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FROM DESIGN RESEARCH TO RESEARCH DESIGN – TRANSFER OF DESIGN THEORY TO NATURAL SCIENCE

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1. Introduction

Today a large (50 % in 1996) and ever growing percentage of the value created in western industrial countries is heavily based on research [OECD 1996] and principally on its outcome, the identification of previously unknown physical and chemical effects [NSF 1968]. Product and process designers use a large variety of theories and models for the design process, which help to formalize, organize and improve the process of product and process development, particularly for the (definition and) the solution of problems. Some of these theories and methods explicitly suggest the systematic use of databases of physical and chemical effects for the design of innovative technical solutions. On the other hand, despite the widely accepted importance of basic and fundamental research and its role in the creation of value [OECD 2004], a descriptive model for the creation of knowledge, which is the fundamental aim of research, cannot be found. There is a need for a model formalizing scientific work and for methods to facilitate it [Jablokow 2005] - methods that can help the scientists in their actual challenge of creating knowledge in ever more complicated and specialized domains in ever decreasing time spans and with decreasing financial and material funding [Jablokow 2005]. Reasons for the lack of models and generic scientific methodology in basic applied natural science are manifold. First, there is resistance among a lot of scientists to recognize that basic research endeavor is an important part of the process of value creation and innovation [Jablokow 2005], which results very often in a refusal to accept methods that are considered to be weak and inappropriate because of a different underlying cognitive style [Jablokow 2005], [Kirton 2003] and in a refusal of innovation itself. Second, there is still a widely held opinion found in scientific work describing the scientists as mysterious geniuses whose creative insight is the result of quasi magical processes that cannot be formalized let alone described [Zuckerman 1977]. Third, there is consensus that scientific activity and knowledge creation are influenced by many factors that necessitate the analysis of scientific processes from as diverse as psychology, cognitive science, epistemology, philosophy, sociology, history, etc. [Holmes 1989]. Fourth, the implementation and propagation of methods in general face significant problems due to complexity, too much required effort to use, etc., as has been stated for design methods by [Geis et al. 2008]. Fifth, it is very difficult to measure the degree of accuracy and the benefits of such a model as it tends to describe and improve the production and transformation of knowledge. The quantification of knowledge is also very difficult since there exist only indirect and partial indicators for knowledge quantification. For instance it is not known how much of the knowledge that is created in a scientific research process is explicit, tacit, uncodified and so on [Dodgson and Hinze 2000]. Among the problems concerning the quantification of knowledge, the [OECD 1996] lists 1: the fact that knowledge production cannot be simply understood as a net addition to the stock of existing knowledge and 2: the lack of formulae for the translation of knowledge creation inputs into knowledge creation outputs.

The aim of this paper is to show that the modification of existing theories and methods from other domains (particularly from the design methodology domain) and their application on the process of scientific knowledge creation in natural sciences could be useful, on the one hand, to give examples for previous transfer from design knowledge to scientific work and, on the other hand, to indicate some (in our view) interesting directions of further research. First we will point out different attempts for describing, modeling and reproducing scientific discoveries. Then we will give examples for theories and methods of design research which we consider to be valid candidates for the application to the research and knowledge creation process. Eventually we will suggest some modifications of the previously mentioned theories and methods in order to improve their applicability to natural science in order to create a Research Design Method.

2. Describing, modeling and reproducing scientific discoveries

Much like the process of product design and development, the process of knowledge creation is characterized by cognitive processes and creativity. Thus the major approaches for the description of the process of scientific knowledge creation have been of psychological and philosophical nature. The commonly held point of view is that the analysis of the process of creative scientific reasoning can be carried out only by the analysis of historical and biographical case studies [Gruber and Wallace 1999], [Holmes 1989]. To our view, the most interesting conclusions from these analyses are the following ones: First, the role of metaphors and analogies and mental concepts in the development of scientific model building and scientific insight has been pointed out [Black 1962], [Gruber and Wallace 1999]; [Holmes 1989], [Osowski 1989], [Boyd 1979]. Osowski [1989] describes, for instance, metaphors as means for the generation of new ideas, for the testing of a theory, the organization of knowledge and as a concrete structure which is the basis for further abstractions and theories. He also argues that formulation of metaphors creates contradictions and ambiguity which are important for progress in scientific reasoning. On the other hand, Keegan [1989], by using the example of Darwin applying geologic concepts on evolution theory points to the importance of analogies as a means of discovery by using expertise acquired in one domain in order to explain phenomena in a completely different one. Second, there is evidence that cognitive processes in science do not significantly differ from strategies of problem solving used in other domains [Perkins 1981], [Weisberg 1993]. This position is supported by Gentner et al. [1997] who describes scientists generating candidate analogies which were designed to understand one domain in terms of another and then describes how they test those analogies for their descriptive value - a process which has been described by Finke et al. [1992] as being used by test persons in a general creativity test. In addition it is found that some scientific discoveries are the result of very general heuristics, which are not based on deep immersion in a domain of expertise [Langley et al. 1987].

Other important aspects in modeling and formalizing scientific discovery are the development of computer systems that are able to reproduce or make scientific discoveries [Langley et al. 1987], [Boden 1999] and the documentation of reproduction of scientific discovery processes under laboratory conditions [Qin and Simon 1990]. For instance a computer program called BACON was able to rediscover: the inverse ratio between pressure and volume - known as Boyle's law - when supplied with unprocessed data about varying gas pressures and accordingly occupied volumes [Gardner 1993]; the relationship between a planet's distance from the sun and the period of its revolution - known as Kepler's third law of planetary motion; Ohm's law of electrical currents; Black's law of temperature equilibrium and others more [Qin and Simon 1990], [Lanley et al. 1987]. Boden [1999] describes another computer system (IDS, Integrated Discovery System) that is able to formulate new hypotheses for which it designs experimental tests and measuring instruments. Boden also points to two computer programs designed by Lenat [1977]; Lenat [1983] which both use heuristics for the alteration of concepts and for the alteration of the heuristics themselves. According to Boden, one of the programs, AM, suggested a theorem about maximally divisible numbers, which is an area that was previously unknown to its designer. The replication of the discovery of Kepler's third law of planetary motion under laboratory conditions was shown by Qin and Simon [1990]. With the relevant data given, four out of fourteen test subjects were able to rediscover the above mentioned law within an hour. From this it is concluded that significant discoveries in natural science can be achieved by the use of general problem solving strategies.

From the previously mentioned findings we conclude the following: It would be naïve and unrealistic to assume that scientific research, which leads to significant discovery, can be carried out only by the use of a small number of heuristics and methods. However it has to be made clear that 1. Metaphors, analogies and images are essential to the scientific process and the ambiguities and contradictions created by them help the scientist to achieve discovery. 2. It is possible to identify certain heuristics and strategies that can help (re)produce scientific discovery. 3. The process of problem definition in scientific reasoning is at least as important as the process of problem solving.

In the following sections we claim that it is possible to transfer certain models, methods and heuristics from design research to the theory and process of scientific research in order to improve and enrich the domain of research design. At first we refer to a design theory from which we think that it is appropriate, some modifications provided, for modeling the scientific research process. Second we make reference to a theory of problem solving that is used in the design process and elsewhere which we think has the potential of providing powerful heuristics and solution strategies for scientific research problems. After that we explain why we are convinced of the potential these theories have for our purpose and propose some modifications for their adaption to the scientific research process.

3. Theories of design and solution of problems in design

An interesting approach to a descriptive theory of design is the Concept-Knowledge theory or C-K theory (CKT) developed by Hatchuel and Weil [2003] that characterizes “[d]esign as the process by which a concept generates other concepts or is transformed into knowledge” [Hatchuel and Weil 2003]. According to this theory, there exist two spaces in design reasoning. On the one hand, there is the Knowledge Space (K), which contains elements, so called propositions, which are either true, false or “undecidable” [Hatchuel and Weil 2003]. On the other hand, there exists the Concept Space (C), which contains elements, concepts, which cannot yet be considered to be true or false in K. All activities in the design process can be characterized by one of the four following operators allowing the expansion of Spaces of Concepts and Knowledge: The K→C Operator generates alternatives of concepts by providing properties from the Knowledge Space to existing concepts in the Concept Space. The C→K Operator tends to search for properties in K that lead to the approval or rejection of initial propositions in C in order to transform the concepts into knowledge. The C→C Operator represents an extension that happens only in the Concept Space. It enlarges the existing concept(s) respecting the rules of set theory for the allowed actions for this operator are partitions and inclusions of the initial concept(s). Finally the K→K Operator extends the space of Knowledge respecting the rules of logic, creating knowledge out of existing knowledge. These definitions being of very theoretic nature, Hatchuel and Weil [2007] give some examples: For instance: C→K Operator: Testing of proposed concepts by experimental trial in order to produce knowledge about its performance; K→K Operator: The study of existing proven solutions, in order to list requirements for a new solution, which serve as new initial knowledge to the design process; K→C Operator: The determination of required characteristics of a future concept which may lead to the definition of this concept; C→C Operator: The combination of characteristics whose value is not yet proven in order to form new objects in Concept Space. According to the creators, this theory is able to describe and model all the actions that exist in a design process. Furthermore the authors claim that C-K Theory has a normative value for carrying out of different design and development enterprises and for making them more innovative [Hatchuel and Weil 2007].

A remarkable approach for a theory of problem solution in the design process is the so called “Theory of Inventive Problem Solving” (russ. теория решения изобретательских задач ; abbr. TRIZ) whose origins lay in the analysis of several thousands of patents by the Russian engineer G. Altshuller. Over time, the theory has been developed further and new approaches, tools, and algorithms have been added [Altshuller 1988]. Due to the facts that TRIZ is a quite extensive and manifold complex, only the basic idea and some of the, in our eyes, most important aspects shall be explained briefly. The underlying principle of TRIZ is the idea that technical systems do not evolve randomly but that their development follows certain general and objective laws. From that, it can be deduced that solutions of technical problems in different domains, like mechanical engineering, electrical engineering and so on, can be developed with a generic problem-solving method. This method can be explained in a simplified way as follows: In order to find a solution to a specific problem, the problem solver has two possibilities: 1. He or she can develop ideas randomly by basic creative techniques like brainstorming and try to apply them in a trial-and-error procedure on the problem. 2. He or she can transform the initial specified problem into a more generic problem setting, apply systematic solution heuristics in order to generate conceptual solutions for the generic problem and finally, transform the conceptual solutions into creative solutions for the specific problem (cf. Figure 1). According to TRIZ, the second possibility allows the generation of more problem adapted solutions in a shorter time when the problem solver considers both, the specific conditions of the initial problem and the objective and generic laws proposed by TRIZ, keeping in mind the ideal desirable solution, also called “Ideal Final Result” [Petrov 2005]. The methodology comprises several heuristics, tools and strategies in order to support the problem solver in following the process of transformation, solution generation and solution transformation [Savranski 2000].

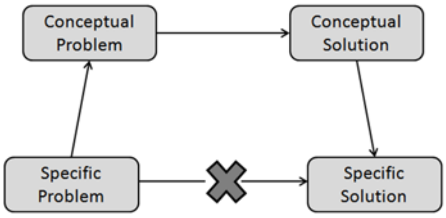

Figure 1. TRIZ model of problem solution

One central concept of the methodology is the notion of contradictions. According to TRIZ, there are three types of contradictions that underlie a technical problem: Administrative Contradictions, Technical Contradictions and Physical Contradictions. These contradictions are indicators for a certain conflict that appears within a system. Standard solutions for this conflict are characterized by compromises causing that none of the parameters reaches its optimum value. In order to generate an effective and creative solution to a technical problem, the problem solver has to overcome the contradiction, which allows the satisfaction of the two conflicting requirements. The identification of contradictions in a specific problem setting is seen as a way to transform the problem on the generic level. TRIZ suggests different heuristics for overcoming different types of contradictions. Problems based on physical contradictions are supposed to be solved by so called Separation Principles whereas the so called Innovative Principles have been developed in order to overcome technical contradictions [Altshuller 1983], [Altshuller 1988].

The Substance-Field Model or VePol (Vestschestvo i Pole, russ: Substance/Field System) is a concept inherent to TRIZ which allows the modeling of technical systems and especially the parts that are in conflict which each other. According to this model, technical systems can be completely described as one or several entities. These entities ideally comprise two substances which are linked by a field. The establishment of a Substance-Field Model of a technical system allows the identification of deficient system parts. Based on the previously mentioned Inventive Principles and the Substance-Field Model, the so called Standards for the Solution of Inventive Problems have been developed. According to the theory they represent specialized solution concepts for different categories of problems which have been formulated by the Substance-Field Model.

The System Operator or Nine Screen Tool is a concept that is supposed to help the designer situate the Technical Problem and the conflicting parts in the system context [Altshuller 1988], [Altshuller 1983]. According to the theory, while looking at a technical system, one has to take into account all the components that it contains as well as the technical super system and the non technical environment which surrounds it. Another important point is the analysis of the development of the technical system in time. This can help to determine tendencies and trends on all system levels over time and thus to identify the correct future problem setting and problem requirements [Savranski 2000].

There exist multiple other important aspects of TRIZ. The Laws of System Evolution, for instance, are based on empirical analyses of existing systems, which help to identify improvement strategies which have been successful in other technical systems in comparable situations. The Model of the Smart Little Creatures (SMC) and the OTC Operator are heuristics that help the designer to overcome “psychological inertia” [Altshuller 1988] by personal analogy or by modification of different system parameters to extreme values.

The Algorithm for the Solution of Inventive Problems (Алгоритм решения изобретательских задач ; abbreviation of the Russian name: ARIZ) can be considered as a concept that integrates most, if not all of the previously mentioned heuristics, notions and concepts into one Meta-Algorithm [Altshuller 1988], [Altshuller 1983], [Altshuller 1999].

Over time there have been several approaches to modify, simplify and adapt the Theory of Inventive Problem Solving which lead to the introduction of new problem solving theories like Structured Inventive Thinking (SIT), Advanced Systematic Inventive Thinking (ASIT) and Unified Structured Inventive Thinking (USIT).

4. Transfer from design process to scientific research process

The potential value of a transfer of design theories to the process of scientific reasoning and knowledge creation is based on the following findings:

The scientific knowledge creation process as well as the design process can be largely described as processes of problem setting and problem solution [Sternberg and Lubart 1995], [Feist 1999], [Zuckerman 1977]. Moreover both processes are described by an initial phase of creative divergent thinking and a second phase of critical or convergent thinking [Gentner et al. 1997]. Finally, as mentioned above, cognitive processes in science do not differ significantly from other strategies of problem solving [Perkins 1981], [Weisberg 1993].

In particular, C-K Theory, due to its very logical and mathematical notions is considered appropriate to describe and map the process of scientific reasoning and to gain acceptance among natural scientists. On the other hand the complementary spaces of Concepts and Knowledge reflect the principal dimensions in scientific activity well: On the one hand, there is the creation or design of new scientific models and hypotheses that belong to the concept space (C) until they are proven by experimental findings (C→K). On the other hand, there is the whole of existing knowledge on which new models and hypotheses are based and which leads directly (through induction) (K→K) or indirectly (through model generation) (K→C→K) to new knowledge.

The reasons for the application of the Theory of Inventive Problem Solving (TRIZ) to the process of scientific activity are manifold: First there have already been successful attempts to model scientific reasoning in Mathematics, Physics, Chemistry and Biology using different aspects of TRIZ. Some of these attempts are shown in Table 1.

Table 1. Examples for the application of TRIZ to natural sciences

Domain	Activity	Source
Mathematics	Modeling of development of methods in numerical mathematics by Inventive Principles (IP)	[Berdonosov and Redkolis 2007]
	Application of IP to calculation of global mobility of mechanisms	[Cretu 2007]
Physics	Explanation of Russell’s Effect using the Physical Contradictions (PC) and Separation Principles (SP)	[Altshuller 1983; Altshuller 1988]
	Modeling of discovery in theory of supra conductivity by ARIZ	[Altshuller 1983]
	Modeling of discovery in astronomy by application of OTC Operator	[Altshuller 1983]
	Modeling of discovery in nuclear physics by using ARIZ	[Altshuller 1988]
Chemistry	Modeling of discovery of benzene structure by the application of the notion of contradiction	[Altshuller 1983]
Biology	Modeling of discovery of DNA structure by Ideal Final Result	[Altshuller 1988]
	Modeling of discovery in physiology by PCs and SPs	[Altshuller 1983]
	Description of evolutionary principles and competitive strategies in animal world by notion of contradiction and IP	[Mann 2006]
	Application of IP for a device for measuring core temperature of bugs.	[Altshuller 1994]

Second the identification of contradictions and the overcoming of the latter are central points in TRIZ and there is evidence that this aspect has similar importance in the solution of problems in science [Holmes 1989], [Osowski 1989]. Third, in our opinion, heuristics in general and TRIZ heuristics in particular can be seen as pre inventive structures, whose successful application to the process of discovery has been shown [Langley et al. 1987]. Fourth there is a need for a framework which allows the generic and neutral description of complicated and codified information in order to foster creative solutions concepts and teamwork in scientific research [Kostoff 1999]. One of the principal strengths of TRIZ and its derivates is that it is considered to have the potential of generic problem description.

5. Suggestion of a model describing the transfer of design methods to the scientific research process

Starting from the classic notion of C-K Theory, which has been described above, we describe the advantages of the use of design methods in research in natural science by a model of the following type (Figure 2), which can be seen as a basis for a Research Design Method. The Knowledge space (K) is divided into two subspaces whose elements differ only in terms of origin. Existing knowledge in the target sector (e.g. in life science) should be used to produce new knowledge in this sector (e.g. a new model describing a phenomenon or the production or interpretation of data). In some cases, direct deduction of the desired knowledge is impossible (a), which can be due to different factors like for example psychological inertia ($K_{barrier}$). The scientist now has to create concepts of models in order to explain the existing knowledge (b). These model concepts are situated in the Concept Space. In order to prevent an undirected and often time, cost and energy consuming trial-and-error process of extension and validation of created propositions in Concept Space (c and d) or in order to get access to new concepts (e), the scientist accesses design theory knowledge ($K_{design\ theory}$) (f). This knowledge provides access to the space of Resource Knowledge ($K_{resource}$) (g), which stems from other scientific disciplines and includes specialized heuristics and analysis methods and allows a certain orientation of scientific reasoning process and/or the consideration of aspects a priori unknown to the scientist. The so created concepts (g) can now be evaluated by assigning to them a logical status in $K_{resource}$ first (i) or by experimentation, to say direct validation in $K_{target\ sector}$ (j).

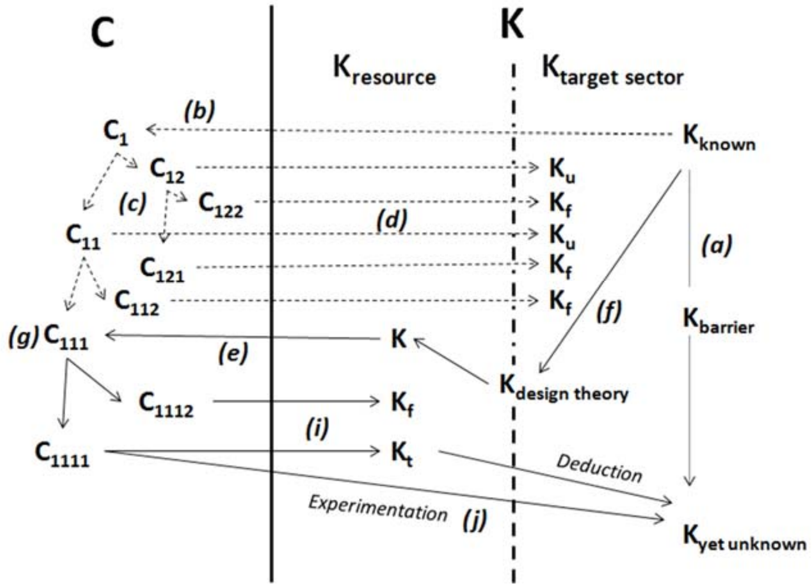

Figure 2. Proposed model in C-K theory notation

6. Suggestions for further research

The theories which have been presented here have originally been developed in order to describe and enhance the process of designing technical products and processes. Hence, in order to adapt the theories to the process of scientific knowledge production, one has to identify those aspects which are the most appropriate for this purpose and develop them further in accordance with the requirements of the researchers and the requirements for successful transfer of methods [Geis et al. 2008]. One principal question in this context is whether to aim at the whole spectrum of natural science as transfer field or whether to focus on a specific field whose philosophy, underlying principles and research structure can be analyzed and identified more easily. We consider the second option to be more promising and propose the domain of biology and life sciences, including zoology, botany, virology, mycology, micro- and molecular biology, biotechnology, etc. The reasons for this choice are the following: 1. As shown above, biological systems are characterized by an evolutionary process of hundreds of millions of years and by the solution of problems that can, in our opinion, probably be described and modeled by the TRIZ Laws of System Evolution and by the notion of contradictions and their overcoming. 2. The complex structure of and relationships between living creatures necessitates, in our opinion, a systemic analysis and synthesis, which can be modeled by the System Operator Tool. 3. In the domains of genetics, virology, mycology, oncology and especially in biotechnology there is an ever increasing need to understand the mechanisms of metabolism, reproduction and the control of life forms such as funguses and cancer cells. These mechanisms can probably be modeled by the TRIZ Laws of System Completeness and of Energy Conversion, which are part of the TRIZ Laws of System Evolution. 4. From interviews with researchers in microbiology we know that different heuristics for overcoming psychological inertia (SMC) can be very fruitful.

In order to provide scientific research in this domain with a powerful methodology, one has to adapt the above mentioned aspects of TRIZ and to implement them into a broader framework providing support for the scientist along the whole research process from problem statement, over generation of hypothesis, to experimentation and interpretation of results. Nevertheless the approach would be too restricted if the transfer of design methods was limited to TRIZ and its derivatives. We think that other theories, like for example the Axiomatic Design Method [Suh 1990], bear a remarkable potential for use in the context of scientific discovery due to its mathematical formalization. Taking into account the previously mentioned significance of metaphorical and analogical reasoning in natural science, we consider an analysis of the metaphors and analogies which have been used from scientists in order to make important discoveries to be very intriguing.

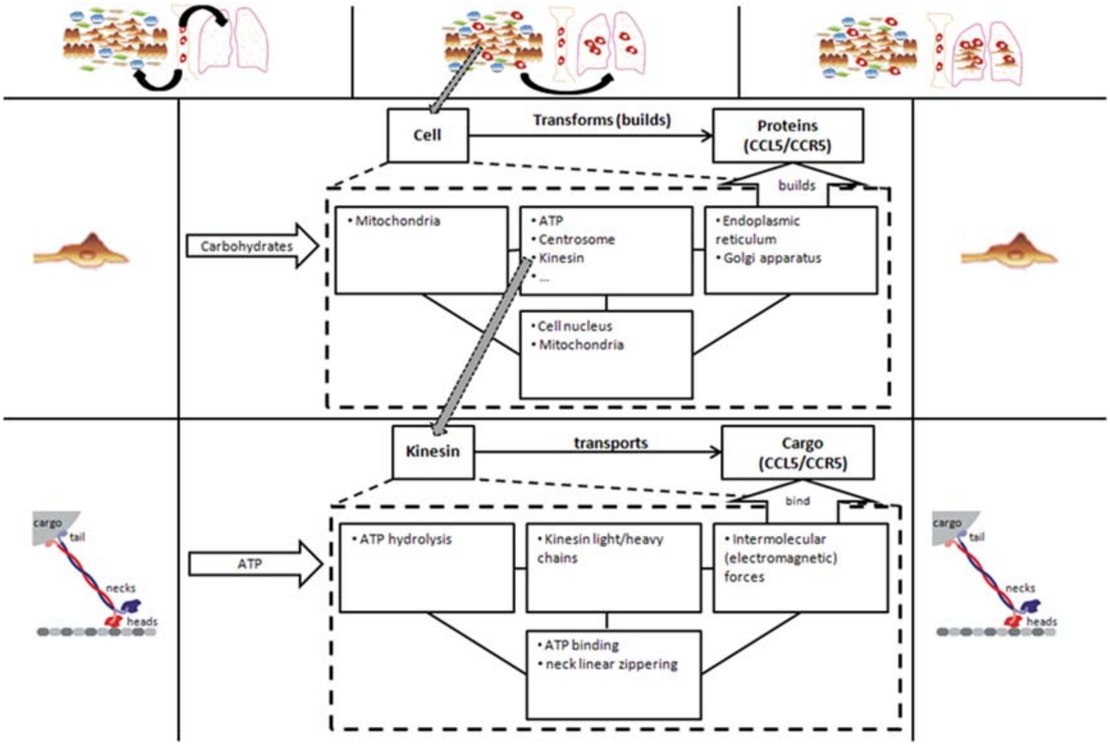

Figure 3. Application of TRIZ tools in the domain of oncology

As mentioned before, the domain of the life sciences is, in our eyes, predestined for the application of design methods. In the following we will briefly discuss the application of the TRIZ tools "System Operator Tool" and "Law of System Completeness" to the domain of oncology, more exactly to the problem of metastatic cancer extension. [Hu and Polyak 2008] point out that especially "[…] transition of *in situ* to invasive carcinoma as a key event in breast tumor progression […] is poorly understood." Further they state that focus on and progress in the analysis of the tumor cells themselves lead to the ignorance of the role of the microenvironment and paracrine signaling within the latter in tumor genesis and extension. The application of the above mentioned TRIZ tools and an analogy between a technical system and both the cancer cell and the Kinesin protein lead to the scheme in Figure 3. This type of representation has several advantages: 1. It underlines and distinguishes both the different phases of tumor extension and the different systemic levels at which the biological and chemical processes occur; 2. The generic, schematic and holistic representation allows for a more easy understanding of the problem by experts of other domains, facilitates interdisciplinary communication and could surely lead to systematization of actual knowledge and the identification of new fields of research (e.g. what is known about paracrine signaling and how can this knowledge be used for new methods of cancer treatment); 3. Eventually the quasi-mechanical representation of biological and chemical "mechanisms" can lead to new ways of problem solving by the application of TRIZ solution principles for example. 4. It is easily possible to extend this simplified fractal model in order to analyse for example the complicated process of transformation of carbohydrates into ATP to the degree of detail which seems opportunistic in terms of problem setting and problem solution. An eventual model of the process of scientific reasoning and discovery and the conclusions and methodological tools that can be derived will have to be based on intensive cooperation with researchers in the respective target domain. This work will be done in the next few years in cooperation with industrial and academic partners.

7. Conclusion

In this article we argue for the benefits of a transfer of design theories into the domain of natural science. First we gave an overview of the attempts to describe and formalize the process of scientific reasoning and discovery. Then we described design theories, C-K Theory and Theory of Inventive Problem Solving (TRIZ), in which we identified a certain potential for benefits in the research process in natural science. Further we suggested how the transfer process could be modeled using C-K Theory Notation. Finally we indicated promising directions for further research in order to create a Research Design Method and gave an example of the modeling of complex processes in life sciences with TRIZ tools. In our eyes, such a method and new of ways of problem identification and problem solution in research in the fields of physics and life sciences would most probably be very efficient for the product design process in major and emerging economical fields. Examples for those fields would be health care and biotechnological sectors (green, red and white biotechnology) as well as product development based on nano technology and design of processes and facilities for the use of biological and chemical processes for energy exploitation.

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