Industry-as-Laboratory Applied in Practice: The Boderc Project

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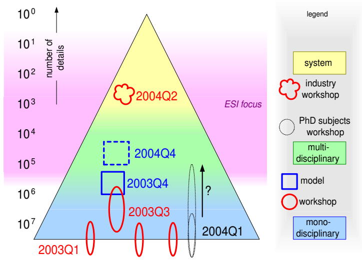

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Abstract

Many academical methods never reach industrial application. Colin Potts has observed this for software engineering methods. He proposed a new research approach: Industry-as-Laboratory. New methods are applied and verified in an industrial context.

The Embedded Systems Institute (ESI) has adopted this approach to research embedded systems creation methods. The Boderc project, which started at the end of 2002, is the first ESI project to apply this method. In this article we discuss the Boderc project, the Industry-as-Laboratory approach, the experiences, and the lessons learned.

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All Gaudí documents are available at:
http://www.gaudisite.nl/

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1 Introduction

The *industry as laboratory* approach, as proposed by Colin Potts[5], 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 1. We use the term *Carrying Industrial Partner (CIP)* for the company that provides the problem and the industrial setting.

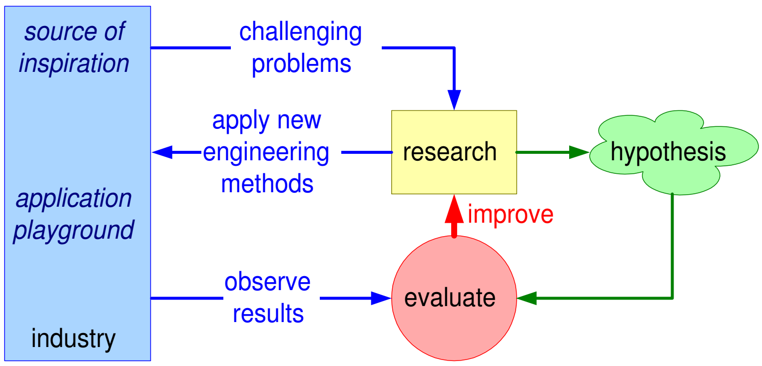

Figure 1: Industry as Laboratory: Research of Engineering Methods

In this article we discuss the application of the *industry as laboratory* approach in the Boderc project. The Boderc project is the first project started by the Embedded Systems Institute. The Embedded Systems Institute is researching multi-disciplinary embedded systems creation methods in large scale research projects. The research is done by a mixed team of academic and industrial people. The research question of an ESI research project is based on actual industrial problems. One industrial partner, the CIP, is chosen as problem owner. The CIP provides the industrial setting to be used as laboratory playground. The CIP of Boderc creates mechatronics systems.

A common problem in mechatronics systems is shown in Figure 2: 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 guaranteed SW response time.

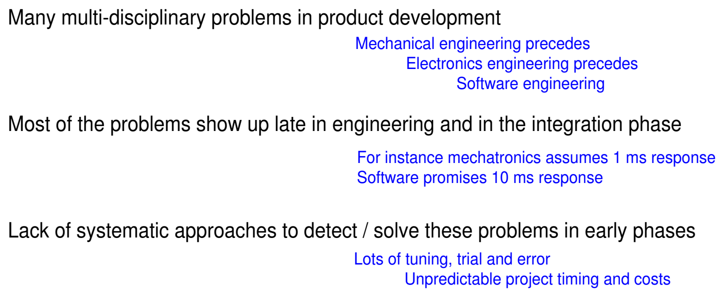

Figure 2: Typical Industrial Problem in Mechatronics Systems

2 The Boderc Project

The Boderc project is the very first project of the ESI. It addresses the problem observed in the creation of many mechatronics products that integration problems delay the delivery. The thesis of the Boderc research project is that the product creation lead time will be reduced significantly by the use of multi-disciplinary models during the early product development phases.

2.1 Goal of the Boderc project

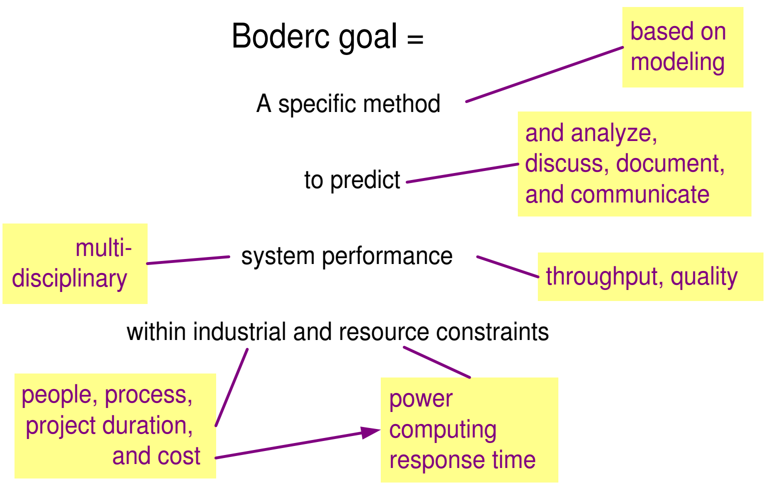

Figure 3: Boderc Research Project Goal

The multi-disciplinary problems in the creation of mechatronics systems are taken as a starting point of the Boderc project. The Boderc project goal, as shown in annotated form in Figure3, 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.

2.2 The industrial context

The laboratory for the Boderc project is Océ. 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 4.

Figure 4: The Domain: Printers and Copiers by Océ

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.

2.3 The Boderc master plan

The master plan for the complete project duration of the Boderc project is shown in Figure 5. The first year has been used to explore and to learn from existing systems. The second and third years shift the focus to the creation of new products. The last year is required for the consolidation.

2.4 2003H1, Exploration

The first half year has been used for exploration:

- What is the problem?
- What is the context?

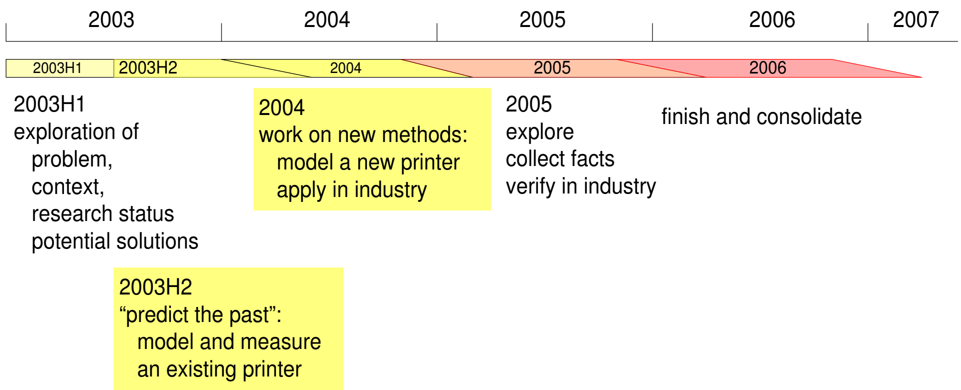

Figure 5: Master plan Boderc Project

- What are potential solutions?
- What has already been published?
- What other relevant research takes place?

The customer context has been modeled by means of a key driver model[3]. This model was immediately used by the industrial partner, because it provided a compact and sharp insight into the relation between the customer environment and the product requirements.

2.5 2003H2, "Predict the past"

During the first year of the project the team has worked on an existing product. This phase was called "modeling the past". The main purpose of modeling something existing is to learn:

- What is multi-disciplinary modeling as a team?
- What is the domain of high volume printers?
- Where are the technological challenges?
- What is the distance between the results of the modeling and reality?

A benefit of modeling something existing is that the target is rather stable; the design and its main parameters don't change suddenly. Another benefit is that the real system behavior itself can be measured, providing a way to verify the modeling results.

Figure 6 shows the part of the printer that has been modeled. The total project team was decomposed into three subteams. One subteam modeled the paper alignment

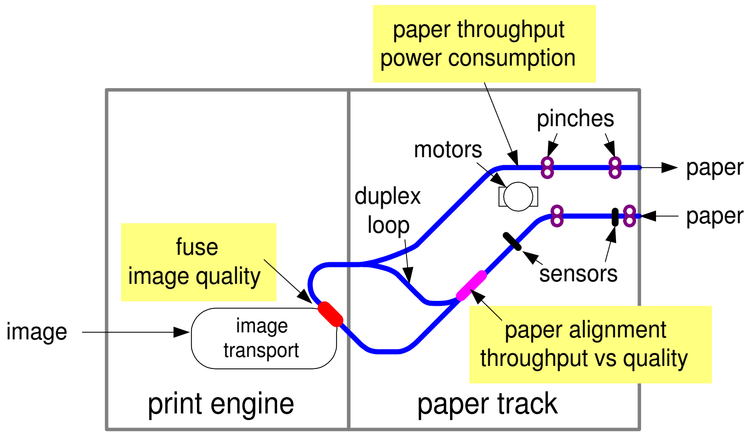

Figure 6: Modeling the Past

segment of the paper track. The second team modeled the fuse, the part of the paper track where image and paper meet and the actual printing takes place. The last team modeled the entire paper track at a higher abstraction level, to study throughput and power consumption. The printer itself was available for verification and has been used for measurements.

These modeling teams were "designed" in such a way that the disciplines, experience, and background of the members were mixed. This mix caused lots of communication problems. We had effectively created a small scale simulation of a multi-disciplinary project environment.

2.6 2004 H1, consolidating the past, preparing for the future

The first half of 2004 has been used to consolidate the results of the first modeling phase and to select and prepare the next modeling effort. The modeling of a new printer was started by a workshop, organized at the industrial R&D center. This workshop focused at the system-level quality attributes, as described in[3]. System-level quality attributes are for example throughput, power, cost, size, and reliability. The user-level system specification describes the requirements for these attributes. Most attributes have impact on detailed design decisions

This workshop with all project members plus a number of designers from the Océ development project itself was a big success. The discussions were lively and very fruitful. The investment of the first year could be harvested completely. The designers from the Océ development project got a lot of useful feedback on their ideas. They also became aware of blind spots, such as system-level consequences of more detailed design decisions. At the end of this phase the value of quality attributes as common denominator was more appreciated by the Boderc project members. The attributes can be used as starting point for multi-disciplinary communication.

2.7 2004 H2, Predicting the Future

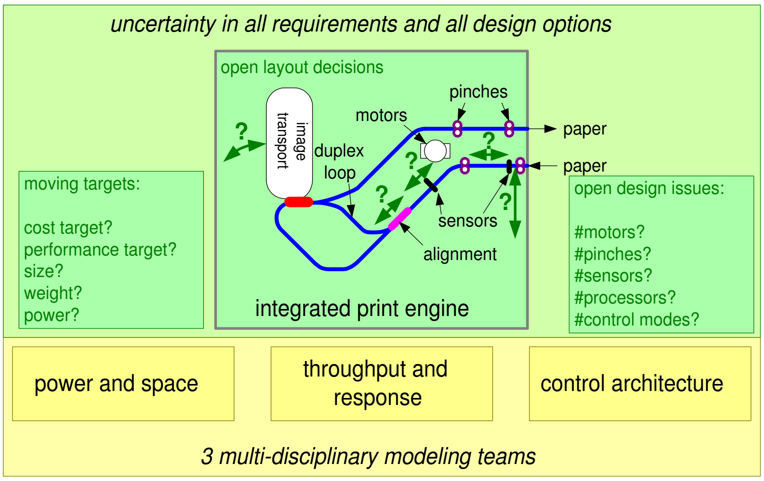

Figure 7: Modeling the Future

The second half of 2004 will be used to model in three subteams different aspects of a new printer under development. This new modeling effort is visualized in Figure 7. The focus of the modeling is again on the paper track of the new printer. One of the main differences with modeling the past is that all design choices are still moving; from requirements to layout decisions to the control architecture. The spatial layout of the machine defines the positions of all components in the system. In this case the modeling must become supportive in the design effort. The models made in this phase should be able to facilitate multi-disciplinary communication, and to facilitate the decision making by predicting system behavior, and by providing design space exploration.

The early results of the modeling teams for the future product are also promising. The first results of the *throughput and response* modeling team with a small MatLab simulation of the paper track, for instance, were highly appreciated by the industrial development team, because the model provided lots of insight into timing, performance, and power usage. This industry is already enthusiast with the results, while the research has just been started. The results so far and the industrial feedback triggers many research questions:

- How was this model conceived?
- What results are being used?
- What extensions are needed?

- What are reusable concepts of the modeling method?

2.8 Project team composition

		fte's	people
	research fellows	1	3
industrial	CIP employees	4	5
	industrial participants	2	4
academic	post doc	0	0
	PhD students	6	6
	academic coaches	2	8
	total	15	26

lesson learned:
1 or 2 post docs might provide a better balance

abbreviations:
fte: full time equivalent
CIP: Carrying Industrial Partner

Figure 8: Boderc Project Team Composition

The Boderc project team is a large team. The typical multi-disciplinary problems are amplified by the team size. The Boderc team combines three disciplines: mechanical engineering, electrical engineering and software engineering. Figure 8 shows the team composition in terms of industrial and academic people.

A significant project contribution is given by Océ, the Carrying Industrial Partner of the Boderc project. Most Océ employees work full-time on the project. The other industrial people are allocated to the project for two days per week.

The academic contribution is provided by 6 PhD students, all working full-time on the project. The benefit of PhD students is that they are not biased by lots of experience and therefore are sufficiently open for exploration.

The ESI has allocated three ESI research fellows to the project. Research fellows are experienced researchers. The research fellows provide direction to the project, coach the project members, maintain the project overview and consolidate the more generic and integral results of the project.

3 Essentials of the ESI Research Approach

The field of multi-disciplinary creation methods is a young research field. The existing scientific disciplines have little experience in this field, most experience can be found in industry. The ESI put quite some effort to determine a feasible research approach that fits with the multi-disciplinary working field.

3.1 Goal of the Embedded Systems Institute

The mission of the Embedded Systems Institute (ESI) is to establish methods to create embedded systems that fit in the industrial context, and to become a center of excellence in embedded systems creation. The methods must support all aspects of the creation: specification, design, integration, test and verification. Modeling, for instance, can be part of such a method. These methods must help to create systems that satisfy the functionality and quality attributes. Typical examples of quality attributes are performance, interoperability, productivity, and reliability. On top of that the methods must be workable in typical industrial constraints, such as: power, cost, economy, skills, and legislation.

3.2 Industry-as-Laboratory

The essence of the *Industry-as-Laboratory* approach has been shown in Figure 1. The research team builds an intimate relationship with an industrial product creation team. This relationship must be mutually beneficial. The research team gets inspiration from real industrial challenges, and at the same time it gets a means to verify research results in industrial settings. The industrial partner gets inspiration from intermediate results, and is continuously challenged by unbiased, creative, and critical people.

3.3 Technology Management Cycle

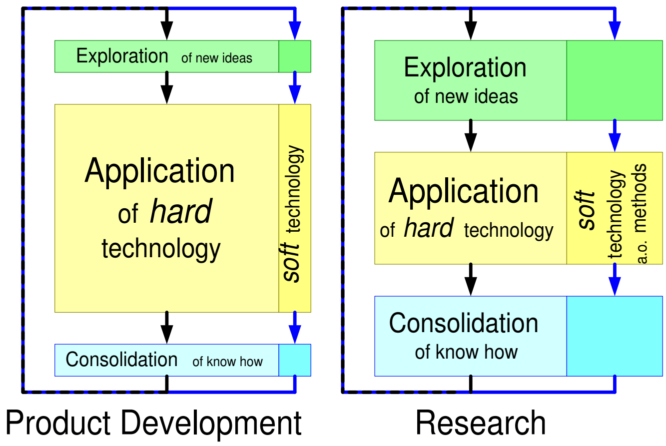

Figure 9: The technology Management Cycle. This cycle is also applicable for method development, also called *soft* technology. In product development the focus is mostly on applying technology, whereas the research focus shifts the attention more to exploration and consolidation.

Establishment of methods requires exploration, application, and consolidation as described in the technology management cycle[1], see Figure 9. 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.

3.4 Distance between industrial practice and method research

Figure 10 shows the growing distance between product developers and methods researchers. The product developers are mainly interested to use technology to create a product solution, $meta^0$. Methods, $meta^1$, are the means for the product developer to create the solution. The research of methods (exploring new ways, comparing alternatives, quantifying characteristics) is the next step in abstraction, $meta^2$. The scientific justification, in terms of the method of research, is the philosophical view on the research work, $meta^3$. The industry-as-laboratory approach must help to cope with the distance between the abstract *research of architecting methods* and the concrete, bottom-line oriented, product creation. Researching architecting methods without a link to the actual product creation does not make sense, because ultimately the results can only be evaluated in the product creation itself.

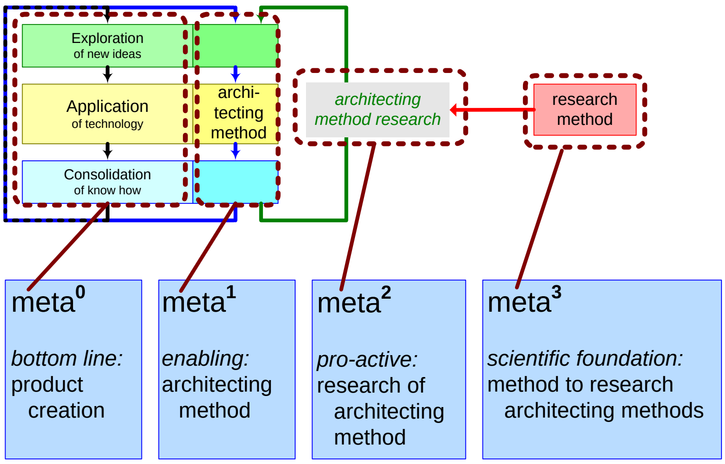

Figure 10: Moving in the meta direction

The proposed way of working at the ESI, also for the Boderc project, is a combination of the conventional hypothesis-evaluation cycle and case descriptions. In new research fields, full of rather soft factors, case descriptions are valuable means to explore and capture know-how. Case descriptions are one of the means to bridge the gap between industry and academics. The hypothesis that is evaluated should address both the methodological value as well as the industrial relevance. If both aspects are present in the hypothesis then it will also help to bridge the gap between industry and academics.

3.5 Multi-disciplinary methods

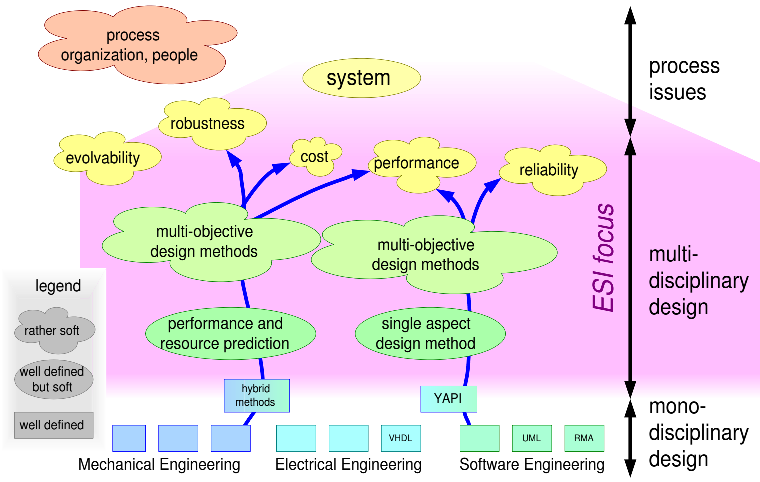

Figure 11: From Mono-Disciplinary to System

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[4]. 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 11 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 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 11 the methods at this level are called *multi-objective design methods*.

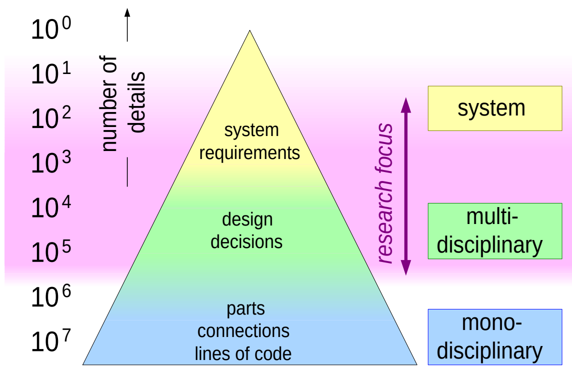

Figure 12: Exponential Pyramid

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 12 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 11 this is the range from *single aspect* to *multi-objective* design methods. In the pyramid, Figure 12, it is the area of translating hundreds of system level requirements into tens of thousands of design choices.

3.6 Summary of the essentials of the ESI approach

Figure 13 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.

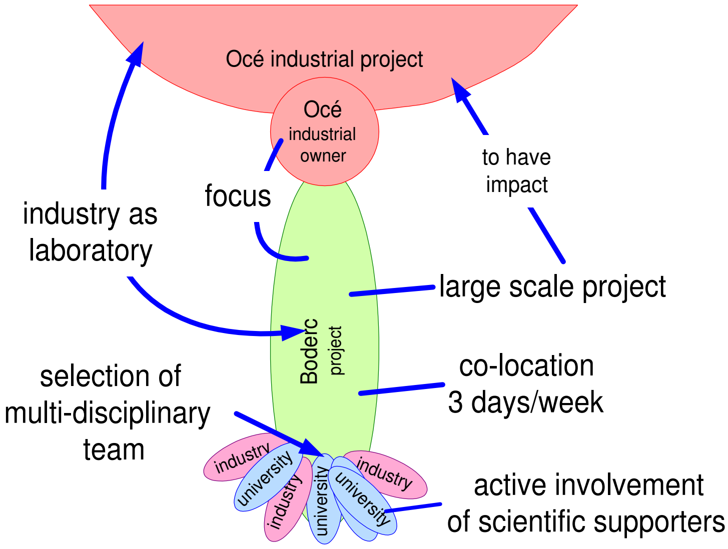

Figure 13: Critical Success Factors for projects

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 14 shows this relationship between capability development and projects.

3.7 Discussion

In order to realize the ESI mission, the gap between academics and industry has to be bridged. We have seen that industrial and academic partners are willing to participate in projects to research multi-disciplinary methods.

4 The Research Approach Applied in the Boderc Project

Superimposed on the pyramid in Figure 15 are several Boderc project activities, annotated with the timing, see also Figure 5. The activities start at a very detailed level. In a first workshop the researchers of different disciplines showed the other researchers their modeling tools applied on one set of pinches. The workshop after half a year of multi-disciplinary models shifted the focus slightly upwards. The main lesson learned for the project members was that communicating across disciplinary boundaries is really difficult. The industrial problem had been repeated on a small scale. The final models at the end of the first year of the project were more or less at the level of connected mono-disciplinary models.

The second project year introduces more real-world uncertainty by cooperating with the developers of a new product. This new product is more or less defined at

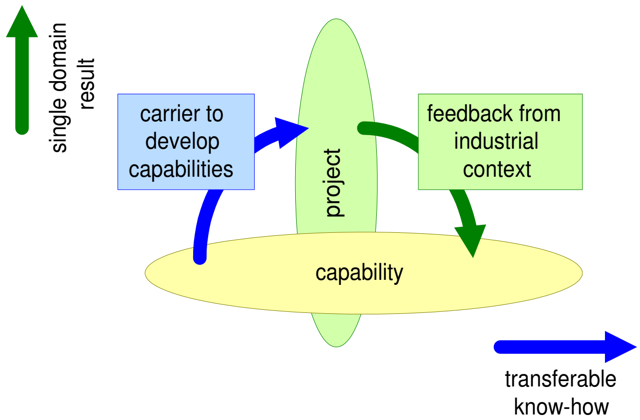

Figure 14: Project as Carrier for Capability Development

the top level (cost, price, size, performance, and introduction date), but all of these targets may change due to feasibility or market issues. The kick-off of this project phase, in the industry workshop, was on purpose focused at the system level, with heavy participation of the industrial carrying partner. The subjects discussed were at the level of the issues in Figure 7. Eight system issues were discussed at the level of hundreds of design parameters. This sandwich approach is intended to help the Boderc project members to create true multi-disciplinary models in the second half of 2004.

A remaining concern at this moment is the tension between the need for depth for mono-disciplinary project partners and the need for multi-disciplinary results of the industrial partners. This tension is most visible in the positioning of the subjects of the PhD-students, as shown in Figure 15. The scientific depth of the dissertation pulls the students downward in the mono-disciplinary field. A main challenge for the Boderc project is to reverse this scientific pull and to achieve scientific justifiable results at the multi-disciplinary level.

If we look at the development of the project members, especially the PhD students, from mono-disciplinary towards multi-disciplinary then we see that we needed at least two years for this growth. When we started we expected that this growth would take one year. This means that we need more time for the total project than the 4 years as originally planned. After two learning years at least two years of exploration and application are needed, followed again by at least one year of consolidation. In total a project duration of 5 to 6 years is needed, at least if we target for the original level of multi-disciplinary methods. In hindsight we might have created a more balanced team in terms of experience by replacing one or two PhD students by post docs.

The non-CIP industrial people are typically allocated to the project for two

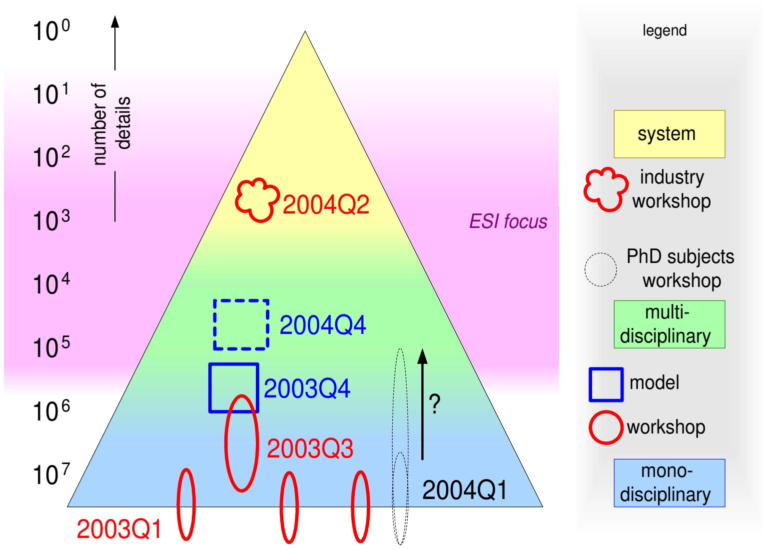

Figure 15: Stretching Upwards

days per week. They find it difficult to contribute in their part-time allocation. Part of the available time is needed for communication and recapturing what the other project members have been doing. The time left is not sufficient to actually build models. The project could benefit more from the existing industrial know-how if these industrial participants would also be full-time available.

5 Lessons learned

Halfway of this first project in which we apply the *industry-as-laboratory* approach to research multi-disciplinary methods, we can already formulate a number of lessons learned:

- The industry-as-laboratory approach addresses the gap between industry and academics. Research in multi-disciplinary methods can benefit significantly from this research approach.
- The gap between industrial multi-disciplinary problems and academic research is **huge**. This is clearly visible in the positioning of the work in Figure 15.
- The planned project duration of four years is too short if the core of the research has to be done by PhD students. Five or six years is more realistic.
- Additional projects are needed to do *research* on methods. These additional projects must apply the researched methods in different settings, and re-evaluate the hypothesis (Figure 10).
- Even more attention is needed for the composition of the project team, in the balance experience-inexperienced and in the balance industrial-academic.
- Part-time people can only be effective in a coaching role. The real research work (exploration, application, and consolidation) requires full-time people, see Section 2.
- Communication across disciplinary boundaries is really very difficult, as experienced in the entire project so far.
- The mix of project members in disciplines, experience, and background in the first year was a good preparation for the industry workshop in Q2 2004. The participants were able to iterate between system requirements and disciplinary design choices. This mix was facilitated by the industry-as-laboratory approach.
- The key driver models for the past as well as for the future were highly appreciated by the industrial partner. The industry-as-laboratory approach facilitates this cross fertilization; this in contrast with conventional research projects that are never confronted with customers or markets.
- The industrial appreciation of research results is a source of inspiration for further research, as can be seen by the initial results of the *throughput and response* model (Figure 7).

6 Acknowledgements

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History

Version: 1.3, date: September 28, 2004 changed by: Gerrit Muller

- minor update
- changed status to concept

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- mirrored figure industry as laboratory

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- many small textual changes
- removed last paragraph of the abstract
- added the project type (research or product development) more explicit throughout the text
- added short explanation of quality attributes
- added *blind spots* as value of 2004Q2 workshop.
- added introductory paragraph to sections 2 and 3
- added some more textual explanation to the Boderc goal
- added the need for a link between research of architecting methods and product creation
- changed the visualization of the ESI focus in the figures

- removed partner names in the figure Critical Success Factors
- added paragraph about underestimated project duration to section 4.
- moved some experience discussions from section 2 to section 4.

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- many small textual changes
- changed status to draft

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- added the formal reference about support

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- added problem statement to the presentation
- added challenging problems from industry to research in figure 1
- added ESI focus to multi-disciplinary figures
- updated lessons learned in presentation
- some language improvements

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- updated the abstract
- moved Boderc goal to section Boderc Project
- Introduction: added the type of product of the industrial partner
- decomposed section Boderc Project in subsections
- made the order chronological of section Boderc Project
- explained the work of the research fellows
- emphasized the importance of fitting in the industrial context in the mission
- added sentence about gap industry and academics
- moved the Boderc specific part from the research approach into a new section
- decomposed the section approach into subsections
- added a subsction Industry as Laboratory
- integrated the section summary of ESI apporach as subsection of the approach section.
- added a general positive lessons learned in the list of lessons
- added acknowledgements

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- added positive lessons learned

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- removed Gaudi distribution text
- added reference to Senter on frontpage
- added a description of Industrial Carrying Partner
- removed many small language errors
- added lessons learned

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- added text to article version
- changed status to preliminary draft
- defined the annotated pyramid as logo

Version: 0.1, date: July 16, 2004 changed by: Gerrit Muller

- added project composition
- added modelling the future
- reversed presentation order

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- Created, no changelog yet