A Multi-Disciplinary Research Approach, Illustrated by the Boderc Project

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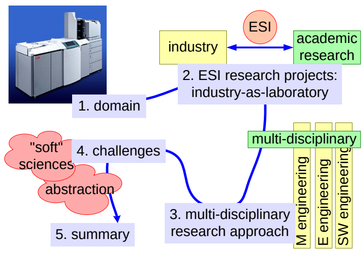

Gerrit Muller

Buskerud University College

Frogs vei 41 P.O. Box 235, NO-3603 Kongsberg Norway

gaudisite@gmail.com

Abstract

Research of Multi-Disciplinary subjects is complicated by its nature. Systems Engineering is the application area of the research results. Systems Engineering is applied in industrial or commercial domains. The drivers and culture in these domains differ quite a lot from the drivers of the (academic) research community. We will discuss and illustrate a research approach called *Industry-as-laboratory*. We will discuss how to get from industrial problem to a research hypothesis, and how to validate the hypothesis.

version: 0.1 status: preliminary draft July 4, 2016

1 Introduction

We will discuss an approach to research the multi-disciplinary questions. The mission of the Embedded Systems Institute (ESI) is to research the field of *Embedded Systems Engineering*. This research field is inherently multi-disciplinary. We will illustrate the research approach with examples from the first ESI research project that ran from 2002 till 2007.

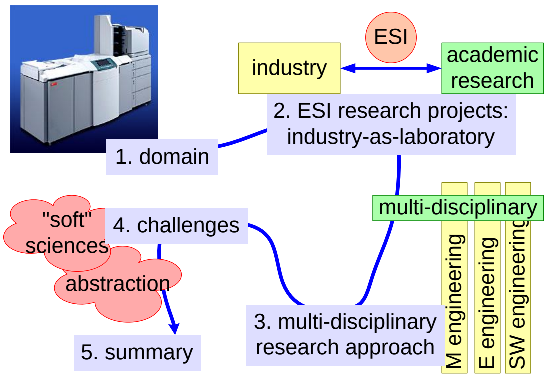

Figure 1: Figure Of Contents$^{\text{TM}}$

Figure 1 shows the outline of this article. We will first discuss the domain where the Boderc research took place. Then, in Section 2, we will elaborate the research project approach chosen by ESI for multi-disciplinary research. Next we discuss the research method to cope with the broadness and the vagueness of the scope in Section 3. Specific challenges in multi-disciplinary research are discussed in Section 4.

The multi-disciplinary problems in the creation of mechatronics systems are taken as a starting point of the Boderc project. The full Boderc story can be read in[3] and all publications can be found at the website[2]. Océ provided industrial problems and case studies to work on. Océ is an international company active in the document handling domain. One of the product families that is designed in the development center in Venlo, the Netherlands, is a range of high volume copiers and printers, see Figure 2.

The creation of a new printer is taken as the carrier for the Boderc project. The Boderc project can use the Océ development project as playground to research the multi-disciplinary modeling methods.

A common problem in mechatronics systems is shown in Figure 3: the organizational decomposition and the natural sequential development order result in integration problems and delays at the end of development projects. The mechanical engineers, for instance, make a design based on the assumption that the software can support a 1 kHz control loop. Later, when the software engineers start 10 ms is defined as

31x5E 2050 2090

Figure 2: The Domain: Printers and Copiers by Océ

Many multi-disciplinary problems in product development

Mechanical engineering precedes
Electronics engineering precedes
Software engineering

Most of the problems show up late in engineering and in the integration phase

For instance mechatronics assumes 1 ms response
Software promises 10 ms response

Lack of systematic approaches to detect / solve these problems in early phases

Lots of tuning, trial and error
Unpredictable project timing and costs

Figure 3: Typical Industrial Problem in Mechatronics Systems

guaranteed SW response time.

2 Industry as Laboratory

Conventional research areas are mono-disciplinary: mechanical, electronics or software engineering. Some bi-disciplinary niches exist, for instance hybrid methods where continuous electro-mechanical models are combined with specific discrete events. These research fields are relatively mature, although some doubts exist about the maturity of software engineering[6]. Researchers in these areas are used to well-defined problems that can be researched in depth. Mono-disciplinary methods are often based on mathematical rigor. A lot of uncertainty pops up when we move to multi-disciplinary problem solving. The problem itself is only partially defined, while at the solution side different formalisms have to interoperate, such as discrete (software) and continuous (mechanical) models. Figure 4 shows the methods with as vertical axis the degree of multi-disciplinary interaction. The form of the method is an indication how well the method is defined and how much uncertainty is left.

In the industrial context the *system* level is often relatively well-defined in a systems requirement specification. Such a specification describes the functionality

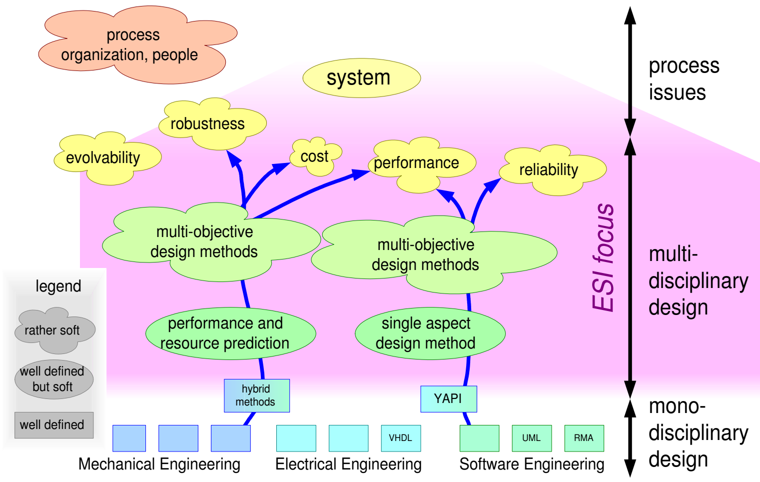

Figure 4: From Mono-Disciplinary to System

of the system and quantifies the main performance characteristics. The translation of these requirements into mono-disciplinary design choices, however, is still full of uncertainty. A lot of uncertainty is caused by the many (dependent and interfering) design dimensions that have to be managed at the same time. In Figure 4 the methods at this level are called *multi-objective design methods*.

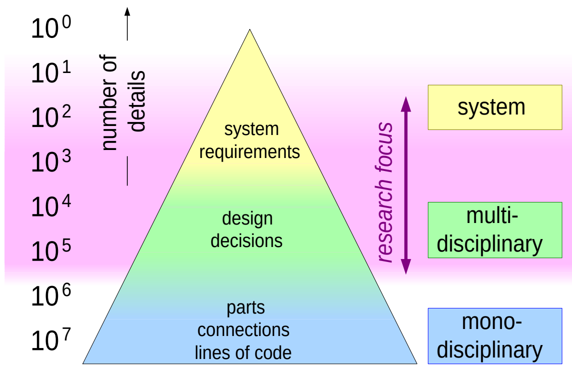

Figure 5: Exponential Pyramid

The translation of system requirements to detailed mono-disciplinary design decisions spans many orders of magnitude. The few statements of performance, cost and size in the system requirements specification ultimately result in millions of details in the technical product description: million(s) of lines of code, connections, and parts. Figure 5 shows this dynamic range as a pyramid with the system at the top and the millions of technical details at the bottom. The methods to be established by the ESI address the multi-disciplinary area. In Figure 4 this is the range from *single aspect* to *multi-objective* design methods. In the pyramid, Figure 5, it is the area of translating hundreds of system level requirements into tens of thousands of design choices.

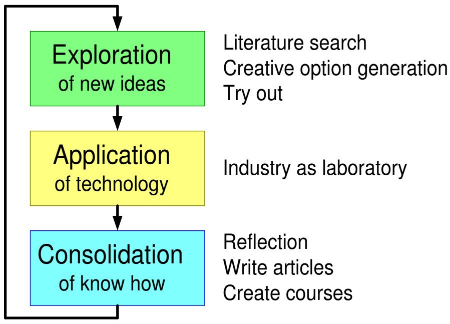

Figure 6: Technology Management Cycle

Technology management can be modeled as a cyclic process [1], as shown in Figure 6. Most of the time is spent in the application of technology, in other words in the creation of new systems. After applying the technology it is recommended to learn from this application by reflection. The learning experience can be made (partially) accessible to others by consolidating the know-how, for instance in documentation.

At the end of the consolidation insight will exist in strengths and weaknesses of the technology, both in the hard technology choices as well as in the soft technology (the approach taken). It is recommended to take this know-how as a starting point for an exploration phase.

The exploration phase should be used to refresh the designers and architects, and to open new opportunities in technology. This requires that they know the state of the art in the world, by reading literature, visiting conferences, et cetera. New technology options can be added by means of creative brainstorms . Promising technology must be explored hands-on.

In the next application phase a limited set of new technologies is applied in practice.

Establishment of methods requires exploration, application, and consolidation as described in the technology management cycle[1], see Figure 7. The focus of *product development* is on the application of technology and methods. Very limited time is spent on exploration and consolidation. The research of methods increases the attention for exploration and consolidation. However, application of the researched method in a realistic context is very important and takes a lot of time and energy. The industry-as-laboratory approach provides the researchers with the means to apply new methods in an industrial context.

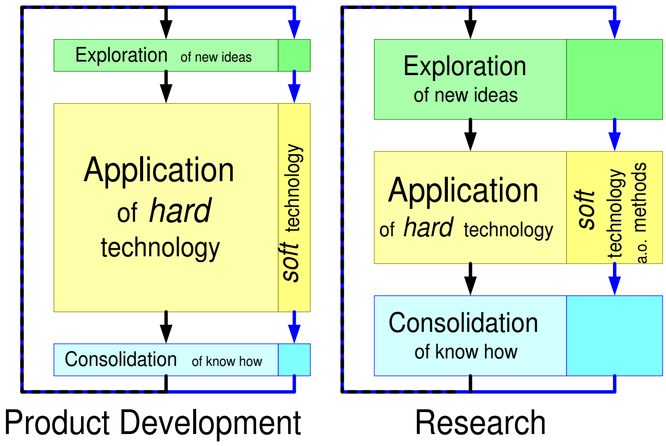

Figure 7: The technology Management Cycle. This cycle is also applicable for method development, also called *soft* technology. In product development the focus is mostly on applying technology, whereas the research focus shifts the attention more to exploration and consolidation.

The *industry as laboratory* approach, as proposed by Colin Potts[8], uses the actual industrial setting as test environment. The research group that is researching a new product engineering method formulates a hypothesis about the application of a new method and applies the method in the industrial setting. The results of this experiment are observed and used to evaluate the hypothesis. The approach is visualized in Figure 8. We use the term *Carrying Industrial Partner (CIP)* for the company that provides the problem and the industrial setting.

Multi-disciplinary research involves many different stakeholders. Figure 9 shows the main stakeholders for the Boderc project. The CIP for Boderc, Océ, is one of the main stakeholders. The researchers themselves come from academia, industry or from ESI. Academic stakeholders are mostly interested in challenging

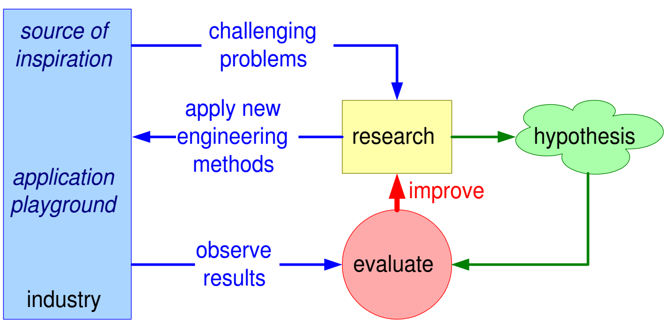

Figure 8: Industry as Laboratory: Research of Engineering Methods

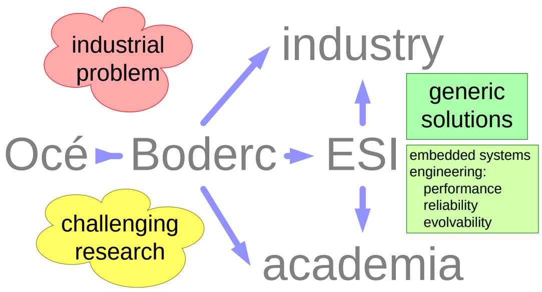

Figure 9: Stakeholders

research problems with sufficient depth, fitting in their own research field. Industrial stakeholders are looking for usable solutions, such as multi-disciplinary design methods. The mission of ESI is to create and disseminate know how in multi-disciplinary design, well-connected to mono-disciplinary know how and usable in industrial context. ESI needs to generalize project solution for the CIP into more generic solutions.

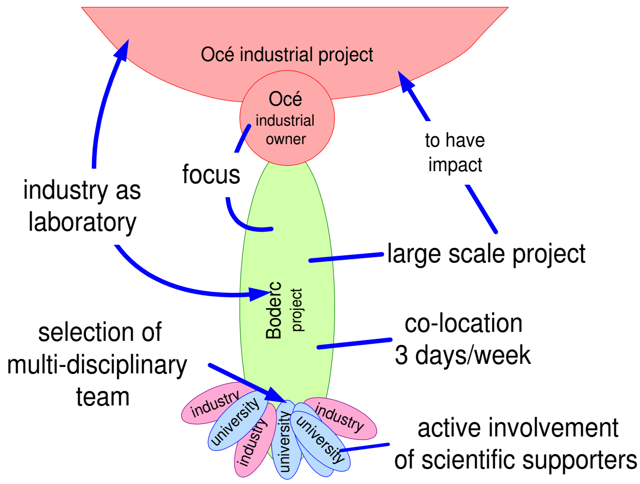

Figure 10: Critical Success Factors for projects

Figure 10 shows the critical success factors for multi-disciplinary method research:

- Focus based on Industrial ownership.
- Industry-as-Laboratory for exploration and verification of methods.
- Multi-disciplinary team.
- Large-scale project, sufficiently large to experience size problems and to

have a visible impact on the much larger industrial partner.

- Co-location of the project members for at least half of their time, to ensure sufficient communication and sharing of project goals.
- Active involvement of scientific supporters, to bridge the gap from mono-disciplinary to multi-disciplinary.

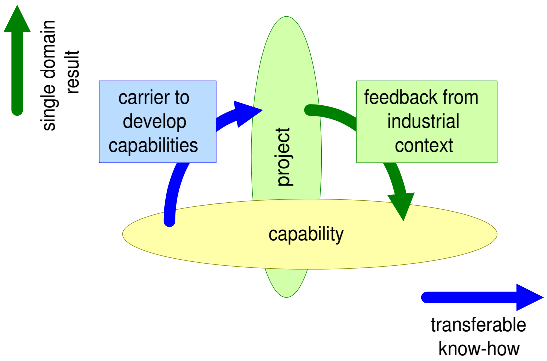

Figure 11: Project as Carrier for Capability Development

The projects are the vehicle to do method research. The goal of the institute is capability development in the area of multi-disciplinary design methods. Figure 11 shows this relationship between capability development and projects.

3 Multi-Disciplinary Research Approach

Industrial partners and ESI discuss potential multi-disciplinary subjects when projects are initiated. The project is then defined around an industrial problem. This problem has to be translated in the expected industrial outcome, the *industrial goal* in Figure 12. The problem should also be transformed into research terms. Usually the problem statement can be transformed into *research questions*. The research questions can be answered initially with (quantified) *propositions*. The quantification forces the research partners to be specific and sharpens discussions. At some moment a *hypothesis* should be formulated. To evaluate the hypothesis it helps to make the criteria for evaluation explicit. The *industrial goal* and the *hypothesis* must be clearly related.

The transformation process from problem to industrial goal and hypothesis is for big projects applied recursively: at project level, sub-project (or in ESI terms Line-Of-Attention, LOA) level, and at the level of individual researchers. The research questions, sub-questions and subsub-questions must again have a clear

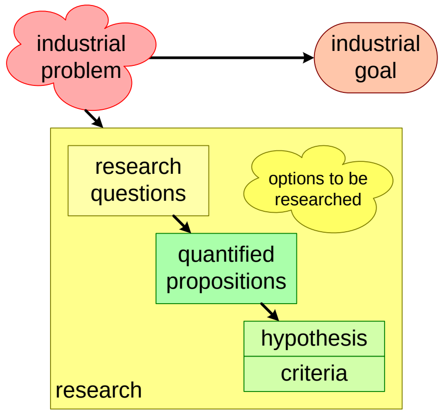

Figure 12: From Industrial Problem to Validated Research

relationship. PhD students working at ESI research projects preferably work on“T” shaped problems. The multi-disciplinary problem is broad (the horizontal bar of the “T”), while for accreditation purposes sufficient depth of the research subject is required (the vertical bar of the “T”). The breadth and depth parts of the work should be well-related and documented.

Note that we ought to explore multiple possible answers to research questions in order to evaluate the answers. Creation of one answer shows feasibility, multiple answers allow for comparison (benchmarking). Quite some researchers tend to stick to their existing research area, which disables them to benchmark against competing approaches. The availability of an industrial problem and playground facilitates comparative evaluations.

The Boderc project goal, as shown in annotated form in Figure13, is to facilitate the multi-disciplinary design by providing a modeling based method that can be applied in early phases of the decision process.

Multi-disciplinary modeling is expected to help in many ways: in predicting system performance, in analyzing design options, in communication between engineers from different disciplines, and in documenting multi-disciplinary design considerations. An important constraint is imposed on the modeling methods to be explored: the method must be practical applicable in the industrial context with its particular people, processes and economic constraints. The economic constraints relate directly to resource constraints of the system to be created.

The research questions of the Boderc project are shown in Figure 14. The first question, “What Formalisms, Models, Techniques, Methods and Tools are needed?” is elaborate further in Figure 15, defining these five words. The *appropriate level of abstraction* is a dominant research issue at multi-disciplinary level, relating to the pyramid in Figure 5. Another hot issue is why some modeling efforts are highly successful, while other models die without much attention. What are the

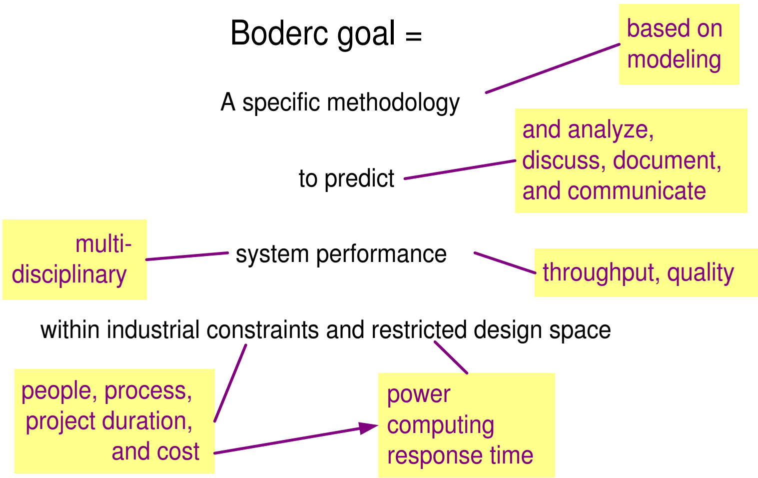

Figure 13: Boderc Research Project Goal

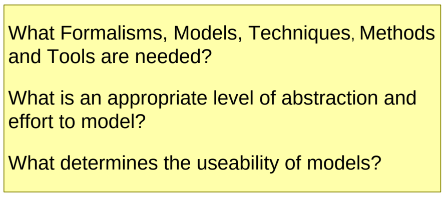

Figure 14: Boderc Research Questions

success factors for modeling?

Figure 16 shows the hypothesis as it was recaptured at the end of the project.

4 Challenges

Science is applied in a wide range of areas, from proof-based mathematics to descriptive reasoning in human sciences, see Figure 17.

The level of certainty of the results decreases when moving from hard sciences to soft sciences. Mathematical proofs provide certainty[1], see also [4]. Physics provides a confidence level that increases by validating predicted outcomes, or it applies a *falsification* process as described by Popper [10].

Medical sciences need a lot more trial and error, where evidence is built up

[1]As far as the proof is verifiable and the verifiers can be trusted. The absolute certainty is here also decreased by the human factor: the proof is as certain as the quality of the provider of the proof and the verifiers of the proof. Automation shifts the problem to the tool, which also in some way originates in fallible human beings.

Formalisms languages/syntax: differential equations, timed or hybrid automata, finite state machines, et cetera

Models instantations of formalisms to understand, explore, optimize or verify specification or design

Techniques to get the required information from models: e.g. performance

Methods to provide guidelines how to use formalisms, create models, use techniques and apply tools

Tools to support efficient application of formalisms, techniques and methods

Figure 15: Methodology

The product creation lead time
will be reduced significantly by
the use of multi-disciplinary models
during the early product development phases.

Figure 16: The Boderc Hypothesis

in extensive statistical studies. The evidence is hampered by many factors that influence the outcome of the medical study, but that are outside the control of the experimenter. Worse is that many of the factors are unknown to the experimenter and his peers. Cause and result are often more ambiguous than people realize. Despite all these disclaimers the medical sciences have created a large body of knowledge.

The human sciences (psychology, sociology, pedagogy, et cetera) have already a tremendous challenge in making statements plausible. Human behavior shows a wide variation, depending on many factors, such as culture, age, gender, and status. Individual human behavior is often poorly predictable. Case descriptions are used in a heuristic approach. The step from case descriptions to a workable hypothesis needs a lot of interpretation. Adding more case descriptions will help in making the issue more plausible, but hard evidence is nearly impossible. A more experimental approach with small scale experiments is possible, but these experiments are often highly artificial.

The scientific community dislikes the charlatans, who can be very convincing by hand-waving arguments, but in fact are selling hot air.

Architecting integrates all of these different types of sciences, from mathematical to human sciences. For instance in security design cryptographic proof

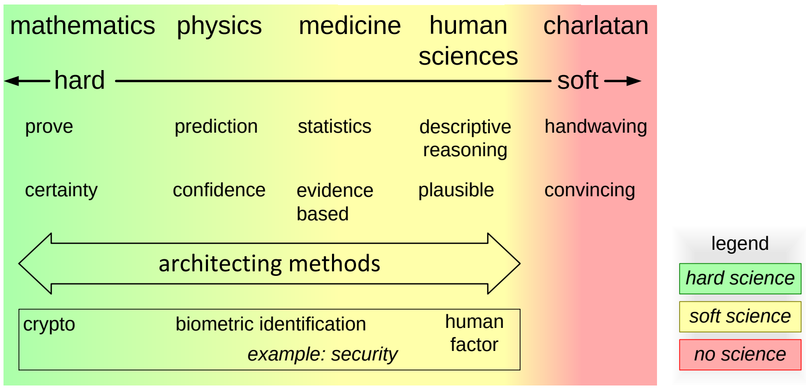

Figure 17: Spectrum of sciences

is important, and also biometrics authentication. However a security solution that does not take the human behavior into account fails even before it is implemented.

Research of architecting methods is inherently the combination of hard facts in an environment full of soft factors. Most of present-day hard disciplines (mathematics, physics, electronics, mechanics, et cetera) are frightened away by the soft factors. Most of the soft disciplines (psychology, philosophy, business management) have no affinity with the complexity in the hard facts. The challenge in the systems discipline is to tackle the soft factors, with sufficient understanding of the hard side.

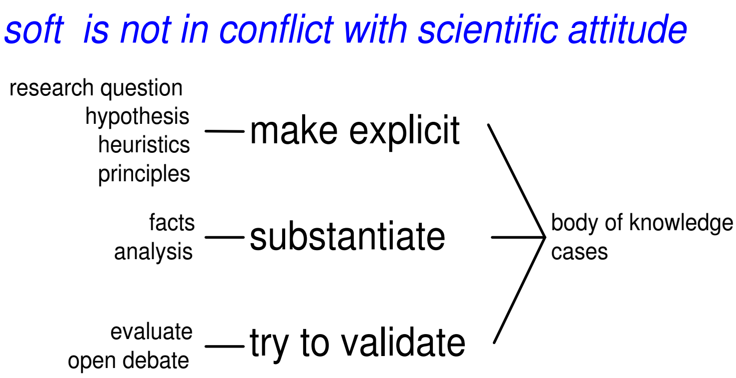

Figure 18: Soft problems can be approached with a scientific attitude

The fact that so many soft factors play a role is no excuse to stay in “trial and error” mode. The scientific attitude, see Figure 18, can also be applied to the soft kind of problems encountered in systems architecting. The Philosophy of Science has a long history. Some inspiration for the approach taken here are the *falsification* process by Popper, summarized by Tuten in [10], and the notion of *paradigms* by

Kuhn, also summarized by Tuten in [11]. Popper formulated the foundation of scientific methodology, for instance based upon open discussion, testable statements and a critical attitude. The weakness of the Popper view is the notion that science progresses linearly. Kuhn introduced the notion of *paradigm shift* to show that scientific progress at some times is non linear and requires a revolution to make progress. In this thesis we want to assess the value of the architecting method for industrial application. The use of a hypothesis and evaluation criteria is less rigid than the Popper approach, but at least it supports an open debate about the merits of the method.

The first step is to make research question and hypothesis explicit. After sufficient research the heuristics and principles will become visible, which can be very powerful means to capture generic know-how, see [9] for an extensive collection of systems architecting heuristics. A nice overview is given by Pidwirny [7], using characteristics such as *neutral* and *unbiased*.

The next step is to substantiate the benefits of proposed methods with facts and analysis. The last step is to strive for validation. For many soft issues validation will be an unreachable ideal. Increasing the plausibility is then the maximum that can be achieved.

These steps together contribute to the building of a body of know-how (as all sciences do), of which a significant part will be based on case descriptions.

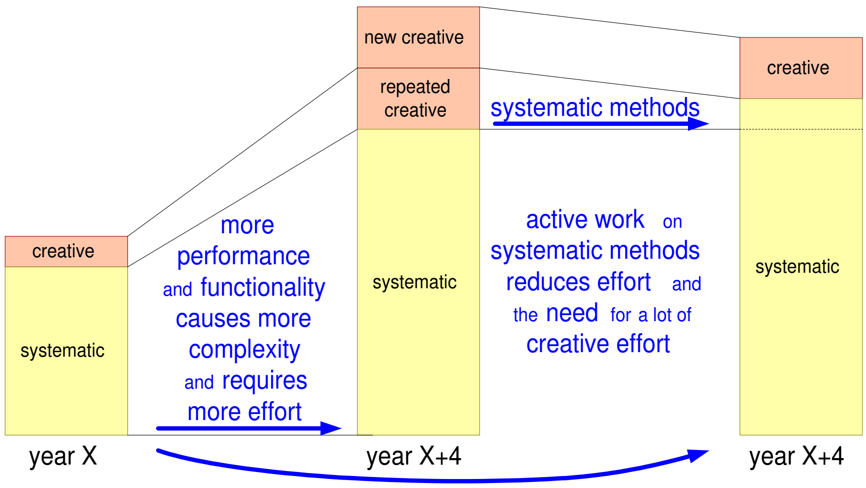

Figure 19: A scientific base is required to cope with the growing system effort. The scientific base provides a systematic approach that helps to solve known types of problems with less, more systematic, effort.

The relevance for the product creation companies is that the increasing effort of creating more powerful, but complex systems, is kept manageable. The ratio between the amount of systematic work, engineering, and the amount of creative/chaotic work should preferable stay the same. Due to the increasing complexity, in both hard and soft issues, this ratio will worsen if we are not able to make part of the system work more systematic.

The main challenge in the research of multi-disciplinary methods is to bridge the distance between the pragmatic world of product creation in the industrial context and the scientifically sound research of multi-disciplinary methods. Figure 20 shows the distance between the practitioners and the scientific foundation as an abstraction hierarchy.

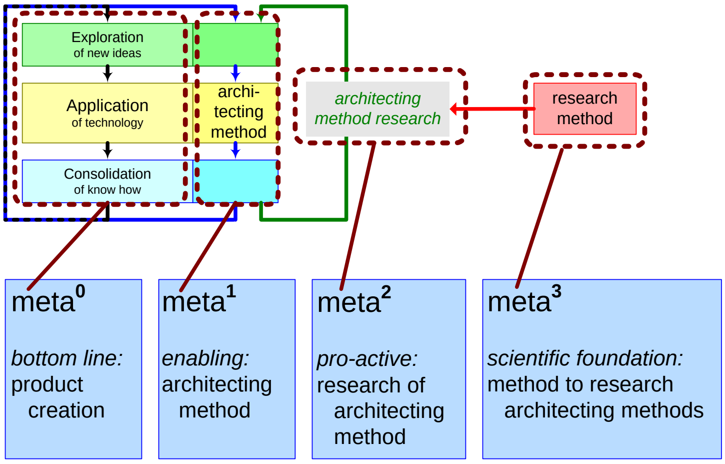

Figure 20: Moving in the *meta* direction. Research of multi-disciplinary methods is two steps of indirection away from the bottom line of product creation. The scientific foundation for this work is another indirection step

The status quo in *systems* architecting is that most architects learn by trial and error[2]

The approach taken in *multi-disciplinary design* can be abstracted into an *multi-disciplinary method*; this is the first step in the *meta*-direction. Doing systematic *research of multi-disciplinary methods* is a second step in the *meta*-direction. The definition of a *research method* (to investigate *multi-disciplinary methods*) provides the systematic research with a scientific foundation: the third step in the *meta*-direction. These three levels of abstractions illustrate the different worlds of practi-

[2] A systematic foundation for *systems* architecting is lacking in the companies I have worked for. Most companies do have extensive process handbooks and quality assurance handbooks, covering documentation, verification, project management, and many more issues. However, the multidisciplinary specification and design at *system* level is left open.

I have made visits to many other companies, explicitly asking for their systems architecting approach and how they develop systems architects. I did not find any systematic foundation at *system* level in any of these companies. The companies I visited are working in the telecommunication fields, computer industry, and electronics industry.

tioners and researchers.

5 Summary

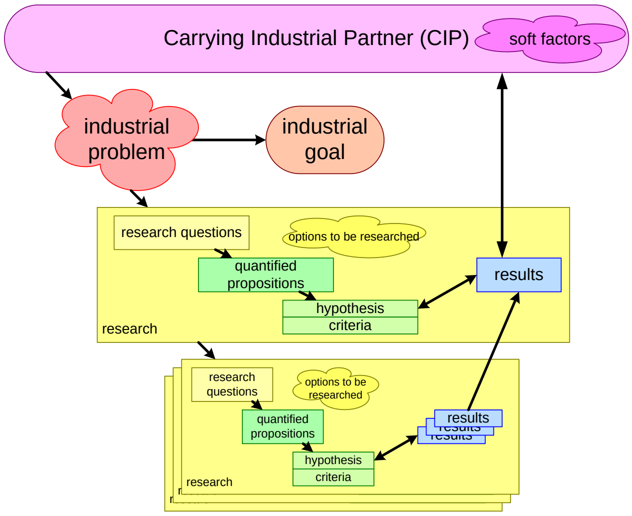

Figure 21: Summary

Figure 21 summarizes how we get from specific multi-disciplinary problems of the CIP to research questions, propositions and hypothesis. In addition this figure shows the recursive nature of the research, with sub-questions et cetera. The research produces results that have to be applied at the CIP, providing feedback to the researchers. This feedback is used in the evaluation of the hypothesis. Note that in the recursive application of this pattern we have to ensure that the sub-project level is well connected to the project level. Feedback from industrial application must take place at all levels of research.

The summary also shows that the industrial context is complex, for example due to all the soft factors that play.

References

[1] Hay Management Consultants. Technology management cycle. Hay Managament Consultants showed me this model in 1997/1998, taken from an article by a Japanese author. The original title of the Japanese article is unknown.

[2] Embedded Systems Institute. Boderc project. `https://www.embeddedsystems.nl/Boderc`, 2003.

[3] Maurice Heemels and Gerrit Muller, editors. *Boderc: Model-based Design of high-tech systems; A collaborative research project for multi-disciplinary design analysis of high-tech systems.* Embedded Systems Institute, Eindhoven, The Netherlands, 2006. `http://www.esi.nl/site/projects/boderc/publications/books/bodercBook20070313.pdf`.

[4] Robert Hunt. The origins of proof iv: The philosophy of proof. `http://plus.maths.org/issue10/features/proof4/`, 2000.

[5] Gerrit Muller. The system architecture homepage. `http://www.gaudisite.nl/index.html`, 1999.

[6] David L. Parnas. Software engineering: An unconsummated marriage. *Communications of the ACM*, page 128, September 1997. This article can also be found in "Software Fundamentals, Collected Papers by David Parnas", Addison-Wesley.

[7] Michael J. Pidwirny. Fundamentals of physical geography; chapter 3a scientific method. `http://www.geog.ouc.bc.ca/physgeog/contents/3a.html`, 1996.

[8] Colin Potts. Software-engingeering research revisited. *IEEE Software*, Vol. 10, No. 5:19–28, September/October 1993.

[9] Eberhardt Rechtin and Mark W. Maier. *The Art of Systems Architecting*. CRC Press, Boca Raton, Florida, 1997.

[10] Henk Tuten. Popper and philosophy of science. `http://huizen.daxis.nl/~henkt/popper-scientific-philosophy.html`, 1999.

[11] Henk Tuten. Thomas kuhn: definition paradigm (shift). `http://huizen.daxis.nl/~henkt/kuhn.html`, 1999.

History

Version: 0.1, date: 19 April 2007 changed by: Gerrit Muller

- changed order of slides
- added summary
- created text version
- changed status to preliminary draft

Version: 0, date: 10 April 2007 changed by: Gerrit Muller

- Created, no changelog yet