différentes phases importantes des processus de R&D industriels. La première investigation (Expérimentation) démarre pendant la phase de génération d'idées du cadre NCD, qui est considérés comme étant une étape critique de la génération de connaissance lors du développement de produits ou de processus. Comme ces étapes précoces nécessitent relativement peu de ressources, une expérimentation laboratoire avec 60 étudiants pouvait être mise en place et fournissait des résultats quantitatifs vis-à-vis des *Hypothèses 1* et *2*. Dans une certaine mesure, l'Etude de Cas couvre aussi les phases de génération d'idées et de sélection d'idées mais elle focalise sur la phase de *développement de concept et de technologie*. Celle-ci ne peut pas être distinguée facilement des processus du NPPD plus formalisés et nécessite des ressources personnelles et financières considérables. C'est la raison principale pour laquelle l'*Etude de Cas* a été développée comme une investigation industrielle pour tester *Hypothèse 3*.

Les deux tests sont décrits en détail dans les Chapitres 4.2 et 4.3 du Rapport.

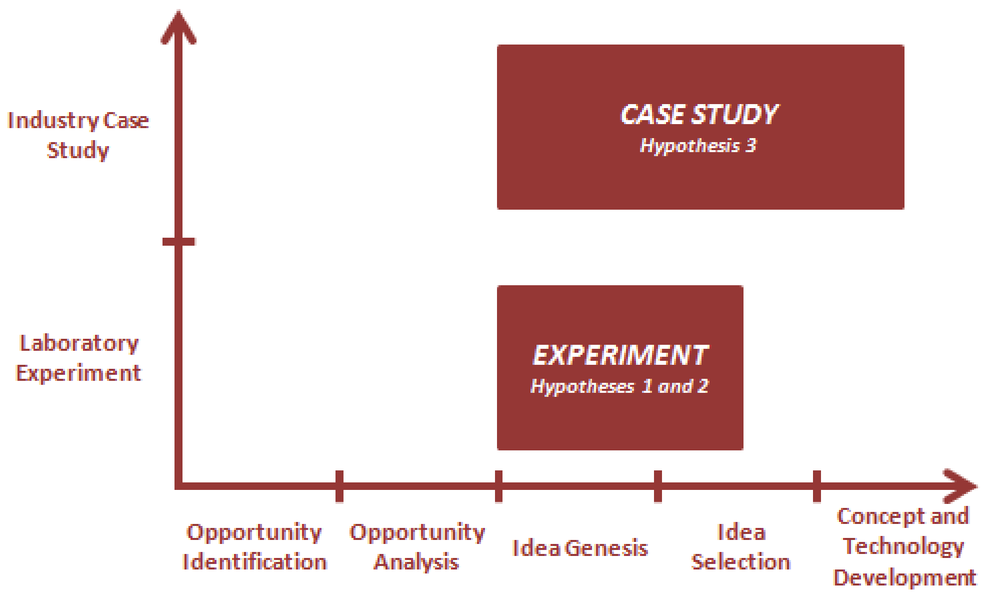


Figure 83

4.2 Expérimentation

4.2.1 Introduction

Comme décrit en Section 3, les hypothèses développées touchent à l'impact de la composition de groupe et de la méthodologie appliquée au processus de résolution créative de problèmes fortement basés sur la connaissance scientifique. L'expérimentation décrite dans ce chapitre a été conçue pour tester les Hypothèse 1 et 2 dans des conditions qui sont aussi réalistes que possibles. Le choix de la procédure expérimentale, le problème à résoudre et la formation des participants tient compte de cet objectif.

Dans les chapitres suivants, la procédure expérimentale sera tout d'abord décrite. Après, on donnera quelques descriptions statistique des résultats produits par les participants. Les résultats de cette analyse seront ensuite discutés par rapport aux hypothèses examinées et par rapport à la recherche précédente.

4.2.2 Méthode

On a demandé à vingt groupes de trois étudiants de générer des solutions créatives à un problème mal structuré en suivant un processus de résolution de problème générique caractérisé par : la définition du problème, l'analyse du problème, la génération (divergente) d'idées, et la génération (convergente) de solutions. Les conditions dans lesquelles les groupes effectuaient le processus de résolution de problèmes différaient en deux dimensions, une dimension de discipline et une de méthodologie.

Il y avait onze groupes monodisciplinaires. Neuf de ces groupes étaient composés de trois membres avec une formation en sciences de la vie (LS (Life Sciences)). Deux groupes étaient constitués de trois membres ayant une formation en génie mécanique (ME (Mechanical Engineering)). Il y avait aussi neuf groupes pluridisciplinaires composés de deux membres avec une formation en sciences de la vie et d'un membre avec une formation d'ingénieur mécanique (L2M). Les participants ayant une formation en sciences de la vie étaient 45 étudiants diplômés de l'Ecole de Biologie Industrielle. Cette école est une école d'ingénieurs dont les étudiants ont suivi des études de premier cycle dans les domaines de la biologie, de la biotechnologie, de la pharmacologie et de la médecine. Les 15 participants ayant une formation en génie mécanique ont été recrutés parmi les étudiants des Arts et Métiers ParisTech, une école d'ingénieurs spécialisée dans la formation des ingénieurs mécaniques et industriels. Les 60 participants ont validé une certaine partie de leurs cours d'innovation en échange de leur participation à cette expérimentation.

La moitié des groupes (5 LS, 1 ME et 4 L2M groupes) ont été formés en Brainstorming et Mindmapping. Ces méthodes sont considérées comme des méthodes de créativité intuitives et génériques et sont donc censées ne pas interférer de façon significative avec une résolution de problèmes intuitive. L'autre moitié (4 LS, 1 ME et 5 groupes L2M) a suivi une formation en TRIZ et USIT (TD = TRIZ et dérivés). La répartition des 20 groupes selon les deux dimensions est montrée en Figure 6.

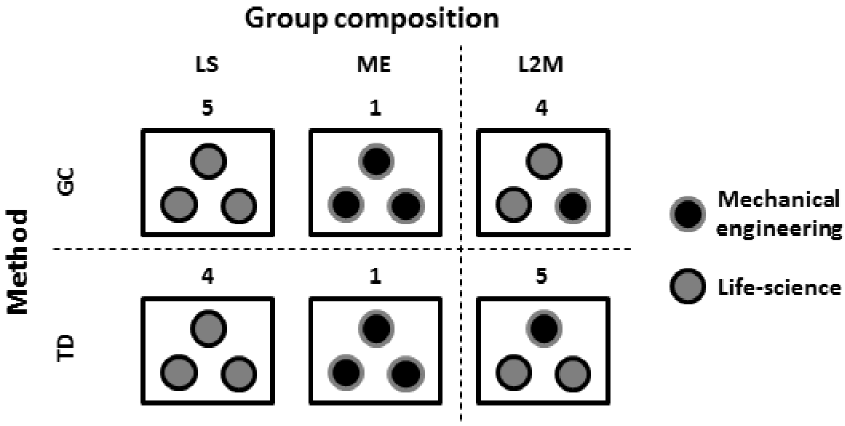


Figure 84

4.2.2.1 Formation Méthodologique

Tous les participants ont suivi une formation de 4,5 heures dans une des deux approches, TRIZ et USIT ou Brainstorming et Mindmapping. Les participants ont tous été autorisés à utiliser le support de formation imprimé pour les sessions de résolution de problèmes ultérieures.

4.2.2.2 Instruction et Etude de Cas Pédagogique

Afin de favoriser la compréhension et l'application méthodologique, tous les groupes ont ensuite été invités à participer pendant deux heures à une tâche initiale de résolution créative de problème. On leur a dit de suivre une méta-stratégie de résolution de problème générique consistant en la Définition du problème; la Génération d'Idées Divergente; l'Évaluation d'Idées; l'Amélioration d'Idées convergente ; et la Génération de Solutions. Au cours de cette étude de cas pédagogique, les participants devaient générer des propositions pour le traitement de cancer par rayonnement ionisant sans nuire aux tissus sains du patient. Ce problème a été dérivé du Problème De Radiation de Duncker [Duncker, 1945 (cité dans [Gick and Holyoak, 1983])]. Au cours de cette étude de cas, les phases de travail autonome ont été suivies par des phases au cours desquelles les résultats obtenus par les auteurs en utilisant différentes approches méthodologiques ont été présentés aux participants.

4.2.2. 3 Questionnaires

Chaque fois, après l'étude de cas pédagogique et après la tâche de résolution de problème de l'expérimentation, les participants ont été invités à remplir des questionnaires sur une échelle de type Likert à sept points. Les questionnaires se sont focalisés sur des aspects tels que la perception personnelle des participants de la valeur de leurs connaissances en ce qui concerne le problème à traiter (avant la préparation du problème et en général), la motivation personnelle, et la valeur de la méthode appliquée pour la compréhension du problème, pour la résolution de problèmes et pour la communication (Tableau 9).

Tableau 9

2Q1	J'ai préparé le problème (infection de l'adénovirus) (en lisant les documents fournis, enquête Internet, etc.) avant le traitement du problème.	Questions en connaissance personnelle
1/2Q2	Avant la préparation du problème, je possédais une certaine quantité de connaissances dans le domaine du problème (infection de l'adénovirus).	
1/2Q3	Mes connaissances sur le problème semblait adéquat pour le traitement du problème.	
1/2Q4	Je crois avoir compris le contenu de la formation qui a précédé l'étude de cas.	Questions sur la compréhension méthodologique et de motivation
1/2Q5	J'ai été motivé pour traiter le problème (infection de l'adénovirus).	
1/2Q6	Les méthodes acquises au cours de la formation m'a aidé à mieux comprendre le problème.	Questions sur la méthode la perception de la valeur
1/2Q7	Les méthodes acquises au cours de la formation m'a aidé lors de la génération de solutions.	
1/2Q8	Les méthodes acquises au cours de la formation ont aidé mon groupe à mieux communiquer.	

4.2.2.4 Problème à Résoudre

Après avoir effectué l'étude de cas pédagogique et après une courte pause, tous les participants ont dû s'engager dans une tâche de résolution de problème qui a été analysée statistiquement après. Cette tâche ainsi que le support apporté aux participants sont présentés dans le Tableau 10.

Tableau 10

Scénario	Les solutionneurs de problèmes sont membres d'une équipe dans le domaine de la médecine quia toute liberté de proposer de nouveaux projets de recherche et tous les types de traitement.
Problème	Proposer des solutions créatives au problème des infections à adénovirus opportunistes des enfants qui sont dans un état immunodéprimé à cause de la transplantation de cellules hématopoïétiques souches.
Ressources fictives	ressources financières, scientifiques et technologiques suffisantes
Ressources réelles	Internet; bases de données scientifiques; publications scientifiques [Howard et al., 1999; et Gonçalves de Vries, 2006; Robin et al, 2007;. Russel, 2009; Yaghobi et al., 2011] afin de donner une vue d'ensemble sur le problème et les stratégies de solutions existantes

4.2.3 Résultats

4.2.3.1 Résultats Descriptifs

Les 20 groupes ont produit un résultat total de

- 83 fiches d'identification des problèmes (PIS)
- 62 fiches de structure de problème (PSS)
- 162 fiches de concept (CS)
- 46 fiches de solution (SS)

de différents types et degrés de détail. La Figure 7 à la Figure 9 montrent des exemples de la PIS, PS, CS et SS.

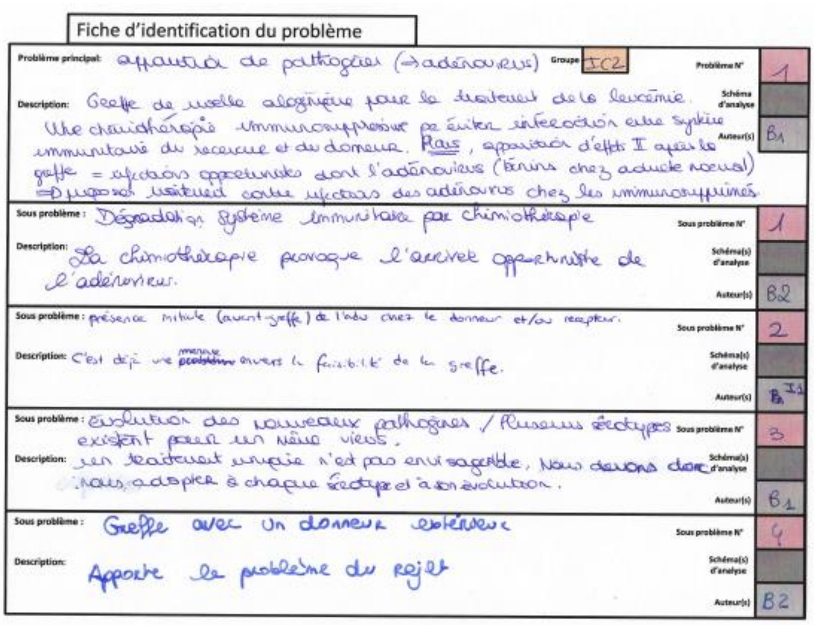


Figure 85

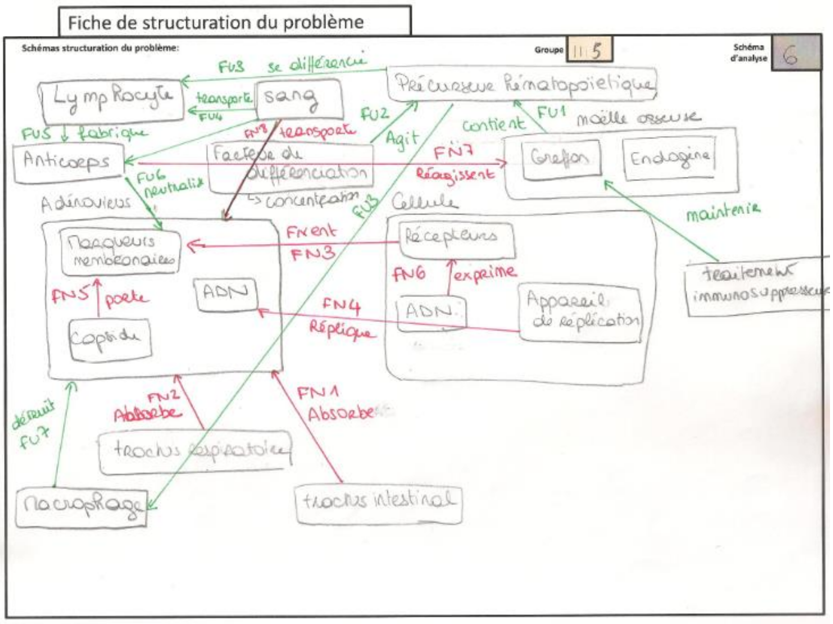


Figure 86

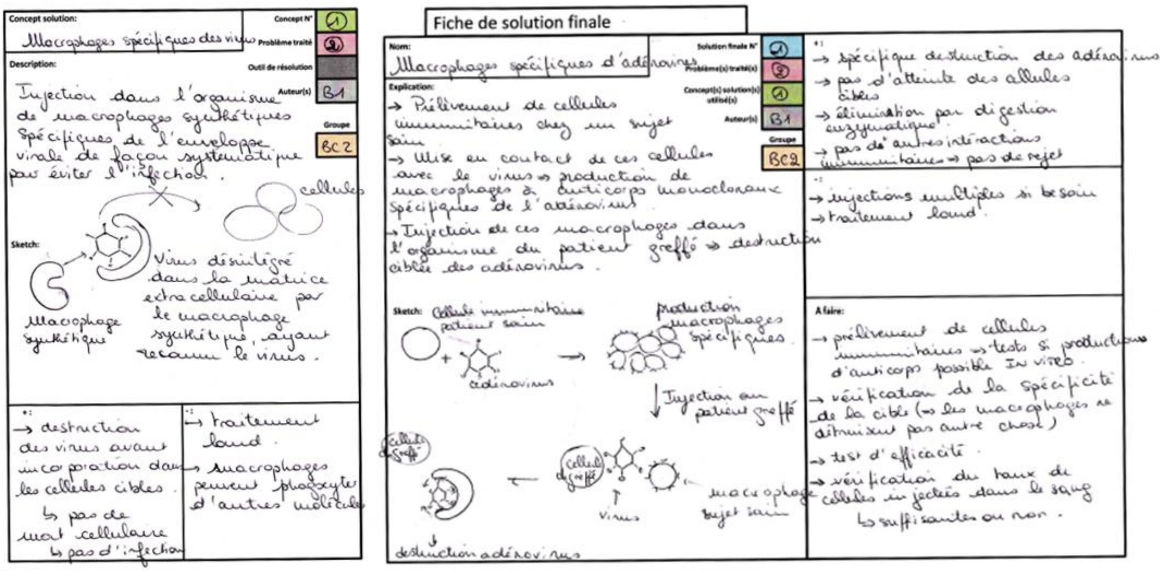


Figure 87

4.2.3.2 Analyse Quantitative

Les concepts et solutions produits ont été évalués par deux experts du domaine, à savoir des chercheurs en microbiologie, et par des échelles de type Likert sept points selon les cinq critères d'évaluation de la créativité indépendants suivants [Dean et al., 2006]:

- Faisabilité
- Applicabilité
- Efficacité
- Profondeur (mélange d'explicitation implicite et l'exhaustivité et
- Originalité

La fiabilité inter-évaluateurs globale pour les concepts générés et les propositions de solution se montent à un alpha de Cronbach de $\alpha = 0{,}728$, qui est considéré comme une valeur acceptable. Trois concepts et une proposition de solution n'ont pas pu être évalués en raison de leur documentation ambiguë ou indistincte. Par conséquent le total des concepts qui est entré dans l'analyse statistique se monte à 159 et le total des propositions de solution à 45.

Le Tableau 11 montre les résultats de l'analyse de la variance (ANOVA) entre les variables indépendantes et dépendantes.

Tableau 11

N°.	Variables indépendantes	Variables dépendantes	Résultat
1.1	Composition (GC) et disciplines (LS / ME / L2M) de groupe	1Q2	$F(1, 26)=3.26$; $p=0.084$ (L2M: LS: ↑, ME ↓; LS/ME: LS ≈ ME)
1.2	Discipline	1Q4	$F(1, 26)=4.59$; $p=0.043$* (LS ↓; ME ↑)
1.3	Composition de groupe	1Q6	$F(1, 26)=14.3$; $p=0.001$** (L2M ↓; LS/ME ↑)
1.4	Méthode (GC / TD)	2Q2	$F(1, 57)=3.67$; $p=0.061$ (GC ↑; TD ↓)
1.5	Discipline	2Q2	$F(1, 57)=62.53$; $p<0.001$** (LS ↑; ME ↓)
1.6	Discipline	2Q3	$F(1, 57)=21.58$; $p<0.001$** (LS ↑; ME ↓)
1.7	Composition de groupe	2Q4	$F(1, 57)=3.98$; $p=0.052$ (L2M ↑; LS/ME ↓)
1.8	Méthode	2Q6	$F(1, 54)=4.7$; $p=0.035$* (GC ↓; TD ↑)
1.9	Méthode	Nombre des PIS	$F(1, 18)=10.0$; $p=0.005$** (GC ↑; TD ↓)
1.10	Méthode	Nombre des PSS	$F(1, 18)=22.62$; $p=0.0002$** (GC ↓; TD ↑)
1.11	Composition de groupe et méthode	Originalité des concepts	$F(1, 59)=4.83$; $p=0.029$* (L2M: GC ↓, TD ↑; LS/ME: GC ↑, TD ↓)
1.12	Méthode	Profondeur des concepts	$F(1, 59)=11.77$; $p=0.001$** (GC ↑; TD ↓)
1.13	Composition de groupe	Profondeur des solutions	$F(1, 45)=4.42$; $p=0.042$* (L2M ↑; LS/ME ↓)
1.14	Composition de groupe et méthode	Originalité des solutions	$F(1, 45)=7.83$; $p=0.008$** (L2M: GC ↓, TD ↑; LS/ME: GC ↑, TD ↓)
1.15	Composition de groupe	Nombre d'outils TD appliqués	$F(1, 7)=4.60$; $p=0.069$ (L2M ↑; LS: ↓)

4.2.3.3 Analyse Qualitative

Le classement qualitatif des concepts générés a été réalisé en deux étapes.

Tout d'abord, les 26 concepts qui ont obtenu les scores les plus élevés en termes d'applicabilité, d'efficacité et d'originalité ont été classés en fonction de leur niveau systémique et du moment dans le temps où ils interagissent avec le problème.
Deuxièmement, tous les concepts générés ont été classés selon les critères suivants qui, selon TRIZ et ses dérivés, sont utilisés pour décrire et modéliser des systèmes et problèmes complexes (Figure 10) :

- Le problème auquel le concept est supposé être une solution. Afin de distinguer les sous problèmes, trois catégories de problèmes ont été distingués en utilisant l'analyse Su-Champ de TRIZ. Exemple: Système Virus-Organisme-Immune
- Le niveau systémique du problème auquel le concept opère principalement. Exemple: Système immunitaire
- L'élément du problème qui constitue l'objet principal de l'interaction du concept (objet). Exemple: cellule infectée

- La sous-zone fonctionnelle de l'élément principal avec lequel l'interaction exprimée dans le concept se produit (composant d'objet). Exemple: La membrane de la cellule infectée
- Le moment du processus d'infection au cours duquel l'interaction principale du concept prend lieu (moment d'interaction). Exemple: Avant que le virus se lie à la cellule
- Les moyens qui sont proposés dans le concept afin d'effectuer l'interaction principale (moyen). Exemple: Anticorps

Figure 11 montre schématiquement le résultat de cette catégorisation qualitative des concepts les plus créatifs.

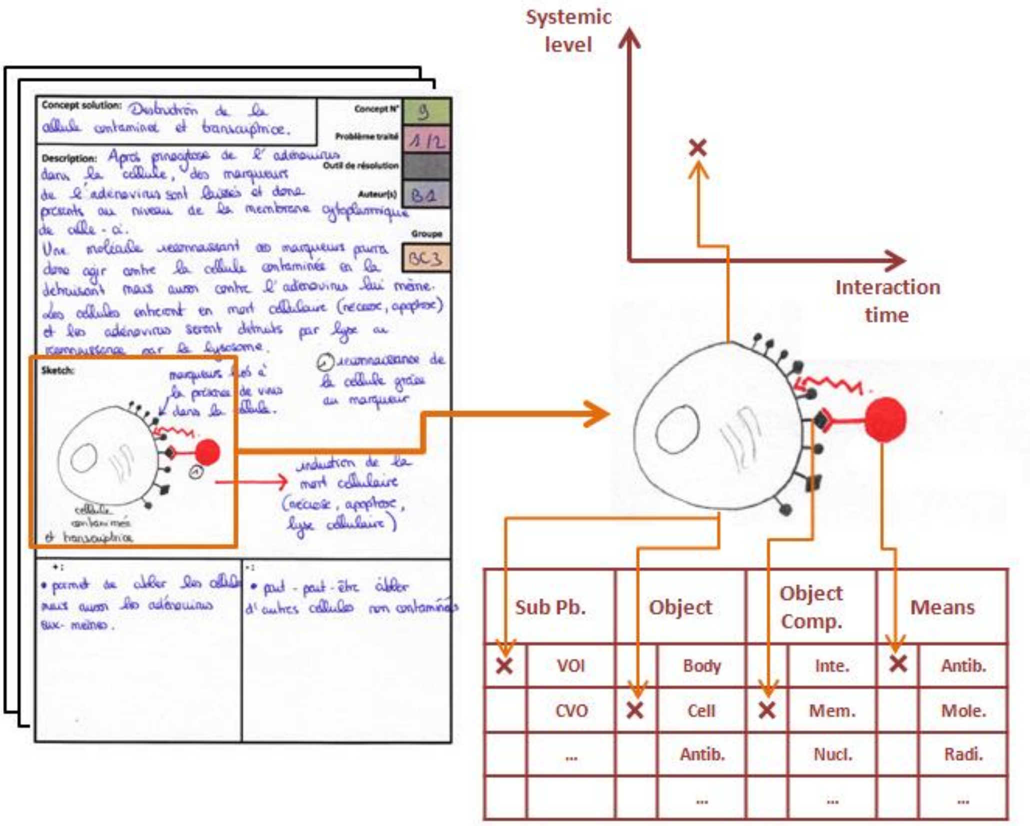


Figure 88

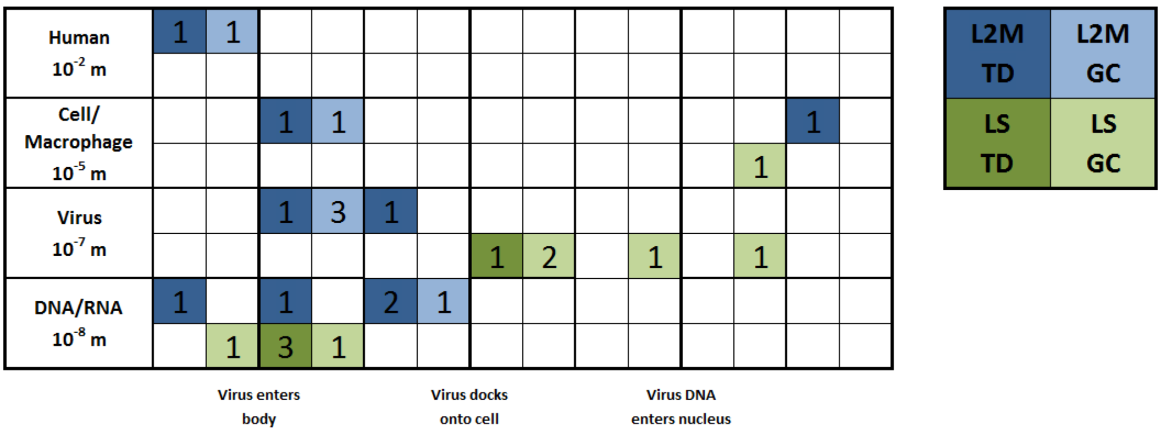


Figure 89

4.2.4 Discussion

Au total, les résultats de l'expérimentation présentée valident les Hypothèses 1 et 2. Figure 12 et Tableau 12 résument le résultat de l'expérience, ainsi que la validation des hypothèses ou sous-hypothèses. Figure 12 montre un modèle du processus de résolution de problème adapté de [Nakagawa, 2005]. Les espaces sur les différentes couches représentent les étapes du processus de résolution de problèmes: le problème spécifique mal défini avec le problème initial (PSE), le problème spécifique bien définie avec le problème identifié (IP) documentée par des fiches d'identification des problèmes (PIS) , le modèle de problème documenté par des feuilles problème de structuration (PSS), le modèle de solution (non documenté), la génération divergente d'idées avec des concepts documentés par des concepts feuilles (CS), et enfin, la génération convergente d'idées avec des solutions documentées par des feuilles de solution (SS).

Tableau 12 résume les résultats expérimentaux qui ont été utilisés afin de valider ou de rejeter les sous-hypothèses et dont les variables (boîtes orange dans Figure 12) ont été analysés pour chaque résultat.

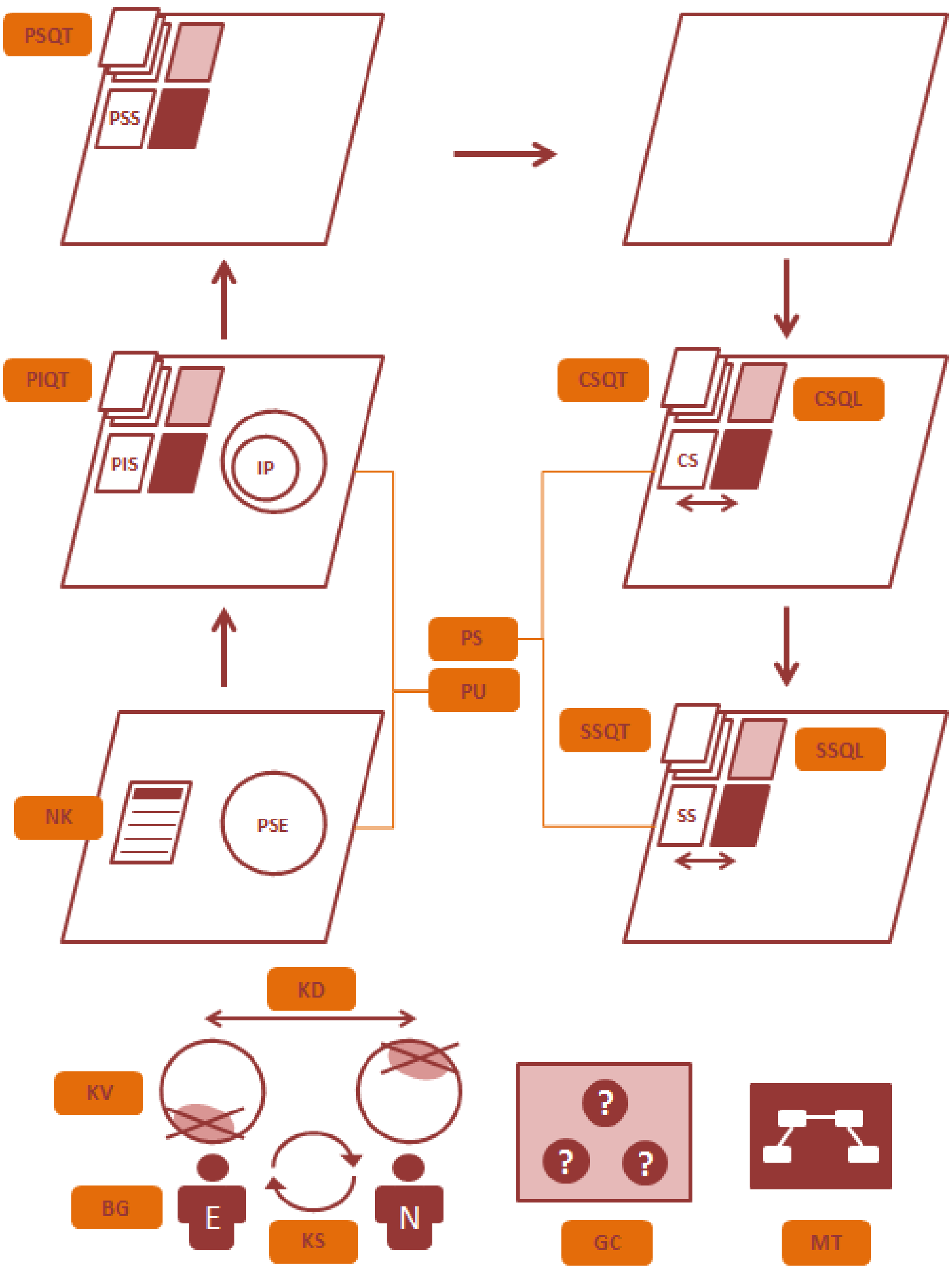

PSQT
PSS
PIQT
PIS
IP
CSQT
CSQL
CS
PS
PU
SSQT
SSQL
SS
NK
PSE
KD
KV
BG
E
KS
N
GC
MT

Figure 90

Tableau 12

Hyp.	Val.	Résultat	GC	BR	PIS QL	MT	KV	SS QT	KD	SSQ L	PU	PIS QT	PSS QT	NK	PS	KS	CS QT	CS QL
H1A	PV	1.15	X	X	X	X												
		1.2		X		X												
		1.7	X			X												
H1B	PV	1.1	X	X			X											
H1C	V	1.13	X					X										
		2.3					X	X	X									
H1D	V	3.1	X							X								
		4.1 - 4.5	X							X								
H2A	V	1.8				X					X							
		1.9				X						X						
		1.10				X							X					
H2B	?	1.4				X	X											
		2.4				X					X			X				
		2.5				X								X	X			
		2.6				X								X		X		
		2.7				X	X								X			
		2.8				X			X							X		
		2.9				X			X							X		
H2C	PV	1.11	X			X											X	
		1.12				X											X	
		1.14	X			X		X										
H2D	V	3.2				X												X
		4.6 – 4.10				X												X

4.2.4.1 *Hypothèse 1*

Sous-Hypothèses 1a et 1b sont partiellement validées. La composition du groupe et le contexte disciplinaire des membres de l'équipe ont eu un impact sur la façon dont les groupes utilisaient des méthodes de TD ainsi que sur l'identification des problèmes et l'analyse du problème. En outre, certains résultats indiquent l'influence de la composition du groupe sur le traitement des connaissances dans une équipe. Parce que ces résultats sont indirects ou parce que leur effet est considéré comme marginal, ces questions nécessitent une enquête plus approfondie. Les sous-Hypothèses 1b et 1c obtiennent une confirmation par les résultats. La composition du groupe impacte les aspects quantitatifs et – à une plus grande échelle – les aspects qualitatifs des produits créatifs. En fonction de la méthodologie appliquée, l'influence de la composition du groupe est même amplifiée. Sur la base de ces résultats expérimentaux, l'Hypothèse 1 est validée.

4.2.4.2 *Hypothèse 2*

Les résultats valident la sous-Hypothèse 2a car ils indiquent des différences en termes d'identification et de structuration des problèmes entre les groupes qui ont utilisé la méthodologie GC et celles qui ont suivi l'approche de TD. En ce qui concerne la sous-Hypothèse 2b, les résultats de l'expérience sont mitigés. L'analyse des résultats du processus de création indique une influence positive de TD sur le traitement des connaissances dans des équipes interdisciplinaires, cependant la perception des participants est différente. Par conséquent, la sous-Hypothèse 2b ne peut être ni validée ni clairement rejetée. L'impact de l'approche méthodologique sur les aspects quantitatifs des produits créatifs, qui est suggéré par la sous-Hypothèse 2c, est partiellement validé. Comme expliqué dans le paragraphe précédent, l'influence méthodologique sur les caractéristiques créatives des concepts et des solutions générées a été montrée comme étant fonction de la composition du groupe. Enfin, la sous-Hypothèse 2d est soutenue par notre expérience. Nos résultats indiquent une relation entre la méthodologie appliquée par le groupe et le type de produit de ce groupe. Compte tenu des résultats des différents sous hypothèses, l'Hypothèse 2 est considérée comme validée par l'expérience.

4.2.5 Conclusion

A la connaissance de l'auteur, l'expérience présentée dans ce chapitre est la première à examiner à grande échelle les impacts combinés de la composition d'équipes disciplinaires et de l'application de méthodes de créativité dans des conditions de laboratoire. Cette expérience fournit des informations sur les processus de résolution créative et collaborative de problèmes interdisciplinaires fortement basés sur la connaissance scientifique - dans le cas de l'expérience présentée, des problèmes médicaux. Jusqu'à un certain degré, les implications de la composition de groupe disciplinaire et de l'ensemble des connaissances différentes dans une équipe aussi bien que du cadre méthodologique sur le premier développement de concept ont pu être mises en évidence. Particulièrement l'impact de méthodes provenant de TRIZ et de ces dérivées sur la résolution de problèmes dans des groupes interdisciplinaires semble avoir un intérêt dans le domaine du NPPD. En allant plus loin, on a également pu montrer que les principes de base des méthodologies de conception rationnelles, que l'on considère généralement comme très complexes, peuvent être appliquées à un degré raisonnable après une formation plutôt courte. Cependant, il semble que la présence d'individus originaires du domaine de la conception soit tout de même nécessaire pour appliquer ces techniques à d'autres domaines d'expertise. Néanmoins, quelques résultats indiquent aussi que les participants voient des inconvénients à la méthodologie TD quant à son applicabilité et à sa capacité à communiquer des connaissances. Par conséquent il semble qu'il y ait un besoin de développer une approche méthodologique qui unifie les avantages des deux concepts méthodologiques identifiés : la capacité de faciliter l'analyse de problème et la compréhension de problème de TD d'un côté et la liberté de suivre et de communiquer le raisonnement et les stratégies de résolution de problèmes personnels que fournissent les approches GC.

Cependant, l'Expérience couvre principalement la première étape du processus de développement, c'est-à-dire la phase de la génération d'idées. Par conséquent elle fournit seulement des réponses à certaines parties de la Question de Recherche, à savoir les réponses relatives aux aspects liés à la façon de soutenir la recherche et - à un certain degré - l'évaluation de la connaissance et des technologies provenant des domaines fortement basés sur la connaissance pour la résolution de problèmes. Néanmoins, l'Expérience ne donne pas de réponses à la question de comment évaluer les concepts de solution qui impliquent l'utilisation de technologies originaires de domaines éloignées. Il ne clarifie non plus comment les problèmes liés à l'intégration de telles technologies peuvent être résolus. L'Étude de cas qui va suivre a été conçue pour fournir quelques réponses à ces questions, qui sont d'une importance particulière pour les stades ultérieurs du processus de NPPD.

L'Étude de cas sera décrite en détail dans les chapitres suivants.

4.3 Etude de Cas Industrielle

4.3.1 Introduction

De la recherche bibliographique nous pouvons identifier deux façons dont les personnes qui doivent résoudre des problèmes (en conception) peuvent profiter des acteurs d'autres domaines.
La première stratégie consiste en l'utilisation d'expertises par rapport à des problèmes et stratégies de résolution de problème provenant d'autres domaines. L'intégration de ces principes abstraits dans la résolution de problèmes de la conception est appelée transfert de connaissance. La seconde façon est d'utiliser les produits de l'activité d'autres acteurs comme par exemple des artefacts et des découvertes afin de résoudre des problèmes de conception spécifiques. Cette approche est appelée transfert de technologie.
L'expérimentation présentée dans le chapitre précédent a étudié la résolution coopérative de problèmes sans faire une distinction explicite entre ces deux approches. Cependant, il reste à savoir comment des solutions générées pendant les phases précoces du processus NPPD et qui sont basées sur l'application de connaissances provenant d'un autre domaine peuvent être développées d'avantage.
L'Hypothèse 3 et l'Etude de Cas, qui a été développé pour tester l'hypothèse ont été formulées pour répondre à cette question.
Hypothèse 3 suggère que certains axiomes et méthodes provenant du complexe TRIZ pour la conception d'un méta-modèle sont pertinents pour l'intégration de technologies fortement basées sur la connaissance dans des applications données. De la littérature, on peut identifier les prérequis nécessaires au développement de ce genre de méta-modèle :

- Il devrait être possible de faciliter un processus de transfert technologique lors de l'identification du problème en identifiant des technologies qui portent le potentiel pour résoudre ce problème, et de les intégrer de manière dans le produit ou le processus cible [Grant, 1996; Alavi et Leidner, 2001] (cf. Le Paragraphe 2.2.4.2.2 du Rapport) [Albers et al., 2014] (cf. Le Paragraphe 2.2.7 du Rapport). Les deux premiers aspects de ce processus, c'est-à-dire l'identification du problème et l'identification de technologies potentielles, sont bien soutenus par la théorie et la méthodologie de conception [par exemple Savransky, 2000; Suh, 2001; Croix, 2008] (cf. Le Chapitre 2.5.3.3 du Rapport) [par exemple. Bhatta et Goel, 1996; Vincent et al., 2005; Verhaegen et al., 2011] (cf. Le Chapitre 2.5.6.3). Le troisième aspect, c'est-à-dire la résolution des problèmes qui empêchent l'intégration de ces technologies, n'a pas obtenu de support méthodologique jusqu'à présent. [Gericke et Blessing, 2011; Chulvi et al., 2013]. Cependant, cet aspect est identifié parmi les raisons les plus importantes expliquant les difficultés à effectuer un transfert technologique avec succès [Albers et al., 2014].
- L'approche devrait combiner
  - Les avantages de méthodes de créativité générales comme
    - Intuitivité [Schah et al., 2000]
    - Applicabilité générale [Ilevbare et al., 2013 ; Gonçalves et al., 2014]

  ainsi que
  - Les concepts de TRIZ et ses dérivées qui sont le plus largement acceptés et qui ont prouvés utiles comme
    - Le concept d'Idéalité [Ilevbare et al., 2013] (Paragraphe 4.2.4.3 du Rapport)
    - Les principes dialectiques [Moehrle, 2005] (Paragraphe 2.5.3.3.1.2) et

   - Les outils de modélisation de problème (ex. l'approche du Monde Clos et la méthode des Particules Magiques).
- Une autre exigence est la facilitation de processus de résolution de problèmes avec la participation de plusieurs experts interagissants et surmontant les inconvénients existants de méthodes comme par exemple Brainstorming [Taylor et al., 1958; Diehl et Stroebe, 1987] (cf. Le Paragraphe 2.3.4.3.1 du rapport).
- De plus, l'approche exigée devrait satisfaire un ensemble de critères comme la simplicité, l'adaptabilité aux ressources disponibles en termes de temps et la connaissance d'expertise, aussi bien que des exigences de temps limitées pour l'apprentissage de l'approche [Geis et al., 2008; Ilevbare et al., 2013] (cf. Le Chapitre 2.5.7 du rapport).
- Finalement, elle devrait présenter un cadre qui est suffisamment ouvert pour permettre l'application de modèles et méthodes qui ont prouvé leur valeur pour des problèmes et conditions plus spécifiques [par exemple Bender et Blessing, 2003, Tomiyama et al., 2009] (cf. Le Chapitre 2.5 du Rapport).

Dans le chapitre présent, un méta-modèle pour aider au processus d'intégration technologiques sera présenté et permettra l'intégration et l'application de différentes méthodes de modélisation et de résolution de problème. De plus, le test de ce méta-modèle, des méthodes associées et par ainsi de l'Hypothèse 3 sera effectuée lors de notre étude de cas. Après l'introduction du méta-modèle d'intégration technologique, des exemples d'application technologiques seront présentés puis une étude de cas en situation réelle sera effectuée. Afin de tester la validité de l'Hypothèse 3, le modèle sera comparé aux approches existantes. Le chapitre termine en mettant en avant les limitations du test présenté.

4.3.2 Présentation du Méta-Modèle

Au cours de cette recherche de doctorat, un méta-modèle qui sert comme cadre pour l'intégration de plusieurs outils méthodologiques a été développé. Ce méta-modèle, qui est censé satisfaire les exigences mentionnées ci-dessus, sera décrit dans les paragraphes suivants.

4.3.2.1 Application et Technologie / Problème et Solution Potentielle

Le méta-modèle qui sera présenté dans ce rapport est composé de deux espaces. Ceux-ci sont l'Espace du Problème (ou l'Espace d'Application) et l'Espace de Solution (ou l'Espace de Technologie). La modélisation de processus d'intégration de technologie en utilisant ces deux espaces est basée sur la théorie de la résolution de problème (cf. le Chapitre 2.5.2.1.1 du rapport) et permet ainsi une description abstraite et générique. L'Environnement du Problème ou de l'Application, qui est un sous-ensemble de l'Espace d'Application, décrit les contraintes du domaine du problème spécifique à résoudre. La Configuration du Problème ou de l'Application, finalement, est définie comme un sous-ensemble de l'Environnement d'Application. Il est composé d'éléments physiques et non-physiques aussi bien que d'interactions et d'interdépendances entre ces éléments, qui décrivent le problème à résoudre de façon exhaustive.

La solution - ou l'Espace Technologique, l'Environnement Technologique et l'Arrangement de Technologie est définie de façon analogue. L'Espace de Solution est un continuum énorme qui couvre toutes les solutions potentielles d'un problème donné. L'Environnement de la Solution, comme un sous-ensemble de l'Espace de Solution, contient toute la connaissance pertinente (appropriée) et les contraintes à l'égard d'un Arrangement de Solution spécifique. L'Arrangement de Solution, à son tour, est défini comme l'ensemble d'éléments physiques et non-physiques et des interactions entre ces éléments, qui décrivent de manière exhaustive une solution dans son domaine initial d'application (cf. la Figure 13).

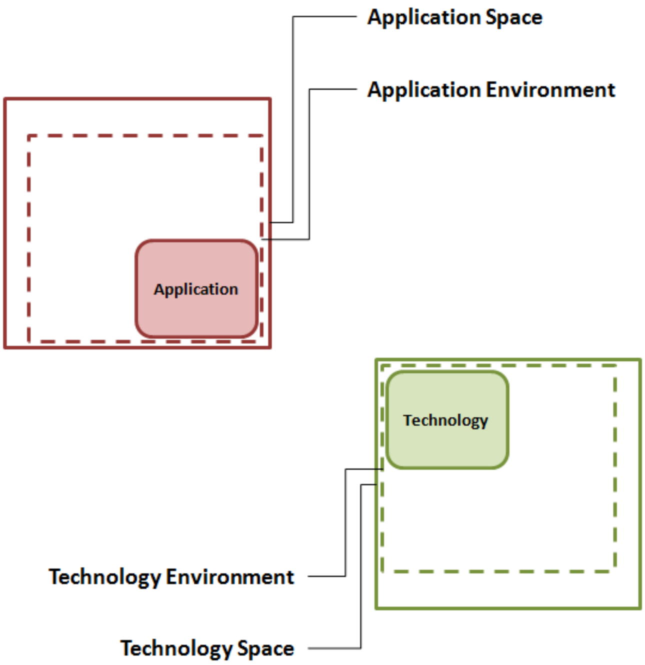


Figure 91

4.3.2.2 *Interactions Souhaitées et Non-Souhaitées*

L'intégration d'une Technologie dans une Application donnée a pour but de satisfaire certains besoins. La modélisation de ces besoins aussi bien que d'autres interactions entre la Technologie et l'Application est exécutée en utilisant des principes de modélisation fonctionnelle comme ceux utilisés par exemple dans l'Analyse Fonctionnelle, TRIZ et USIT (cf. Le Chapitre 2.5.3.1).

Selon le méta-modèle, quatre types d'interactions sont possibles entre l'Application et la Technologie. Tout d'abord, la Technologie exécute un certain nombre d'Interactions ou fonctions Désirées sur l'Application. Ces fonctions sont la raison du choix d'une Technologie spécifique. Cependant, dans la majorité des cas imaginables la Technologie exécute aussi un ensemble d'effets secondaires (ou interactions) non-désirés sur l'Application.

De même, l'Application doit exécuter un certain nombre d'Interactions Désirées sur la Technologie. Celles-là peuvent prendre la forme de ressources comme le matériel, l'énergie ou des informations, ou l'infrastructure par exemple. Finalement, et de façon analogue à la Technologie, il arrive souvent que l'Application exécute des Interactions Non-Désirées sur la Technologie. Ces effets indésirables peuvent réduire ou éliminer le fonctionnement de la Technologie ou ils peuvent affecter voir même détruire cette Technologie (cf. la Figure 14).

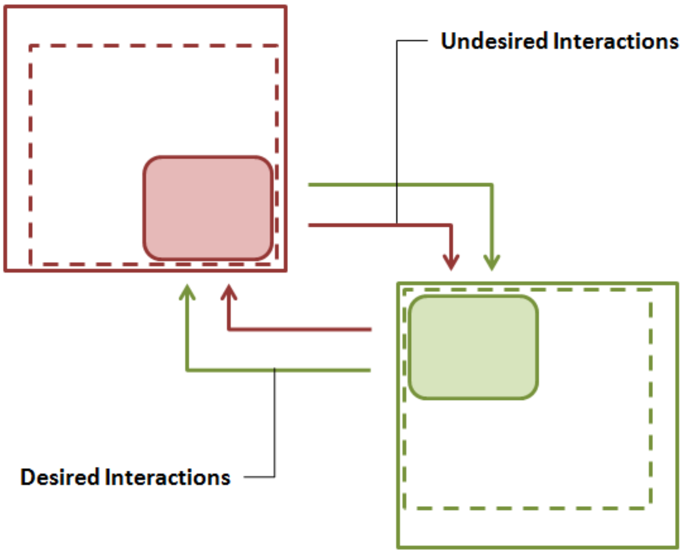


Figure 92

4.3.2.3 Potentiels, Risques, Besoins et Protections

Selon le méta-modèle, l'Application et la Technologie possèdent un ensemble des Propriétés qui influencent leurs Interactions mutuelles. Ces Propriétés sont appelées le Potentiel, le Risque, le Besoin et la Résistance (cf. la Figure 15) et se lisent comme suit :

Propriétés Technologiques :

- Potentiel Fonctionnel (P_T) : Cette Propriété indique la capacité qualitative et quantitative de la Technologie à exécuter des Interactions Désirées sur l'Application.
- Le Risque d'Affecter l'Application (A_T) : Cette Propriété décrit le risque d'exercer des Interactions Non-Désirées sur l'Application.
- Besoin de Ressources (N_T) : Cette Propriété indique les exigences de la Technologie pour effectuer ses fonctions correctement.
- Résistance aux Effets Secondaires de l'Application (R_T) : Cette Propriété se réfère à la robustesse d'une Technologie quant aux conditions nuisibles possibles de l'Application ou de l'Environnement D'application.

Propriétés D'application :

- Potentiel de Ressource (P_A) : Cette Propriété indique la capacité de l'Application à fournir les ressources nécessaires pour assurer un fonctionnement approprié de la Technologie.
- Le Risque d'Affecter la Technologie (A_A) : Cette Propriété se réfère au risque d'exercer des Interactions Peu désirées avec la Technologie.
- Besoin de Fonction (N_A) : Cette Propriété décrit les exigences fonctionnelles de l'Application.
- Résistance aux Effets Secondaires Technologiques (R_A) : Cette Propriété indique la robustesse d'une Application et de ses constituants quant aux effets secondaires nuisibles de la Technologie.

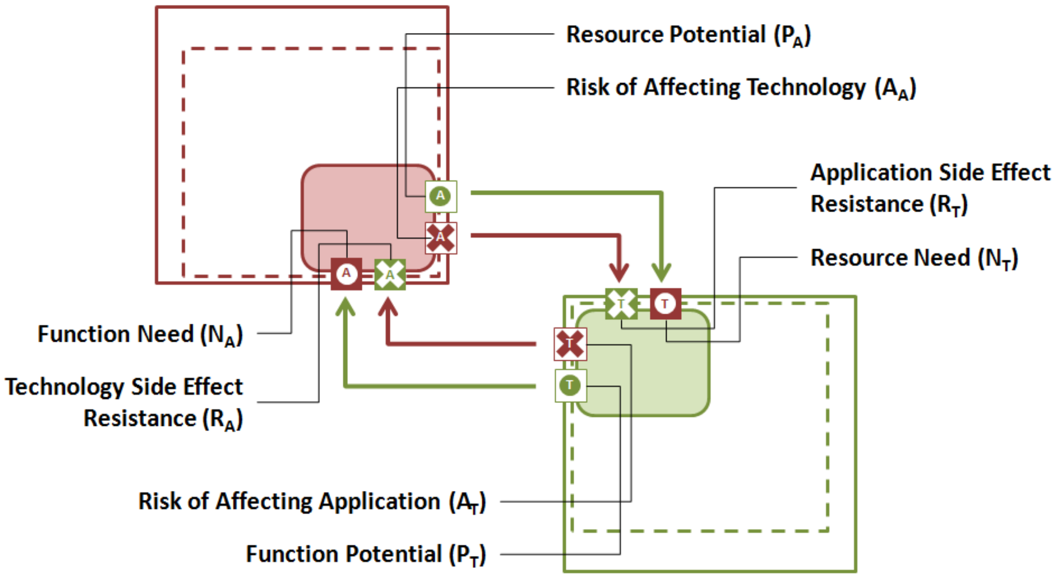


Figure 93

4.3.2.4 Idéalité

Le concept d'Idéalité (le Paragraphe 2.5.3.1.1.2) est une des caractéristiques les plus importantes de TRIZ et ses dérivées. Il cherche à guider la recherche de solutions une fois que le problème a été défini. De plus, la modélisation de la solution idéale fait partie des concepts de TRIZ et ses dérivées le plus fréquemment utilisés par les participants pendant l'Expérience.

Basé sur le meta-modèle présenté dans les paragraphes précédents, deux types d'Idéalité peuvent être définis. D'abord, la Technologie Idéale, du point de vue de l'application, facilite la recherche des technologies qui pourraient résoudre un problème donné. Deuxièmement, l'Application Idéale, du point de vue Technologique, permet la recherche de nouvelles applications à une solution donnée.

Renvoyant à ces deux perspectives d'Idéalité, deux scénarios génériques idéaux peuvent être dessinés. Ces scénarios sont nommés des Idéalités Partielles et sont décrits comme suit cf. (la Figure 16).

La Technologie Idéale (I_T), du point de vue de l'Application, possède les propriétés suivantes (cf. aussi la Formule 1) :

- Haut Potentiel Fonctionnel : les fonctions que la Technologie exécute correspondent en termes de qualité et de quantité au Besoin de Fonction de l'Application.
- Haute Résistance aux Effets Secondaires de l'Application : la Technologie est résistante aux interactions négatives spécifiques qui pourraient résulter des conditions dans l'Environnement de l'Application.
- Risque faible d'Affecter l'Application : le risque que les éléments ou les principes de fonctionnement de la Technologie affectent ceux de l'Application est bas.
- Besoin de Ressource Bas : la Technologie exige peu ou pas de ressources pour fonctionner correctement.

$$I_T = \lim_{\substack{P_T,R_T \to \infty \\ A_T,N_T \to 0}} \frac{P_T + R_T}{A_T + N_T} \qquad \text{(Formule 1)}$$

De la même façon, l'Application Idéale (I_A), d'une perspective de la Technologique, dispose des propriétés suivantes (cf. aussi la Formule 2) :

- Haut Potentiel de Ressources : Les ressources qui sont disponibles dans l'Application ou son Environnement de l'Application correspondent aux exigences de la Technologie pour fonctionner correctement.
- Résistance aux Effets Secondaire de la Technologie Elevée : L'Application résiste aux interactions négatives spécifiques qui pourraient résulter de la Technologie ou de son fonctionnement.
- Risque faible d'Affectation de la Technologie : Le risque que les éléments ou les principes de fonctionnement de l'Application affectent ceux de la Technologie est bas.
- Bas Besoin Fonctionnel : Les exigences fonctionnelles de l'Application correspondent exactement aux fonctions que la Technologie peut fournir, en termes qualitatifs aussi bien qu'en termes quantitatifs.

$$I_A = \lim_{\substack{P_A, R_{A \to \infty} \\ A_A, N_{A \to 0}}} \frac{P_A + R_A}{A_A + N_A} \qquad \text{(Formule 2)}$$

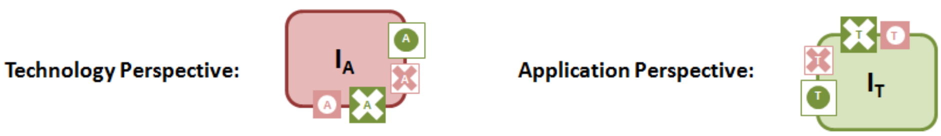


Figure 94

4.3.2.5 Modélisation de Problèmes

Le meta-modèle présenté permet aussi la modélisation et la catégorisation des problèmes qui arrivent une fois qu'une technologie a été choisie pour être intégrée dans une application donnée. De plus, en utilisant ce méta-modèle, des Stratégies Génériques pour surmonter les problèmes d'intégration peuvent être identifiées. Ces Stratégies Génériques, à leur tour, indiquent les sous-problèmes spécifiques qui peuvent être assignés aux domaines d'expertise concrets dans lesquels la résolution des problèmes peut avoir lieu. Cette catégorisation systématique de Problèmes d'Intégration Technologiques dans un ensemble fini de sous-problèmes peut être comparée à la Méthode de Factorisation, qui suit des principes semblables [Pahl et al., 2007].

Quatre types de Problèmes d'Intégration Technologiques existent :

- Interactions Technologiques Insuffisantes (ITI) : les Interactions désirées que la Technologie est censée exécuter sur l'Application ne correspondent pas aux exigences.
- Effets Secondaires Technologiques Nuisibles (DTS) : la Technologie exerce une influence négative sur l'Application.
- Des Ressources Insuffisantes pour le Fonctionnement de la Technologie (IRF) : Les ressources que l'Application fournit ne sont pas suffisantes pour un fonctionnement approprié de la Technologie.
- Effets secondaires Nuisibles D'Application (DAS) : L'Application) exerce une influence négative sur la Technologie.

Pour chaque type de Problème d'Intégration Technologique, deux Stratégies Génériques peuvent être identifiées (Figure 17) :

- Interactions Technologiques Insuffisantes (ITI) : Les tentatives de résolution de problèmes peuvent se concentrer sur l'amélioration du Potentiel Fonctionnel de la Technologie (P_T) ou sur la réduction du Besoin de Fonctionnel de l'Application (N_A).
  - Effets secondaires Technologiques Nuisibles (DTS) : Ceux qui doivent résoudre le problème peuvent travailler sur l'amélioration de la Résistance de l'Application aux Effets Secondaires de la Technologie (R_A) ou sur la réduction du Risque que la Technologie Affecte l'Application) (A_T).
  - Ressources Insuffisantes pour le Fonctionnement de la Technologie (IRF) : Dans ce cas, les Stratégies Génériques sont l'amélioration du Potentiel de Ressource de l'Application (P_A) et la réduction du Besoin de Ressources de la Technologie (N_T).
  - Effets secondaires Nuisibles à l'Application (DD) : Pour résoudre ce problème d'intégration, la Résistance aux Effet Secondaires de l'Application de la Technologie (R_T) peut être augmentée ou le Risque de l'Application d'Affecter la Technologie (A_A) peut être réduit.

La subdivision des Problèmes d'Intégration Technologiques souvent complexes dans des Stratégies Génériques de domaines spécifiques permet aussi bien la résolution créative de problèmes dans des équipes mono-disciplinaires que la résolution de problèmes communs dans des groupes interdisciplinaires. Comme les problèmes sont subdivisés en plusieurs sous-problèmes, l'application de techniques de créativité de groupe comme par exemple l'Enquête Dialectique, le Brainwriting, la Méthode 635 ou la Méthode de Galerie (cf. Les Chapitres 2.3 et 2.5 du rapport) sont possibles.

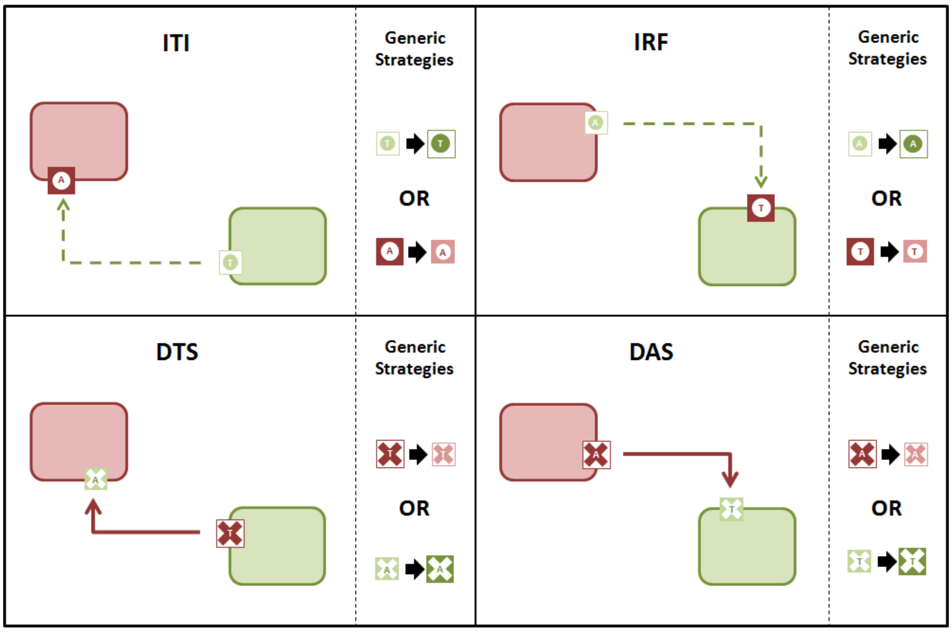


Figure 95

4.3.3 Application du Méta-Modèle

Le méta-modèle pour l'intégration d'une technologie dans une application spécifique présenté (cf. Le Paragraphe 4.3.2) et le processus associé ont été testés (cf. le Paragraphe 4.3.3 du Rapport) lors d'une étude de cas industrielle. Cette étude sera présentée dans le chapitre suivant. À cause des raisons de confidentialité, le sujet exact de l'étude aussi bien que les résultats exacts ne peuvent pas être révélés.

4.3.3.1 Contexte Industriel

Le partenaire industriel pour cette étude de cas était SKF (Svenska Kullagerfabriken) AB, un fabricant suédois de roulements à bille dans le segment haut de gamme. Le département partenaire à Saint Cyr était l'unité qui est responsable des *Deep Groove Ball Bearings* (DGBB) et des *Self-Aligning Ball Bearings* (SABB) pour des applications industrielles.

SKF a appliqué plusieurs méthodologies de développement de produits et de gestion de qualité depuis 1990. Particulièrement des ensembles d'outils de Six Sigma et le Design pour Six Sigma (DFSS) [cf. Staudter et al., 2013 pour une synthèse] ont été appliqués sur plus de 1000 projets par plus que 20 *« Master Black Belts »*, 400 *« Black Belts »* et 2100 *« Green Belts »* à partir de 2011 [Johnstone, 2011].

L'étude de cas a été exécutée en coopération avec un manager d'innovation Black Belt DFSS et un chef de projet Green Belt DFSS (ingénieurs de développement chez SKF), qui avaient obtenu une formation de trois jours dans des méthodes de créativité aussi bien que dans TRIZ et ses dérivées.

4.3.3.2 Résumé des Phases de l'Application du Méta-Modèle

Pendant l'étude cas, les cinq phases du Méta-Modèle pour l'intégration d'une technologie dans une application spécifique ont été appliquées. Pendant que certaines phases ont été effectuées par l'auteur avec les ingénieurs de développement de SKF, d'autres ont été effectuées par l'auteur seul. Les phases du processus mentionné sont :

- Définition de l'Application et de son environnement
- Définition des Propriétés de l'Application (N_A, R_A, P_A et A_A)
- Identification des Technologies Potentielles
- Evaluation des Technologies Potentielles et sélection de technologies
- Résolution de problèmes liés à l'intégration de technologies.

4.3.4 Evaluation du Méta-Modèle

Pour comparer notre méta-modèle pour l'intégration technologique avec des approches méthodologiques existantes, on a demandé aux participants de l'étude de cas, c'est-à-dire les ingénieurs de développement SKF, d'évaluer la performance du processus et des outils associés contre des processus suggérés et facilités par DFSS. Cette évaluation sera discutée dans ce chapitre.

4.3.4.1 Critères d'Evaluation

Pour évaluer l'approche globale appliquée, on a demandé aux participants de comparer la performance de l'approche avec la performance de méthodes utilisées normalement vis-à-vis des paramètres de performance présentés ci-dessous [Thiebaud, 2003] (Tableau 13).

Les critères d'évaluation sont classifiés dans quatre groupes. Le premier groupe représente deux aspects de performance relatifs à la capacité de l'approche à indiquer et traiter la connaissance provenant d'autres domaines. Le deuxième groupe liste des critères de performance qui concernent la diversité, l'originalité et la qualité du résultat du processus. Les deux dernières classes de critères contiennent respectivement deux et trois critères et touchent aux aspects d'acceptabilité des méthodes et aux efforts nécessaires pour comprendre la méthode.

4.3.4.2 Performance du Processus Proposé

On montre les résultats de l'évaluation dans la Figure 18.

On a jugé que l'approche présentée a été supérieure aux approches actuelles en termes de performance par rapport au transfert de connaissances lorsque la différence du score moyen des deux critères (QDE et IMK) était d'au moins de 2.5 points.
Lorsqu'il s'agit des critères de performance liés à la qualité des concepts produits, les résultats sont quelque peu mixtes. L'approche présentée donne de meilleurs résultats en ce qui concerne l'originalité (OGC) et la diversité (DGC) de concepts produits. Cependant, l'explorabilité des concepts générés (EXGC) par l'approche présentée est seulement légèrement meilleure que celles des approches actuellement utilisées. En termes de niveau d'élaboration des concepts (ELGC), les approches actuellement utilisées (l'Hybridation de Matrice Pugh [cf. aussi Staudter et et al., 2013] a été mentionné) ont été jugés comme fournissant des résultats légèrement meilleurs.
Les approches déjà établies ont été évaluées comme exigeant moins de ressources en termes de temps et de moyens auxiliaires pour la préparation des ateliers de résolution créative de problèmes (EWP) comparé avec l'approche présentée. Le temps qui est exigé pour la génération de concepts pendant l'atelier (FCG) a été évalué égal pour les deux approches.
Finalement, l'approche présentée a obtenu des résultats légèrement plus élevés dans les critères liés à l'apprentissage. Comparé aux méthodes actuellement utilisées, elle a été évaluée comme disposant d'une logique et d'une structure plus explicite (PS). De plus, les ingénieurs participants ont trouvé que l'approche appliquée exige des outils et techniques moins sophistiqués que les processus actuellement utilisés (EI). On a considéré le temps qui est nécessaire pour être capable d'appliquer avec succès la méthode (EL) était égal pour les deux approches.

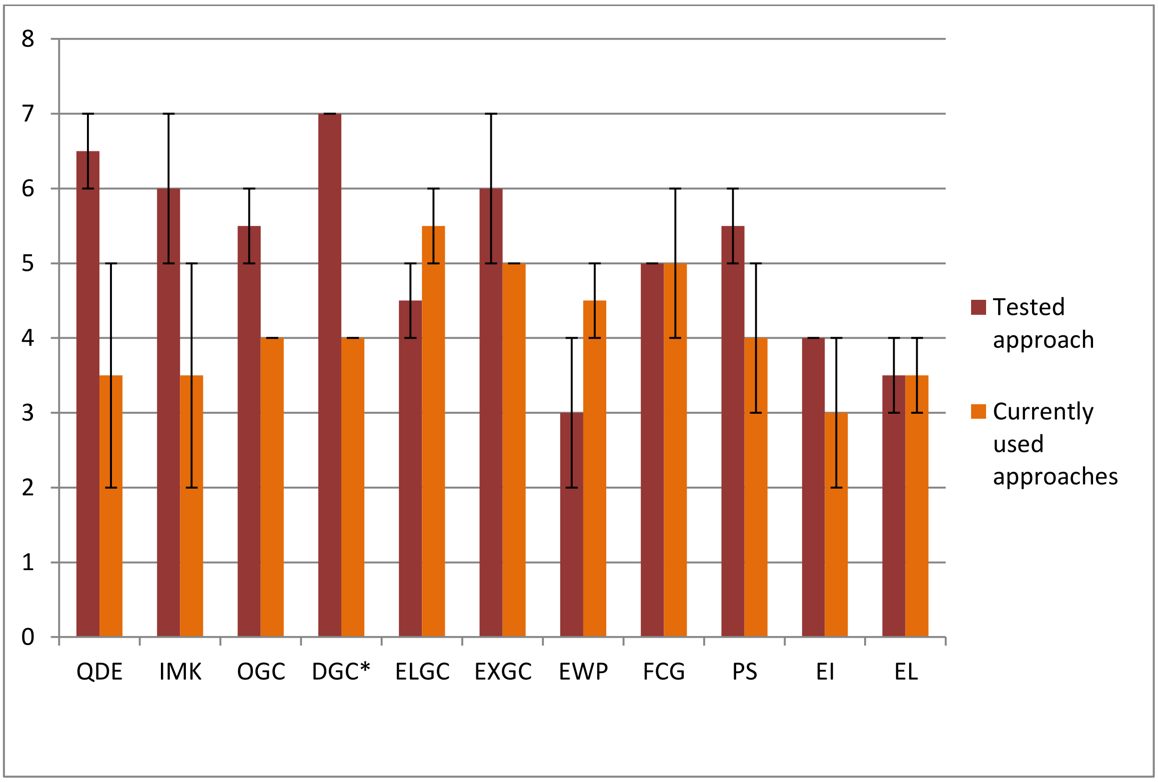


Figure 96

Tableau 13

No.	Critère	Abrév.	Description	Evaluation
1	Mécanisme pour quitter le domaine d'expertise	QDE	Est-ce la méthode aide le concepteur à considérer autres solutions que celles liées à son domaine d'expertise ?	Lié au transfert de connaissance
2	Indication de connaissance manquante	ICM	Est-ce que la méthode aide à identifier informations/connaissance/capacités qui devraient être obtenus pour continuer le développement de l'idée / de la solution ?	
3	Originalité des concepts générés	OCG	Est-ce que la méthode favorise la génération d'idées qui n'ont pas été générées avant ?	Lié à la qualité des concepts
4	Diversité des concepts générés	DCG	Est-ce que la méthode permet la génération d'idées qui implémentent différente connaissance (ou expertise) dans les limites du problème données (application donnée / fonction à réaliser donnée / technologie à utiliser donnée)	
5	Niveau d'élaboration des concepts générés	ELCG	Est-ce que la méthode favorise la combinaison de différentes solutions (ou technologies) pour développer des idées/solutions plus sophistiquées/développées ?	
6	Exploitabilité des concepts générés	EXCG	Est-ce que les solutions générées sont estimées de valoir une exploration d'avantage est est-ce qu'elles semblent exploitables ? / Quelle est le pourcentage des idées explorables et ou exploitables ?	
7	Facilité de préparer les sessions	FPS	Combien de temps et quels moyens sont nécessaires pour préparer une session de workshop.	Lié aux ressources
8	Fluidité de génération des concepts	FGC	Est-ce que la méthode permet la génération rapide d'idées multiples par rapport à un sujet (une technologie) ?	
9	Structure du processus	SP	Est-ce que la méthode propose un processus, une logique explicite d'implémentation ?	Lié à l'apprentissage
10	Facilité d'implémentation	FI	Est-ce que l'implémentation de la méthode nécessite des techniques sophistiquées ?	
11	Facilité d'apprentissage	FA	Est-ce que la compréhension initiale de la méthode demande plutôt quelques heures ou plusieurs mois ?	

4.3.5 Discussion

Les résultats de l'Étude de Cas seront discutés en ce qui concerne l'Hypothèse 3 en particulier dans ce chapitre.

4.3.5.1 Discussion par Rapport à Hypothèse 3

L'hypothèse 3 postule que les axiomes et les méthodes de TRIZ et ses dérivées ont une valeur pour l'évaluation et l'intégration de technologies fortement basées sur la connaissance pour résoudre des problèmes lors des processus de NPPD industriels.

Pour tester cette hypothèse, ces axiomes et méthodes de TRIZ et ses dérivées qui ont été les plus acceptées et appliquées pendant l'Expérience ont été intégrés dans un méta-modèle pour la recherche de l'intégration de technologies. Ce méta-modèle a été alors testé dans une étude de cas industriel.

Dans le contexte de l'Hypothèse 3, les critères liés au transfert de connaissance et à la qualité des concepts ont été d'un intérêt particulier.

Les premiers indiquent à quel degré l'approche présentée et les éléments TRIZ et dérivées mènent à la considération d'espaces de connaissance éloignés et au raisonnement dans ces espaces. Le

derniers apportent, dans une certaine mesure, de la connaissance sur l'efficacité des axiomes et méthodes de TRIZ lorsqu'il s'agit de l'intégration de connaissance dans des concepts de résolution de problème.
Comme mentionné dans le Paragraphe 4.3.4.2, l'approche proposée présente des avantages en ce qui concerne les critères liés au transfert de connaissance et mène à plus de concepts originaux et diversifiés que les approches actuellement utilisées. La performance des deux approches est quelque peu comparable en termes de niveau d'élaboration et d'explorabilité des concepts.
Ces résultats donnent des premières indications que le méta-modèle présenté et les méthodes associées pourraient représenter une approche utile pour soutenir la recherche et l'évaluation de technologies fortement basées sur la connaissance aussi bien que pour l'intégration de ces technologies afin de résoudre des problèmes de NPPD.
Cependant, en raison de plusieurs limitations de la configuration de l'étude de cas - l'approche n'a pu être testée que dans seulement une étude de cas industrielle et seulement deux participants ont évalué l'approche - l'Hypothèse 3 ne peut pas être validée avec une certitude statistique. Des études plus quantitatives couvrant un spectre de domaines d'application plus large devraient ainsi être conduites.

4.3.5.2 Discussion Supplémentaire

Pendant le développement du méta-modèle présenté et du processus associé, un focus a été mis sur la simplicité et l'adaptabilité de l'approche ainsi que sur un temps nécessaire limité pour les participants avant de pouvoir appliquer l'approche avec succès.
Les ingénieurs participants ont évalué la préparation d'une session de résolution de problèmes avec l'approche présentée comme exigeant plus d'efforts (EWP) que dans le cas d'approches actuellement utilisées. Il pourrait être argumenté que l'effort supplémentaire a été dû à un autre aspect ayant seulement un lien indirect avec l'approche. En fait, les enquêtes qui ont dû être exécutées pour obtenir des informations manquantes et la connaissance - qui, à son tour, avait été identifiée pendant le processus - étaient chronophages. En ce sens, l'effort supplémentaire serait un prix à payer pour présenter et traiter la connaissance provenant de domaines plus éloignées pendant les sessions de résolution de problèmes.
De plus, le processus testé a été jugé comme étant plus structuré que des approches actuellement utilisées et comme fournissant une logique plus explicite qui améliore les chances d'une mise en œuvre correcte. Ce résultat est interprété comme étant un indice que l'approche présentée, au moins à un certain degré, représente un pas en avant vers des stratégies d'intégration de connaissance plus pédagogiques.

4.4 Conclusion sur les Tests des Hypothèses

Les expériences rapportées dans ce chapitre ont été conçues pour examiner la question de recherche: Comment soutenir méthodologiquement la recherche, l'évaluation et l'intégration de connaissance et technologies provenant de domaines fortement basées sur la connaissance (scientifique) dans les processus de conception de produit et de processus.
L'hypothèse 1 a postulé un impact de composition de groupe disciplinaire sur le processus de résolution créative de problèmes de groupe et son résultat. L'Hypothèse 2 a suggéré que les méthodes choisies pour soutenir la résolution de problèmes de groupe interdisciplinaire avaient aussi une influence significative sur le processus de résolution de problèmes et son résultat. Pour tester ces hypothèses, une expérience a comparé les tentatives de résolution de problèmes de groupes monodisciplinaires avec celles d'équipes interdisciplinaires. De plus, l'expérience a mesuré les différences qui résultent de l'utilisation des méthodes intuitives pragmatiques comme le

Brainstorming comparés aux approches analytiques hiérarchiques comme TRIZ et USIT. En plus de la validation partielle des hypothèses, l'expérience a fourni un aperçu détaillé des avantages et inconvénients des différentes approches méthodologiques pour la résolution de problèmes en groupes mono- et interdisciplinaires.

L'hypothèse 3 a postulé la possibilité d'intégrer les concepts principaux des théories et méthodes provenant TRIZ et USIT dans un méta-modèle pour l'intégration d'une technologie dans un cadre de problème donné. Le méta-modèle donné, qui est présenté dans ce chapitre a été testé dans une Étude de cas industriel et comparé à des approches existantes par des ingénieurs méthodologiquement expérimentés. Les résultats de l'évaluation pointent vers des avantages du méta-modèle présenté en termes de facilitation de transfert de connaissance et en termes de qualité des concepts. Comme l'Étude de cas représente un test singulier, une validation du Meta-modèle d'Intégration Technologique et par ainsi de l'Hypothèse 3 exige encore des analyses plus quantitatives.

5 Synthèse des Contributions de Cette Recherche

Des contributions tant académiques qu'industrielles sont synthétisées dans la section présente. Les premières se réfèrent à un aperçu dans des processus créatifs dans des groupes, à un développement d'un méta-modèle pour la recherche et l'intégration de technologies dans le NCD/NPPD, aussi bien qu'à l'application des méthodes de conception existantes aux systèmes et applications non techniques. En tant que tel, des contributions académiques sont le résultat de l'Expérience, de l'Étude de cas (Figure 19) et d'autre projets et activités.

Les contributions industrielles consistent dans la fusion des approches méthodologiques existantes en conception et des méthodes de gestion pour l'assistance de processus de NCD/NPPD industriels (des Projets 1, 2, 3A, 3B de la Figure 19). La contribution supplémentaire est le développement d'un processus pour la modélisation et la formulation de problèmes pour favoriser des processus d'Innovation Ouverts dans l'industrie pharmaceutique (cf. Projet 4 de la Figure 19).

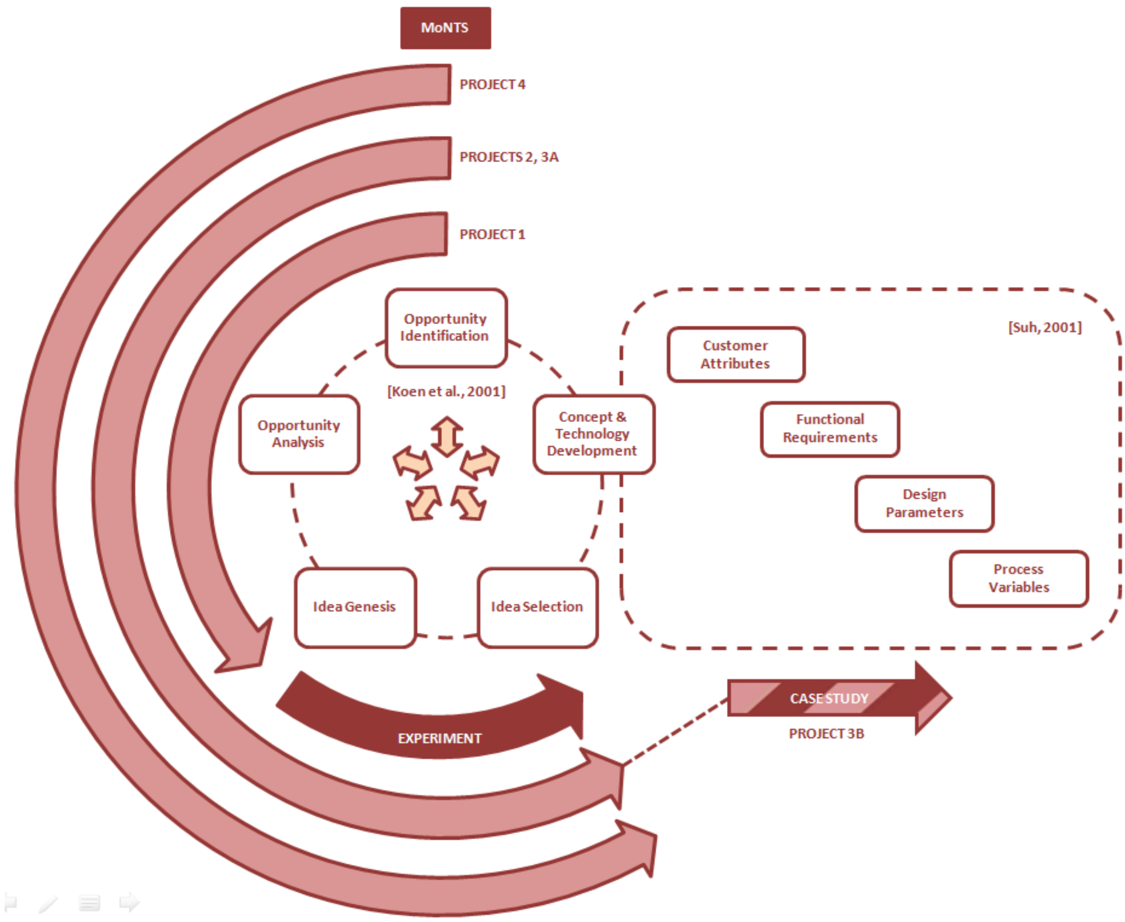


Figure 97

6 Conclusion et Perspectives

6.1 Conclusion

La recherche qui est présentée dans cette dissertation a été pensée pour traiter la question de comment soutenir méthodologiquement la recherche, l'évaluation et l'intégration de la connaissance et des technologies provenant de domaines fortement basés sur la connaissance des sciences naturelles dans des processus de conception de produits et de processus. Elle donne des réponses à cette question en fournissant un aperçu du processus de résolution créative de problèmes interdisciplinaire dans le NCD/NPPD. De plus elle éclaire la valeur des certains concepts de la méthodologie de conception pour l'intégration de technologies fortement basées sur la connaissance dans le contexte de résolution des problèmes de conception. En particulier nous avons pu montrer l'impact de la composition de groupe en association avec le choix de la méthode sur le processus de résolution de problème. Ces impacts ont été aussi bien quantitatifs que qualitatifs. De plus, les avantages et les inconvénients des approches plus pragmatiques comparées aux méthodes plus analytiques et hiérarchiques ont été identifiés. Finalement, un méta-modèle consacré à la description et à la prescription du processus de recherche et d'intégration de technologies fortement basées sur la connaissance a été présenté et testé. Les découvertes les plus importantes de cette recherche sont les suivantes :

- La composition de groupe disciplinaire en termes de formation initiale des membres de groupe ex : formation en design et en science) affecte le traitement de l'information pendant la résolution de problèmes ainsi que les produits du processus créatif termes de qualité et de type.
- L'approche méthodologique utilisée influence le processus de résolution de problèmes ainsi que le type d'idées produites.
- Les groupes monodisciplinaires d'experts de domaine utilisant des méthodes de créativité générales pragmatiques utilisent des processus de résolution de problèmes qui diffèrent de ceux utilisés par des groupes interdisciplinaires utilisant des méthodes hiérarchiques et analytiques : sont différents le processus lui-même, le traitement d'informations pendant le processus, la qualité de production créative et le type de production créative.
- On soupçonne que les raisons de ces différences sont de plusieurs natures. Tout d'abord, la participation de novices dans un domaine donné mène à des discussions plus intenses et plus vastes à propos de la connaissance existante et manquante liée au problème. Ensuite, les approches méthodologiques ont un impact sur l'intégration des idées spécifiques aux domaines dans les concepts et solutions produits. Finalement, la présence de membres de groupe provenant de la même discipline que la méthode appliquée favorise la compréhension et l'application de cette méthode dans le groupe.
- Certains éléments indiquent qu'une approche intégrant les concepts et les stratégies des deux approches méthodologiques utilisées pourrait avoir des avantages pour l'intégration créative de technologies pendant le NCD/NPPD.
- La modélisation des connaissances et des systèmes liés aux sciences naturelles en utilisant des modèles et axiomes de TRIZ et ses dérivées ont potentiellement de la valeur. Elle peut mener à l'identification de stratégies de résolution de problèmes provenant de domaines externes.

Ces découvertes ont des implications significatives et ouvrent plusieurs perspectives de recherche.

6.2 Implications et Perspectives

Tout d'abord, les résultats de l'Expérience ont des implications pour la gestion de R&D. Les découvertes confirment et étendent les théories qui suggèrent un impact important de la composition de groupe disciplinaire et des méthodes appliquées sur la résolution de problèmes de groupe pendant les premières étapes des processus de conception [par exemple. Plattner et al., 2010]. En conséquence, la gestion de R&D devrait considérer l'implication de perspectives disciplinaires plus éloignées dès que possible pendant les phases de l'identification et l'analyse du problème. De plus, les résultats de cette expérience indiquent un besoin d'adaptation des approches méthodologiques appliquées à la composition de groupe et vice versa. Les méthodes qui sont appropriées pour des processus de résolution de problèmes en groupes monodisciplinaires (où les participants possèdent la connaissance semblable et parlent essentiellement la même « langue ») ne peut pas satisfaire les exigences de groupes interdisciplinaires. Au contraire, l'application fructueuse d'approches méthodologiques plus 'sophistiquées' pourrait exiger la participation d'individus qui sont déjà familiers avec ces approches. Ainsi, si on considère par exemple le besoin d'appliquer les méthodes de la conception pour la résolution de problèmes dans le domaine de la médecine, la participation de designers pourrait être indiquée. D'autre part - et dans le contexte de la conception le plus important - l'intégration des méthodes et des solutions provenant des sciences naturelles pourrait exiger une implication assez précoce des experts biologistes.

Le dernier aspect est intéressant particulièrement pour des approches comme la conception bio-inspirée où les concepteurs cherchent des solutions aux problèmes de la conception parmi des organismes vivants. Pour optimiser la recherche et l'intégration de la connaissance et des solutions biologiques, nous considérons que l'implication des experts biologiques dès l'étape d'identification du problème est importante. Cette question spécifique est le sujet des recherches actuellement entreprises au LCPI [Fayemi et al., 2014].

Aussi en ce qui concerne le paradigme d'Innovation Ouvert [Chesbrough, 2003], les résultats de l'Expérience et de l'Étude de cas sont importants. Les découvertes peuvent mener à la conclusion que les concepts comme des plates-formes d'innovation ouvertes [par exemple NineSigma, 2013; InnoCentive, 2014] qu'utilisent les entreprises pour favoriser des projets d'innovation, pourraient être améliorés dans une certaine mesure. Ici particulièrement les processus d'identification et de formulation de problème, qui sont effectués dans une entreprise avant le passage à travers les frontières organisationnelles, pourraient être modifiés selon les découvertes de cette recherche de doctorat. Dans ce sens, AIM s'est récemment engagé dans des collaborations avec les acteurs majeurs de l'industrie pharmaceutique pour développer de nouvelles approches d'identification et de modélisation de problème qui sont basées sur le travail décrit ici.

De plus, et peut-être plus ambitieux, cette recherche de doctorat représente un pas supplémentaire vers ce qui pourrait être appelé un modèle unifié de connaissance. Ce dernier, à son tour, pourrait mener à la possibilité de création d'un groupe cible où la sélection de chaque membre de groupe est fonction de son adéquation avec le problème donné et du type de solution exigé.

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PROCESSUS ET METHODES POUR LA RESOLUTION DE PROBLEMES INTERDISCIPLINAIRE ET POUR L'INTEGRATION DE TECHNOLOGIES DANS DES DOMAINES FORTEMENT BASES SUR LA CONNAISSANCE

RESUME :

Les enjeux technologiques d'aujourd'hui nécessitent de plus en plus la résolution de problème interdisciplinaire. Malheureusement, les approches méthodologiques existantes sont souvent mises en défaut lorsque le problème à résoudre nécessite un transfert de connaissances ou de technologies entre différentes disciplines.
Les travaux présentés dans ce rapport ont pour objectif de répondre à la question de comment soutenir méthodologiquement la recherche, l'évaluation et l'intégration de la connaissance et des technologies fortement basées sur la connaissance scientifique lors des processus de la conception.
Pour faire ceci, une expérimentation a été établie qui investigue l'impact de la composition de groupe et des approches méthodologiques utilisées sur le processus de résolution créative de problème multidisciplinaire ainsi que sur les résultats de ce processus.
Les résultats de cette expérimentation ont, par la suite, mené au développement d'un méta-modèle et d'un processus qui décrivent et prescrivent la résolution de problème lors du transfert d'une technologie fortement basée sur la connaissance scientifique.

Mots clés : *interdisciplinaire, méthodes de conception, transfert de connaissance, transfert de technologie, intégration de technologie, TRIZ, USIT*

PROCESSES AND METHODS FOR INTERDISCIPLINARY PROBLEM SOLVING AND TECHNOLOGY INTEGRATION IN KNOWLEDGE-INSTENSIVE DOMAINS

ABSTRACT:

The technological challenges of today increasingly require interdisciplinary problem solving. Unfortunately, as of today, existing methodological approaches are unable to provide answers to problems which arise from the need to effectively transfer knowledge and technologies between different disciplines.
The work that is presented in this report aims at answering the question of how to methodologically support the process of search, evaluation and integration of scientific knowledge-based knowledge and technologies during design processes.
In order to do so an experiment was set up that investigated the impact of group composition and methodological approaches on the process of creative multidisciplinary problem solving on the one hand and the outcome of this process on the other and.
The results of this experiment influenced the development of a meta model and a process describing and prescribing problem solving during the transfer of an scientific knowledge-based technology.

Keywords: *interdisciplinary, design methodology, knowledge transfer, technology transfer, technology integration, TRIZ, USIT*

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