Amaresh Chakrabarti · Udo Lindemann
Editors

Impact of Design Research on Industrial Practice

Tools, Technology, and Training

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Preface

This book grew out of a single question: what is the impact of design research on practice? The question was sparked off by the persistent belief that design research has little impact on practice.

The question led to a collaboration between the two editors in the summer of 2013, when Amaresh Chakrabarti took his sabbatical at Technical University of Munich to visit Udo Lindemann. An international workshop was organised by the editors at the Institute of Product Development, Technical University of Munich, Germany in 2013 called "International Workshop on Impact of Design Research on Practice" (IDRP 2013).

Most of the authors of the book participated in the workshop and deliberated on two major questions:

- What guidelines can be formulated for successful transition of outcomes of design research into practice?
- What kinds of platform are needed for supporting ongoing interactions between academia and practice for carrying out academically worthwhile yet practically relevant design research?

These questions were further discussed in breakout sessions, and summarised by Rapporteurs; the goal of the workshop was to learn from each other as to what contributed to the success of cases where research were transferred to practice, so as to achieve the following: to formulate guidelines for other researchers, especially young researchers, to support transition to practice; and, to help evolve common platforms on which transition of design research to practice could be discussed and supported as an ongoing process.

This book is intended to provide an anthology of work that together showcases exemplars of how various aspects of design research were successfully transitioned into, and influenced, design practice. The chapters are written by both academics and practitioners. It also contains surveys: of organisations engaged in design practice; of views of researchers and practitioners of design; and of publications and research outcomes from the academic community. Further, it documents learnings as to what worked in the successful cases of transfer, and what did not in some failed cases. Through the surveys, several of these chapters encapsulate experience of a much wider community than the one that participated in the IDRP 2013 workshop.

The work and the success stories shared in the chapters in this book show, emphatically, that design research has indeed made a significant impact on design practice. People trained in academia play a key role in impacting practice; therefore, education plays a key role in this process. Further, the impact of design research is not only via design research being transferred to existing practice; it is also about how design research helps create new practice, new jobs, new philosophies of practice, and so on.

This book is meant to instill confidence in the community that the work being carried out in its research and education are indeed important and impactful. It is also meant to provide areas in which the community needs to improve so as to further enhance its impacts on practice and education of design.

The editors wish to thank Technical University of Munich and its Institute of Product Development for their generous support in organising the IDRP 2013 workshop. In particular, the volunteers who worked hard to make the workshop a success, without which this book would not be possible, are gratefully acknowledged. Christopher Münzberg and Srinivasan Venkataraman have been the main support for the workshop. Thanks are also to them and to Hugo d'Albert for editorial and secretarial support for the book.

The editors thank Springer Verlag, in particular Anthony Doyle and Gabriella Anderson for their contributed editorial support.

Finally, Amaresh Chakrabarti wishes to thank Anuradha and Apala for their support and encouragement during the long gestation period for the book, as does Udo Lindemann to Edeltraut.

March 2015

Amaresh Chakrabarti
Udo Lindemann

IDRP Editorial: How Design Research Impacts Practice

Introduction

Design research (DR) is a relatively young discipline with about 50 years of clearly identifiable work as a research community. However, like all progressive research communities with application as a goal, an often-asked question in design research is: what is the impact of design research on practice?

According to Blessing and Chakrabarti (2009), the term 'Design Research' refers to the development of understanding of and support for phenomena associated with design in order to make design more effective and efficient, so as to help practice of design and its education to become more successful. Similarly, Telenko et al. ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid) define 'design research' as the scholarly inquiry that seeks to advance design by studying and improving it in systematic and scientific ways. More specifically, they see design research as the means to expand, test and operationalise the findings of design science.

Telenko et al. ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid) define impact and influence as transfer of knowledge between design researchers and practicing designers. Knowledge transfer is not necessarily measurable and direct; it may take many forms, involving people, products and partnerships.

There is a persistent belief that design research has made little impact on practice. However, as observed in "Changing Conversations and Perceptions: The Research and Practice of Design Science" (ibid), it is "largely a matter of perspective based on limited assumptions, narrow definitions, and stereotypical views."

Many issues of transferring knowledge from design research to practice are not unique to design research. For instance, as quoted by Telenko et al. ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid), some of the major challenges in medicine include difficulties faced by health practitioners in approaching scientific literature, assessing validity and practical relevance of new knowledge, and incorporating results into their practice

(Greenhalgh 2010); studies also show that research that should change medical practice is often ignored for years.

This book is intended to provide an anthology of chapters that showcase exemplars of how various outcomes of design research successfully transitioned into and influenced design practice. The chapters written by researchers primarily showcase examples of findings, products and curricular programmes that grew out of design research conducted in academia and influenced the practice of design. The chapters from practitioners primarily showcase experiences from practice as to how design research or training in design methodology influenced design practice.

The evidence from several surveys undertaken in the broader literature, and the surveys undertaken by Telenko et al. ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid) and Graner ("Are Methods the Key to Product Development Success? An Empirical Analysis of Method Application in New Product Development", ibid) in this book, as well as the success stories shared across the chapters in this book bust several myths. "Researchers do engage with industry. Industry professionals do participate in academic venues, and many design researchers do have experience in practice as consultants, industry employees or both" ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid).

People trained in academia play a key role in impacting practice; therefore, education plays a key role in this process. It is not only about how design research is transferred to existing practice, it is also about how design research creates new practice, new jobs, new philosophies of practice and so on.

As a background, the topic of the book was discussed in a workshop organised at the Institute of Product Development, Technical University of Munich, Germany in the Summer of 2013 called the "International Workshop on Impact of Design Research on Practice" (IDRP 2013). Most of the authors of the book participated in the workshop and deliberated on two major questions: *What guidelines can be formulated for successful transition of outcomes of design research into practice? What kinds of platform are needed for supporting ongoing interactions between academia and practice for carrying out academically worthwhile yet practically relevant design research?* These questions were discussed in breakout sessions, and summarised by Rapporteurs.

The goal of the workshop was to learn from each other as to what contributed to the success of the cases where outcomes of design research were transferred to practice, so as to help achieve the following: to provide guidelines to other researchers, especially new researchers, to support transition to practice; and to help evolve common platforms on which transition of design research to practice could be discussed and supported as an ongoing process.

This editorial provides a summary of the chapters and the breakout sessions from the workshop to highlight some of the examples of successful transfer of design research into practice. It also looks across the chapters and the breakout session summaries to obtain a broad brush picture of the overall impact of design research on practice. The chapters are written by academics and practitioners from twelve countries spanning three continents: Asia (Japan, India, Singapore), Europe

(Finland, France, Germany, Italy, Luxembourg, Spain, Sweden and the UK), and North America (USA). Further, several of these chapters provide surveys of experience from a much larger array of academic researchers and practitioners, and therefore encapsulates experience of a much wider community beyond the one that participated in the workshop.

The book is divided into three parts. The first part “Surveys and Summaries” comprises five chapters: three of these are surveys of impacts of design research on practice; the remaining two are summaries of the breakout sessions from the IDRP 2013 Workshop. The second part “Experience from Academia” contains fifteen chapters. The third part “Experience from Practice” comprises ten chapters. Even though the authors of “Verification Upstream Process, a Quality Assurance Method for Product Development in ODM Mode” and “Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry” are now in academia, the chapters are written based on the experience of their authors in industry. Except for the summaries from breakout sessions that are placed at the end of the first part, all chapters within each part are organised using an alphabetical order, based on surname of the first authors.

Beyond the two major questions asked at the workshop, this editorial asks some more questions that are related to the two major questions; it then gleans possible answers to these questions from the chapters. In order to assess success of transition of design research outcomes to practice, one needs to understand what metrics could be used for assessing success, and the possible routes through which success could be achieved. The first two questions below explore these aspects. The editorial then seeks possible answers to the two major questions asked in the book. The expanded list of questions explored thus is given as follows:

- What are the metrics with which to assess success of transition of DR results on practice?
- What are the routes through which DR impacts practice?
- What guidelines can be formulated for successful transition of design research results into practice?
- What kinds of platforms are needed for supporting ongoing interactions between academia and practice for carrying out academically worthwhile yet practically relevant design research?

Summary of Chapters and Key Points

In this part, we provide a brief summary of, and the key points made, in our view, in each chapter. “Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics”–“Results From the Breakout Sessions of Group B” is on Surveys and Summaries.

In “Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics”, based on a study of transfer of research results to practice, Blessing and

Seering have identified a number of heuristics for successful transfer. The key points from the chapter are:

- A large concentration of successful applications of research results are in the area of support for a specific design task that is applicable in multiple settings.
- The three heuristics that were considered applicable in most cases are: The question being addressed will be of substantial interest to practitioners; Research results will be evaluated by practitioners; Tools will improve process effectiveness and/or efficiency measurably.
- Industry and academia must be in continuous engagement. The authors suggest the following routes: Academia: findings (practice as sample or data source) → development (practice as sounding board) → verification (practice as test bed).

Graner in "Are Methods the Key to Product Development Success? An Empirical Analysis of Method Application in New Product Development" reports on a major study on application of design methods in the context of new product development. Based on a study of 410 new product development projects conducted with feedback from experienced product development managers and project managers in 209 manufacturing companies that operate their own new product development from bases in Germany, Austria and Switzerland, it was found that applying methods in new product development led directly to superior financial performance of the developed product, and indirectly to a greater degree of innovativeness, better cross-functional collaboration and shorter time to market. The key points from the chapter are:

- Use of design methods increase chances of product success in New Product Development projects via time to market, cross-functional collaboration and innovativeness—all factors influencing product success. Product development teams should foster adoption of methods in their design process. Companies that use a combination of methods to consider the aspects of customer demand and willingness to pay, technical feasibility, product cost and project management together, will meet with an overall higher product success.
- Companies that have formally defined the new product development process, which split this process into individual process steps that evaluate the status of development at the end of each step and that decide whether to continue the development project at defined gates in the process tend to use more methods in new product development.
- Product development teams that receive greater support from the management adopt substantially more methods. Rigorous project management is also needed if new products are to be developed quickly and with efficient use of resources.

In "Patterns and Paths for Realising Design-Led Impact: A Study of UK REF Cases Studies", Hicks examines 22 case studies taken from two of UK's leading

Mechanical Engineering Departments. The case studies were prepared in 2013 for the purposes of the UK's Research Excellence Framework assessment. The cases are categorised and grouped according to the dimensions of impact, sector, timescale and core mechanisms employed, with the aim of eliciting common routes to influencing practice, product design and policy. The key points from the chapter are:

- There is a greater focus on research into new/improved products rather than process improvement. Product-led research gave rise to greater international impact and hence reach. Process-led research was generally restricted to more national/local impact. Product-led impact and research generally had a more significant measured economic impact in the timescale considered than process-led research.
- The most common mechanisms for achieving impact were Technology Strategy Board (TSB) funding, Knowledge Transfer Partnerships and consultancy activities. Spin-outs were the key mechanism for product-led impact while consultancy was the key mechanism for tool/method-led impact.
- General insights for realising impact from design process research revealed seven challenges concerning: the limitations of studying what is rather than what should be; the general lack of verification of practice-led research; the difficulty of balancing generality and specificity; the proliferation of tools/approaches; the need to directly support practice and training; the need for integrated funding; and the need for benchmarking and performance measurement.

"Results From the Breakout Sessions of Group A" and "Results From the Breakout Sessions of Group B", rapporteured by Lucienne Blessing and Chris McMahon respectively, are not further summarised here, since these are already summaries of breakout sessions from the IDRP 2013 Workshop. Both chapters contain a series of recommendations as to which guidelines should be followed to support successful transfer of research results to practice, and as to which platforms between academia and practice should be helpful for identification, development and transition of research outcomes to practice.

"Impacts of Function-Related Research on Education and Industry" by Arlitt et al. speaks about the function-based paradigm, which focuses on abstracting what a system does separately from what it is. Within this paradigm, it is important to communicate abstract functions in a consistent manner, without binding them to their embodiments. This chapter discusses two recent outcomes in function-based design research, their impacts on education and industry, and the authors' observations regarding their adoption into practice. The first of these outcomes is an information schema for capturing design artefact knowledge, which includes a standardised function taxonomy. The second research outcome is a conceptual linking between functions and failure modes, enabling new types of failure analysis techniques in early design. The key points from the chapter are:

- Education and training activities provide direct bottom-up influence, though tracing the impacts caused by newly trained engineers is challenging; cultural inertia within established organisations can present barriers to acceptance of new design techniques.
- Direct collaboration with industry provides top-down influence, but requires buy-in from key people in the organisation. Small start-ups represent a compromise between receptiveness to new ideas and capacity to impact practice; a combination of top-down and bottom-up techniques is needed to produce noticeable change in practice.
- Research outcomes must possess demonstrable utility by providing direct solutions to practical problems in an easy-to-use manner. Simplicity and flexibility of core research contributions are critical to facilitate transition into practice, such that interested stakeholders can adopt and adapt the research outcomes with low effort.

"A Framework for the Dissemination of Design Research Focused on Innovation" by Becattini et al. presents a framework for transferring results of design research into practice, specifically addressing the need to create a circle of players from companies interested in being part of the mass dissemination process of already tested methodologies as well as in pilot experiences and preliminary dissemination activities with latest design research developments. Moreover, the chapter focuses attention on existing metrics for evaluating impact and viability of adoption of design methodologies in practical contexts, showing their lack in covering aspects related to the dissemination of design research concepts. A new metric is then proposed and applied to six case studies of industrial interest. The results highlight the potential benefits from adoption of a shared metric for measurement of knowledge transmission of this kind from design research to practice. The key points from the chapter are:

- It is recommended to rely on a structure that links together academia and industry, such as a centre of competence, with mutual exchanges on research objectives, best practices on design methods and punctual assessment of the related impact; a structure is proposed where students, innovators and early adopters work in collaboration with a design research-centre of competence combination to generate interesting research results, develop new methods and apply on practical case studies, and generate a culture of design research respectively.
- It is recommended to assess the goodness of the outcomes of design research through intensive tests before their dissemination to a bigger audience. A reliable assessment should consider the effectiveness of the proposed methods and tools by validating them with statistical significance (e.g.: by involving students in academia as testers, if needed) and on the field with companies to evaluate their industrial impact;
- It is recommended to measure the outcomes of the transfer by means of appropriate metrics that also allow the identification of issues and troubles of the applied methods and tools, as well as the need of new ones addressing emerging situations.

"Impact of Design Research on Practice: The IISc Experience" by Chakrabarti analyses the broad development of design practice, research and education in India, and uses some of the major developments at the Indian Institute of Science (IISc.) as exemplars to illustrate the impact of design research on design practice, research and education. The outcomes of design research can influence practice through multiple routes: the chapter illustrates each route with exemplars from work carried out at IISc. The key points from the chapter are:

- A variety of platforms are possible through which design research can impact practice: the most direct is via products. The next is via methods and tools, which can be used on multiple products. The third is via people who move to, or change practice. The fourth is via organisations created around research results. The fifth is via platforms for training.
- A matchmaking of the needs of industry and offerings from academia should happen, where scientific needs of the academia and practical needs of the industry must meet on a platform. The platform should encourage exchange of problems, and the timescale associated with them. It should also encourage 'tweeting' on the emerging solutions being developed in academia.
- A more direct platform is not necessarily more impactful. For instance, a specific product may lead to a certain income for an organisation, whereas a person can initiate a variety of products and organisations. However, the more indirect the platform is, the harder it is to assess its impacts. Appropriate metrics need to be developed to support assessment at different levels.

In "Industrial, and Innovation Design Engineering", Childs and Pennington describe a 34 year old, highly successful, double-masters programme called Innovation Design Engineering (IDE), run jointly by the Royal College of Art and the Imperial College London. IDE's teaching philosophy is trans-disciplinary, where students are competent across several disciplines as represented by an 'm' shaped profile of multiple discipline competence. While traditionally graduates gained employment in corporations and design consultancies, the past 5 years has seen a shift with the greater proportion of graduates setting up their own businesses and consultancies on completion of the programme. A characteristic of many IDE alumni is that they do not tend to be designer names per se but are transdisciplinary team players. The key points from the chapter are:

- Educational programmes in design have a major impact on practice, and the IDE course is an example case. They impact as resources for fresh inputs to existing industry, its knowledge, its effectiveness and its efficiency in innovation, as well as providing people who will create new practice altogether.
- The course is based on three key principles: diversity, design and engineering mix, and making it real. The programme embraces a wide range of disciplinary entrants, and guides them on a journey through experiences in design, technology and engineering towards a destination of innovation enabled by their diverse skills and experience.

- A highlight of the course is the industrial embedding of some of its student projects. This provides both a contextual exposure to students to industrial problems, and demonstrates to practice the value of what is learnt in design courses.

In "Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA", Fadel et al. summarise design research at Clemson University and its impact on industrial practice, particularly in the evolution and transition of disparate ideas into cohesive concepts that were eventually transitioned to industry. In design research, a broad area of endeavour, design theories take the longest to develop and are the slowest to transition to industry. The development of methods, practices and their applications to industrial problems are much quicker to transfer, however, since industry professionals see the immediate potential benefits or shortcomings of the methods and issues of interest to them. The training of students at all levels in design practice also affects industry as many assume positions in and affect the practices of their companies. The key points from the chapter are:

- Transfer of research results directly to practice are enabled by: close collaboration with industry, where Principal Investigators and students remain intimately involved with industry—often through interns or extended work periods; research is both demonstrated and validated with real problems; projects have a clear value proposition for industry.
- Both undergraduate and graduate teaching impact and are impacted by research and together make the biggest impact on practice. Industry sponsored, undergraduate, capstone, design-build-test projects solving industry-provided problems using design methodology with graduate advisors who coach the students as well as use the data from the projects for research have been useful in training students in practical problem solving using design methodology, testing design methods and tools, and demonstrating to industry the power of design methodology.
- A route to industry is industry-sponsored research developing new methods and tools, leading to training programmes for transition to practice (practice → methods → training → practice).

"Evaluating Tactual Experience with Products" by Georgiev et al. focuses on design research that analyses users' tactual experience with product interfaces, especially the analysis of users' impressions of such experiences. The method was developed in a case to evaluate users' tactual interactions with product interfaces in the context of the car industry, particularly for research and development of interfaces of vehicles. The method was applied in a trial evaluation for vehicle interfaces of navigation systems, audio systems, and air conditioning systems. The key points from the chapter are:

- The form of the research content must show clear developments in the specific area.
- The expected benefits must be clarified in terms of outcomes and required resources.
- Sustainability and support for the project are important.

In "Multiple Forms of Applications and Impacts of a Design Theory: 10 years of Industrial Applications of C-K Theory", Hatchuel et al. argue that the very abstract nature of C-K Theory and its high degree of universality were instrumental in supporting a large variety of industrial applications. Three types of applications are distinguished: C-K theory provides a new language, that supports new analysis and descriptive capacity and new teachable individual models of thoughts; the theory provides a general framework to better characterise the validity domain and the performance conditions of existing methods, leading to potential improvement of these methods; the theory is the conceptual model at the root of new design methods that are today largely used in the industry. The key points from the chapter are:

- Assessment of industrial applications and impact of a design theory consists of evaluation in four dimensions:
  - improvement of analytical and descriptive capacities;
  - improvement and positioning of existing methods and processes;
  - development of new tools and processes;
  - impact on other disciplines and on design professions.

Stanford University's Center for Design Research (CDR) has been in operation for 30 years. Its primary impact on practice comes through its people. In "People with a Paradigm: The Center for Design Research's Contributions to Practice", Ju et al. summarise the CDR's research approach and themes, and then look at the mechanisms through which the people of CDR affect the landscape of industry and education, and impact the practice of design. Research at the center has three characteristics: its Design research is embedded in the empirical; the Research both focuses on designers working on technical problems, and features researchers who readily employ technical solutions in their research tools, metrics and interventions; and its Research focuses on design as a social process between teams of people. The key points from the chapter are:

- People are the ultimate vehicles by which research is converted to practice:
  - Some people take the ideas from their research and turn them into products, which are then sold to and used by thousands of people.
  - Others employ the paradigms of the research mindset in their own practice, thereby increasing the use of qualitative reflection as well as data-driven empiricism in the design of goods and services.
  - Finally, a number of people go on to share the ideas of design research by continuing to research design, and teaching students to research design, and diffusing the ideas generated by design research into the broader culture.

Design research is well established within many universities primarily within developed countries. In Germany, about 50 years ago, a number of institutes were founded or existing ones moved to design research and teaching. With time, the interdisciplinary character of engineering design and design research became more visible. It is a good tradition in scientific communities to evaluate the impact of research activities, usually on a long-term basis. "Impact of Design Research on Practitioners in Industry", by Lindemann, is based on the experience and observations of the author on a long-term basis. Further research regarding the impact of design research is urgently required, although it is difficult to assess because of long-term effects and a large number of influences that cannot be controlled. The key points from the chapter are:

- Investing efforts in transfer requires possibilities of measuring the real impact or at least identification of indicators. Reliable ways of measuring the impact requires long term analyses of changes; this is hard because of a large number of influences that are difficult to control.
- Academia aims to create sustainable impact on teaching, research and practice. The last one requires an intensive exchange with practice. The most effective and sustainable way of impacting practice is via people. Academia should see the long term effects, as much of learning is implicit by doing, reflecting, copying, improving and gaining experience. This takes time.
- Both industry and academia must understand and accept the difference in their goals and cultures. Researchers from academia have to be able to formulate their content in a way that practitioners are able to understand and are willing to accept.
- Based on types of actors on management and operational levels in industry, five different categories of impact on practice are possible: there is a good chance for successful transfer via PhDs or MScs if management and operation both see the need; there is a small chance for successful transfer via PhDs or MScs, if management is not interested but operation sees the need; in case of transfer via MScs there is a small chance, and in case of PhDs and joint projects a realistic chance, if management sees the need and operation is at least interested; in case of transfer via MScs there is no chance, and in case of PhDs and joint projects a small chance, if management has at least some interest and operation sees no need; if neither management nor operation sees the need, there is no chance for successful transfer.

In "Rationalization Process for Industrial Production: Centres of Design Excellence and Prototyping", Lloveras proposes a rationalisation process of industrial production of consumer products. The application of a double filter to industrialise products is proposed, consisting of an initial evaluation of innovation quality and design improvement, followed by an assessment of design excellence and production viability from a social point of view. This chapter also lists several doctoral theses and other research work on the enhancement of conceptual design and manufacturing processes of innovative products developed in Universitat

Politècnica de Catalunya Barcelona, and the impact on practice of the university's design research. The key points from the chapter are:

- A new concept of design and prototyping in specialised centres, where up-to-date design methods and tools would be used to develop designs with significant socio-economic need and quality would compete for take up by manufacturing companies is proposed as a possible route to using design methods and tools in practice.
- Education plays the central role in transfer of design research to practice. In this case, it influences the way education is imparted, research results are utilised, and how the design paradigm is spread across other parts of the world.
- University-industry agreements for joint product development projects is the third route used for impacting practice, leading to joint designs and patent applications.

In "Facing Complex Challenges—Project Observations", Maurer presents a process for identifying types of complexity, promising strategies and useful methods in a project context. The chapter also clarifies as to why established methods of complexity management can result in insufficient solutions when applied in the wrong context. The key points from the chapter are:

- Complexity is a poorly understood area even in practice, where complexity is meant to be managed on a regular basis.
- Carrying out a research project in an industrial setting provides a reliable test-bed for demonstrating design research results.
- Start-ups based on design research results are a possible route to impacting practice.

In "Faceted Browsing: The Convoluted Journey from Idea to Application", McMahon describes the development of a team's research in engineering applications of faceted classification and search over 20 years, from early experiments in novel information systems to routine use and development of a growing body of knowledge about how the techniques may be applied. It illustrates not only an outcome from design research that has influenced practice but also some of the socio-technical patterns that may be observed in the development and exploitation of research outputs, and to be taken into account for transferring research results to practice. The key points from the chapter are:

- Research and knowledge transfer in the development of new ideas and tools often take convoluted, socio-technical patterns that are important to take into account for transferring research results to practice. A development occurs in multiple places simultaneously because it is timely. While the ideas may only take root if they are particularly timely, they all form part of the knowledge-base of the research team, perhaps to be picked up again at some later point.
- It is important in collaborative research between academia and industry to have a portfolio of work from short term to more speculative, and to use each type of work to inform the other.

- Research teams should continually monitor technical maturity of its research outputs, e.g., using 'technology readiness level'. It takes time for technologies to be adopted to new applications.
- Research teams need very good understanding of the mechanisms for commercial development of research through venture capital, seed-corn and other early stage funding. Industry partners and users of research outputs should be aware of the influence they can have with early-stage funders and the benefits to the research team of targeted support for commercialisation efforts.

In "Successful Industrial and Academia Cooperation in Technology Industry", Riitahuhta and Oja speak about the influence of the establishment of Governmental Technology Development Agency TEKES in 1983 on research and its impact on practice. TEKES and Technology Industries jointly created several technology development programmes, which became the most important platforms for industry-academia cooperation. The technology programmes have also worked as bridges to international co-operation and exchange of people, leading to awareness and absorption of various design methods: e.g., Creativity techniques such as Synectics, TRIZ; Generic Design Methodology; Design Structure Matrices (DSM); Quality Function Development (QFD); Expert Systems; Product Lifecycle Management (PLM), etc., by Finnish research and teaching. The key points from the chapter are:

- Besides teaching material, industrial doctors support creation of the research agenda as Industrial Advisory Board and many of them participate in teaching specific parts of courses.
- An important route to academia-industry engagement is industrial funding for research. The demand is set by the government funding body that certain industrial funding is necessary for governmental research grant. Because industry benefits from knowledgeable staff members, concepts and phenomena models through cooperation, it is possible to get research funding.
- Training has industrial components at all levels: problem based learning with real industrial problems; Master's theses with a theory framework and an industrial solution; or doctoral theses with a novel theory validated with industrial examples.

Although design science is a relatively young field, the impact of design research upon industry, according to Telenko et al. (authors of "Changing Conversations and Perceptions: The Research and Practice of Design Science"), is evident in the literature, in the practice of design by academics and in the experience-set of the authors. "Changing Conversations and Perceptions: The Research and Practice of Design Science" provides evidence of impact from three sources: two studies of design literature and one survey of design researchers. It is found that over one third of design research articles, despite focussing on theory, include engagements with industry, and, complementarily, a majority of design researchers have patents, industry experience or both. These studies change common perceptions of the impact of design research on practice. Building upon these analyses, the authors develop a first set of guidelines for transferring design research to practice. The key points from the chapter are:

- Bridging research and industrial, commercial or entrepreneurial applications is a two-way relationship. Very often new systems, products and processes spur, support or enable new fundamental questions that reveal new and valuable understandings and further new systems.
- A wider range of models and guidelines are needed to cover the varied conditions in the design research–practice relationship. Strategic policies and incentives are needed to build bridges between design research and practice.
- Thirteen broad guidelines for integrating design research and practice are proposed: connect direct value; partner with product development firms; assess industry processes; incubate companies; invent within design research; collaborate with industry partners as PIs; practice design; commercialise methods and techniques; brand and disseminate; develop standards in design; house practitioners on campus.
- Many interactions between industry and research occur outside publishable research, through consulting, workshops, and in the trenches of design. The most powerful mechanisms for transferring research to practice engage students. Education of future designers and industry leaders is one of the most important tools for bringing research to practice.

In "Development of Function Modeling and Its Application to Self-maintenance Machine", Umeda and Tomiyama discuss the impact of design research on practice by taking two cases; function modelling, and self-maintenance machines deployed from function modelling research. The key points from the chapter are:

- Research results may impact practice directly, or impact further research. FBS modelling and FBS Modeller were not directly used in practice, but, the research results worked as a normative model that encouraged engineers and designers to understand function modelling, function reasoning, and functional design support, and together with other research encouraged further to expand the research domain of function modelling/reasoning/design, which is still active.
- It is very important to share the basic concept with industry (e.g., the self-maintenance machine). The demonstration of the research results and prototype machines was effective to transfer the concept of the self-maintenance machine from academia to industry.
- A clear and agreed target was set early on in the project that was important for the business of the company and for demonstrating academic work. This early consensus was important as a common win–win ground for progress of the project.

"Experience with Development Methods at Three Innovative Hidden Champions"–"When and How Do Designers in Practice Use Methods?" is based on Experiences from Practice.

In "Experience with Development Methods at Three Innovative Hidden Champions", Fricke discusses various design methods and tools that have been implemented, used and found useful in the two organisations, both international market leaders, in which the author worked for almost 20 years in product development at various levels: from project leader to the CEO level. It also enlists a number of enablers of method implementation that were found to be effective. The methods span from project planning, through product development to project management. The key points from the chapter are:

- An intensive investigation into practical use of design methods and its optimisation to bridge the gap between sophisticated method development in universities and dissatisfying assignment of successful methods in industry is needed so that the methods can be implemented simply and used sustainably.
- Such methods should be taught in universities and professional training programmes to accelerate their successful application in industry.
- Intervention of leadership is needed to improve implementation of product development methods in practice so as to develop better products with efficient development processes. Leadership should engage and educate methodical experts to participate in projects as internal project supporters, with further support from universities or consultant firms.

"Design as an Unstructured Problem: New Methods to Help Reduce Uncertainty—A Practitioner Perspective" is by Garvey and Childs. Taking the view that design is solving of unstructured problems, entailing high risk, the authors argue that use of design methods helps reduce uncertainty. They see, as core, two conditions that designers have to come to terms with in this process: how can problems be categorized and which of these variants is the most problematical, and argue for two methods that support decision-making and mitigate risk, under the broad category of Problem Structuring Methods (PSMs), when faced with qualitative judgment rather than observed metrics: Morphological Analysis to help generate and identify viable possibilities, followed by Multi-criteria Decision Analysis which can help position these possibilities in a hierarchy. The key points from the chapter are:

- The relevance of use and application of design methods is less to do with the efficacy of the methods and more to do with awareness, ease of use and operational resource constraints.
- Design research can gain from an examination of methodologies, methods and frameworks used in other disciplines, such as Operations Research, and indeed vice versa.
- Given the prevalence of "complexity" within the broader design process, complex decision support issues would be better served by integration of methods, which will enhance execution and end-user acceptance.

In "Executing Distributed Development in Industry and the Influence of Design Research", Grieb and Quandt look into distributed development in industry, describe an example of distributed development in practice, and discuss the connections to design research. They also discuss communication and transition of insights between industry and academia. Besides already successful cooperation, the authors identify room for improvement and propose to deliberately consider three different roles, “academia”, “industry partner” and “industry consumer”, when setting up information exchange or joint research projects consisting of members from industry and academia. The key points from the chapter are:

- One of the most common links between academia and industry are people who come from academia to industry and transfer insights by carrying these with them. Another common link is students who carry out their thesis in industry and are supervised by academia. Joint research projects with partners from academia and industry is another link at a more intense and detailed level, providing opportunities for exchange of knowledge. Other routes are via spin-offs from academia or other companies who are specialised in supporting the product design process and are funded by people from academia. Generally, the latter involves external consultants who are in close contact with academia.
- A conduit for continued exchange between academia and practice is needed for transfer of knowledge about relevant problems from industry to academia and important research results from academia to practice. Such platforms should include three roles: “academia”, “industry partner” (who supports development) and “industry consumer” (who develops products).
- It is useful to transfer academic insights into a tool. If a company wants to implement a new method or tool, it is important, that the benefit is considerably greater than the effort and that this is clearly recognisable in advance!
- Research results are usually too generic to be readily used in practice, while practice looks for concrete outcomes that can be readily used in product development. This transition could be done by an intermediary—an industry “partner” who is familiar with these research topics. This could be a company or spin-off which transfers research results into methods or tools that can be used in product design and “consumed” in development practice.

The main focus of “A Collaborative Engineering Design Research Model—An Aerospace Manufacturer’s View”, by Isaksson, is on how to make use of industry–university collaboration to enable improvements in competitiveness through adopting research results. The university and industry collaborative research is a necessary means to improve practice in industry, and the experience narrated through the cases presented gives some basis as to why this continues to be the case. Three cases from GKN Aerospace Engine Systems are presented where design research has made impact in several ways. The chapter also presents a four-mode research portfolio model as a means to organise and clarify how to make use of research in engineering design into practice. The four modes are: exploratory research, descriptive research, prescriptive research and exploitation research. The key points from the chapter are:

- Exploitation through people. Transferring and implementing design research results in engineering design follow the competence and dedication of skilled people. Researchers progress in their expertise, Ph.D. students learn and develop new ways of working, and industrialists can be stimulated by new thoughts stemming from research. Allowing people to develop experience from both the university-based side and the industrial-side is important, ranging from student projects to researchers and professors.

- Continuation and change management. None of the success stories in the chapter delivered results through a single research study. Establishing long-term relations between universities and companies are needed to act quickly once the timing is right, and achieve a relevant understanding of opportunities and needs. Engineering design research must therefore be seen as an integral part of a strategic and tactic change management process within companies.
- Alignment of expectations. University-based research and running industrial operations have different objectives. To use this difference there needs to be a mutual understanding of these differences in objectives. This requires being interactive and engaged in explaining effects and implications of research or needs in as many ways as possible. The use of demonstrators and prototypes, the use of Technology Readiness Level scales and the use of dedicated collaborative workshops and events are all examples of mechanisms that enable alignment of expectations and innovation.

"Implementing Product Architecture in Industry: Impact of Engineering Design Research", by Kreimeyer, details the set-up of how a new engineering design approach, namely systematic design of "product architecture" in the early phases of the engineering design process at the commercial vehicle manufacturer MAN Truck & Bus AG, was integrated into an existing process landscape. As part of this implementation, models, methods and tools from engineering design research were drawn upon, and their impact as part of the implementation is discussed. MAN Truck & Bus AG is a major producer of commercial vehicles with a product portfolio consisting of light- and heavy-duty trucks, city and long-distance buses and components. The key points from the chapter are:

- Researchers should understand the need for pragmatism in industry. Basic training in industrial practice, and close discussion of research with industry to ensure its relevance, are advisable. An ongoing dialogue between industry and research is needed to ensure mutual understanding. This needs effort, especially to overcome the mismatch of abstraction needed on the academic front but that makes immediate implementation in a company difficult.
- The actual contents and results obtained at research institutions, mostly as published work is useful as basic ideas and as a starting point. However, they are too high level to be implemented directly. Availability of tools, templates and demonstrators from research projects would be a good step to illustrate research results and make them more accessible for practice. Topic maps on research solutions and industrial problems would be a positive way to help the dialogue and mutual understanding.
- The role of consultants needs more consideration. From an industrial point of view, consultants are the typical means of implementing new procedures and tools; therefore, their access to the state-of-the-art methodology helps transferring this knowledge into industry.

During the past few years, product development of many high volume consumer products has moved to Original Design Manufacturers (ODM). In ODM business mode, ODM customer sets requirements for the product, carries out quality assurance activities and approves the product. ODM's role is to manufacture the product and to carry out alone, or participate in product development with ODM customer. "Verification Upstream Process, a Quality Assurance Method for Product Development in ODM Mode" by Perttula describes the benefits and challenges of ODM mode, and with a focus on quality assurance activities, outlines a quality assurance method called Verification Upstream Process (VUP) and its successful transfer to ODM business. The key points from the chapter are:

- It is harder to deploy a method that requires large initial investment: At the beginning the greatest challenge in VUP deployment was to get full commitment from the management of ODM customer because a lot of investments were needed to create full set of requirements for the product including its modules and components.
- There should be clear benefits for practice: One step towards getting commitment was to clarify what kind of problems product development with suppliers had at that time and explain in what areas VUP could help.
- Having bridge people who understand both academic and practical issues helps: The author prepared his dissertation research in a similar area of product development, and acted as a link between industry and academia, which were influential to success of this knowledge transfer.

In "Understanding the Gaps and Building Bridges for Synergy—How to Promote a Dialogue Between Design Research and Design Practice", pathways from academia into industry for impacting practice are discussed in general and by concrete examples taken from the personal background of Ponn—the author of this chapter. A major prerequisite for generating impact is to maintain a dialogue between both parties. The current situation of this dialogue is reviewed, leading to identification of major gaps and hurdles. Based on an analysis of these gaps, a proposal is made for enhancing communication between design research and design practice. The key points from the chapter are:

- Transfer between research, academia and industry takes place in concrete activities. In research projects, methods are developed by researchers. If conducted jointly with industrial partners, a better understanding for industrial practice can be used. In lectures and practical courses methods are taught. In consulting projects methods are implemented and applied. These activities serve as platforms and carriers for the knowledge transfer between the domains.
- The key to developing academically and practically worthwhile knowledge is an exchange that is bidirectional, a give-and-take for academia and practice. This requires: a change in mindset: be open to other's perspective; bridging the gap: reach a "common ground" for discussion: researchers explain their work using "cookbooks" and examples, practitioners describe their problems at a general level and create "stories"; and platforms: set up suitable formats of dialogue and

exchange, e.g., people as binding links, joint projects, common knowledge bases.

"Development and Application of an Integrated Approach to CAD Design in an Industrial Context", by Salehi, presents the results of a descriptive study to identify the challenges, problems and weaknesses in current use of parametric associative CAD systems in automotive design. A prescriptive study is then undertaken in which a newly-developed parametric associative approach (PARAMASS) is described. Using design of an inlet valve assembly, the different phases of the developed approach are demonstrated and presented. Finally, a quantitative evaluation of the important factors of the integrated approach developed is presented. The work led to a novel approach to methodical application of PA CAD systems, based on the V-model approach to systems development. Evaluation of the approach shows that by using it designers were able to identify and determine required parameters and associative relationships faster than without using any support. The key points from the chapter are:

- Ph.D. in collaboration with a company is a route in which data and expert opinion availability, often serious hurdles in research into industrial practice, are much easier.
- The same route makes it easier to translate the outcomes of the research into practice.
- Using a systematic research methodology helps streamline the process and defend outcomes.

Based primarily on the experience of the author as first an employee in, and then as a consultant to Audi AG, "Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry" by Stetter contributes to the exploration of the causes for failure or success of transfer of design research results to practice in the automotive industry from one viewpoint. The chapter first explains the view point and the source of insight, presents the design research outcomes to be transferred and discusses some specialties of the specific industry branch. Then a model of transfer of design research results into industry is presented. The key points from the chapter are:

- Transfer of design methods and tools to practice can be seen as a four-stage process: Initiation of transfer process, analysis of design system, choice and adaptation of research findings, implementation of research findings and evaluation of its impact.
- Evaluation of impact of strategies, methods and tools is aggravated by various aspects; the most severe are: measurement indicator problem; probability problem; and attribution problem.
- The distinct characteristics and challenges of industrial product development process and the product itself need to be understood in detail by the academic partner in order to enable the transfer of research into practice.

- Academia needs to respect certain characteristics of industrial design processes such as the evolutionary nature of design in industry in order to create useful research outcomes.

The experience of Wolf, the author of "When and How Do Designers in Practice Use Methods?" suggests that designers in practice do not use methods as explicitly as design teachers and researchers would expect. Observing good experienced designers, one often can discover methodical skills and intuitive systematic approaches. Methods—as taught in design courses in academia—can only be found in the daily routine, when it is demanded by the management, e.g., in companies' design project guideline. The key points from the chapter are:

- The overall goal of a design department in industry is to develop good solutions in a short time. This demand is easy to understand, but is struggled for all the time to achieve 'good' and 'short'.
- For designers in industry a platform for discussion and exchange with people from other companies is highly meaningful. Design researchers could chair such a platform. They can help open the minds and question the frequently continued and hardened convictions and habits in design practice. The common aim is to find out the most relevant and promising results of research that make design practice more efficient and attractive.
- Collaboration on interesting—and therefore confidential—projects needs confidence among the involved people. A high-level exchange platform will lead to a network, which overcomes mistrust and leads to win-win projects for industry and academia.
- Design researchers can accompany important design projects from outside the company. With this approach one can analyse relevant design projects—even crucial ones—instead of studies.

Metrics for Assessing Impact

Transfer of research outcome to practice has multiple steps. A common metric for assessing effectiveness of transfer is desired. *It is important to measure the outcomes of a transferby* means of *appropriate metricsthat also allow theidentification of issues and troubles of the applied methods and tools*, as well as the *need of new ones* addressing emerging situations ("A Framework for the Dissemination of Design Research Focused on Innovation", ibid).

In general, there are *three broad areas where impact can be made: research and its administration, education and its administration, and practice* ("Impact of Design Research on Practice: The IISc Experience", ibid). In research, the impact of individual pieces of research can be assessed using metrics such as peer-reviewed conference publications, peer-reviewed journal publications, citations by peers, etc., to state a few. Impact of research administration can be assessed using metrics such as peer-reviewing of papers, serving on editorial boards, serving as associate or chief editors, organising conferences, serving on peer-society, etc. In education, this can take the form of courses offered in academia (for students), courses offered in academia (for teachers), courses offered for practitioners, consultancy in using design methods and tools, new product development etc., and development of new products for industry (using these methods).

UK research excellence scheme depicts these research impact routes ("Patterns and Paths for Realising Design-Led Impact: A Study of UK REF Cases Studies", ibid): *Spin out, Joint Ventures, Secondment, Consultancy, Knowledge Transfer Partnership, Collaborative R&D, EngD, Ph.D., and Fundamental Research* (from more to less direct impacts). The technology readiness level (TRL) framework was first introduced by NASA (Mankins 2002; Hicks 2009) and is now widely used to represent the transformation and translation of research into technologies and new products. Within TRL ladder, the above are classified as follows: TRL1-3: EngD, Ph.D., and Fundamental Research, TRL4-6: Secondment, Knowledge Transfer Partnership, Collaborative R&D; TRL7-9: Consultancy, Spin out, Joint Ventures.

Hicks ("Patterns and Paths for Realising Design-Led Impact: A Study of UK REF Cases Studies", ibid) argued/s that product-led research output/findings generally more directly affect the performance of a product. Correspondingly it is possible to measure more objectively the impact on the product itself and/or the market e.g., improved performance or function, or business activity, market share and sales. In contrast, for process-led research it is more difficult to cite explicit measures, and researchers rely more on qualitative and subjective measures, such as time saving or improved working culture. Hicks provides a *list of factors that makes assessing impact difficult: Type, Reach, Reach (partiality), Timescale, and Significance (dilution).*

In Hicks' study ("Patterns and Paths for Realising Design-Led Impact: A Study of UK REF Cases Studies", ibid), the *'nature of impact' spans internal impact (intra-organisation) such as processes, tools and infrastructure/equipment, and extra-organisational such as new products, increased business activity, entry into new markets and patents*. Further to this, impact can be extended to transfer of technology to industry, trial with practical cases outside, or with cases within practice. This would give various levels of 'impact', from initial to mature from the first to the last in the list below:

- Testing with practical cases outside practice
- Testing with practical cases within practice
- Application for patents
- Grant of patents
- Transfer of knowledge or technology to industry
- New product development in practice
- Creation of start-ups
- Intra-organisation impact
- Increased current business activity
- Creation of new markets and jobs

Hatchuel et al. ("Multiple Forms of Applications and Impacts of a Design Theory: 10 Years of Industrial Applications of C-K Theory", ibid) propose, for assessment of industrial applications and impact of a design theory, evaluation in four dimensions: *improvement of analytical and descriptive capacities; improvement and positioning of existing methods and processes; development of new tools and processes; impact on other disciplines and on design professions.*

The evaluation of impact of strategies, methods and tools is aggravated by many aspects: measurement indicators problem; probability problem; and attribution problem ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid).

Routes for Transfer

There are a variety of routes through which design research can impact design practice. At the most direct level it is via *products*. The next is through *methods and tools*, which can be used on a variety of products. The third is via *people* who move to change practice with results of design research. The fourth is via *organisations* created around research results. The fifth is via *platforms* for education and training ("Impact of Design Research on Practice: The IISc Experience", ibid).

Telenko et al. ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid) propose *thirteen broad routes for integrating design research and practice*: Connect direct value; Partner with product development firms; Assess industry processes; Incubate companies; Invent within design research; Collaborate with industry partners as PIs; Practice design; Commercialise methods and techniques; Brand and disseminate; Develop standards in design; House practitioners on campus.

Research results may impact practice directly, or impact further research, which may eventually impact practice. For instance, FBS modelling and FBS Modeller were not directly used in practice, but, the research results worked as a normative model that encouraged engineers and designers to understand function modelling, function reasoning, and functional design support, and together with other research encouraged further to expand the research domain of function modelling/reasoning/design, which is still active ("Development of Function Modeling and Its Application to Self-maintenance Machine", ibid). Research and knowledge transfer in the development of new ideas and tools often take convoluted, socio-technical patterns. A development occurs in multiple places simultaneously because it is timely. While the ideas may only properly take root if they are particularly timely, *they all form part of the knowledge-base of the research team, perhaps to be picked up again at some later point* for further applications ("Faceted Browsing: The Convoluted Journey from Idea to Application", ibid).

Many interactions between industry and research occur outside publishable research, through consulting, workshops, and in the trenches of design ("Changing

Conversations and Perceptions: The Research and Practice of Design Science", ibid).

As stated by Ju et al. ("People with a Paradigm: The Center for Design Research's Contributions to Practice", ibid) *people are the ultimate vehicles by which research is converted to practice*. Some people take the ideas from their research and turn them into products, which are then sold to and used by thousands of people. Others employ the paradigms of the research mindset in their own practice, thereby increasing the use of qualitative reflection as well as data-driven empiricism in the design of goods and services. This is one of the most common links between academia and industry. Another is, students who carry out their thesis in industry and are supervised by academia ("Executing Distributed Development in Industry and the Influence of Design Research", ibid). Finally, a good many people go on to share the ideas of design research by continuing to research design, and teaching students to research design, and diffusing the ideas generated by design research into the broader culture ("People with a Paradigm: The Center for Design Research's Contributions to Practice", ibid).

The most powerful mechanisms for transferring research to practice therefore, engage students. *Education of future designers and industry leaders is one of the most important tools for bringing research to practice* ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid).

Being a direct route does not necessarily make it more impactful. For instance, a specific product may lead to a certain income for an organisation (e.g., Apple iPad), whereas a person (e.g., Steve Jobs) can initiate a variety of products (e.g., in Apple, Pixar, etc.) and organisations (Apple and Pixar for instance). However, the more indirect the platform is, the harder it is to assess its impacts ("Impact of Design Research on Practice: The IISc Experience", ibid).

Typical route from research to practice involves the following: scientific research (at research centres, universities), to pilot experiences (at technology transfer institutes, leading companies), to preliminary dissemination (consultants, universities in optional courses) to mass dissemination (universities in regular courses, schools). However, the situation is different for diffusion of conceptual design methods. Design methods (specific procedures, techniques, tools etc. aimed at improving effectiveness and efficiency of design processes) suffer from the lack of subjects pushing their dissemination in the long term: after the preliminary dissemination stage, this absence may trigger a drop in the interest of a wider audience ("A Framework for the Dissemination of Design Research Focused on Innovation", ibid).

Joint research projects with partners from academia and industry is another link at an intense and detailed level, providing opportunities for exchange of knowledge. *Other routes are via spin-outs from academia or other companies who are specialised in supporting the product design process and are founded by people from academia*. Generally, the latter involves external consultants who are in close contact to academia ("Executing Distributed Development in Industry and the Influence of Design Research", ibid).

The role of consultants is an important one. From an industrial point of view, *consultants are the typical means of implementing new procedures and tools*; therefore, their access to the state-of-the-art methodology helps transferring this knowledge into industry ("Implementing Product Architecture in Industry: Impact of Engineering Design Research", ibid).

Design and prototyping in specialised centres, where up-to-date design methods and tools would be used to develop designs with significant socio-economic need and quality would compete for take-up by manufacturing companies is another possible route to using design methods and tools in practice ("Rationalisation Process for Industrial Production. Centres of Design Excellence and Prototyping", ibid). *University-industry agreements for joint product development projects is another route used for impacting practice*, leading to joint designs and patent applications (Implementing Product Architecture in Industry: Impact of Engineering Design Research, ibid). Yet another route is industry-sponsored research developing new methods and tools, leading to training programmes for transition to practice (practice → methods → training → practice) ("Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA", ibid).

Educational programmes in design have a major impact on practice and therefore are a major route for transfer. It impacts both as resources for fresh inputs to existing industry, its knowledge, its effectiveness and its efficiency in innovation, and by providing people who will create new practice altogether ("Industrial, and Innovation Design Engineering", ibid).

An important route to academia-industry engagement is government-industrial joint funding for research. The demand is set by the government funding body that some industrial funding is necessary for governmental research grant. Because industry benefits from knowledgeable staff members, concepts and phenomena models through cooperation, it is possible to get such research funding and the research becomes practically worthwhile ("Successful Industrial and Academia Cooperation in Technology Industry", ibid).

Typically practice is a consumer rather than a partner in design process research. Even if there might be some specialists in practice who think about development processes, most practitioners think about products only; companies typically do not have the capability to make consumable products to support design out of insights offered by academia. This will normally lead to the situation where the insights are not implemented in practice. Research results are usually too generic to be readily used in practice, while practice looks for concrete outcomes that can be readily used in product development. *This transition could be done by an intermediary—an industry "partner" who is familiar with these research topics.* This could be a company or spin-out which transfers research results into methods or tools that can be used in product design and "consumed" in development practice ("Executing Distributed Development in Industry and the Influence of Design Research", ibid).

Transfer between research, academia and industry takes place in concrete activities. In research projects, methods are developed by researchers. If conducted jointly with industrial partners, a better understanding for industrial practice can be used. In lectures and practical courses methods are taught. In consulting projects, methods are implemented and applied. These activities serve as carriers for knowledge transfer between domains ("Understanding the Gaps and Building Bridges for Synergy—How to Promote a Dialogue Between Design Research and Design Practice", ibid).

Guidelines for Transfer

The guidelines for successful transfer of research results into practice, outlined in this part, should be read in conjunction with those in the survey "Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics"–"Results From the Breakout Sessions of Group B", as well as those in "Changing Conversations and Perceptions: The Research and Practice of Design Science" (ibid). In order to categorise the guidelines, the major *activities* and *carriers* by which exchanges are carried out and impacts are caused between academia and practice are used. There are four major activities:

- *Research* into practice and education,
- *Implementation* of research outcomes into practice and education,
- *Development* of new practice and education, and
- *Use* of research outcomes in practice and education.

Knowledge required for carrying out each task is obtained from four major sources:

- *externalised sources* of knowledge (e.g., papers),
- *people* (e.g., researchers, designers, educators, consultants, entrepreneurs, etc.),
- *products*, and
- design and curricular *methods and tools* (which are referred to collectively as 'support').

Transition across tasks requires transfer of this knowledge via various routes. For instance, research into use of support in practice requires knowledge of research and of practice, which may come, among others, from interaction between people involved in practice and people involved in research. Implementation of research results requires, among others, knowledge of research outcomes and knowledge of how to implement these outcomes in practice. Sometimes the people who do each (research and implementation) are the same, e.g., a student having done some research into distributed product development goes on to join industry to implement this in practice. Sometimes the actors are different, e.g., practice becomes aware of new research via externalised sources, and hire people from research (academia) and implementation (consultants) to work together to implement in practice.

The four tasks, people involved in these tasks, their education and their engagement with one another seem to play major roles in this transfer process.

Since development of new educational systems is not much discussed in the chapters, the focus is primarily on research into practice. Therefore, these five categories are used to categorise the guidelines for successful transfer identified from the chapters of this book:

- Education and Training
- Engagement and understanding among people
- Research into practice
- Implementation and use of research in practice
- Development of new practice

Education and Training

Both Isaksson from practice ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid), and Lindemann from academia ("Impact of Design Research on Practitioners in Industry", ibid) make the same point: *the most effective and sustainable way of impacting practice happens via people with their knowledge, skills and competencies*. For instance, transfer of organising and structuring using functional thinking was transferred by people who had been in contact with design research and implemented these insights out of their knowledge of research findings ("Executing Distributed Development in Industry and the Influence of Design Research", ibid). Education influences transfer of design research to practice by impacting the way education is imparted, research results are utilised, and how the design paradigm is spread across other parts of the world ("Implementing Product Architecture in Industry: Impact of Engineering Design Research", ibid). *Education and training, therefore, play a crucial role*.

According to Fricke ("Experience with Development Methods at Three Innovative Hidden Champions", ibid), an intensive investigation into the practical use of design methods and its optimisation to bridge the gap between method development in universities and assignment of successful methods in industry is needed so that the methods can be implemented simply and used sustainably. *Such methods should be taught in universities and professional training to accelerate their successful application in industry*.

Both undergraduate and graduate teaching impact and are impacted by research, and together make the biggest impact on practice. In the USA, industry-sponsored, undergraduate, capstone, design-build-test projects solving industry-provided problems using design methodology with graduate advisors who coach the students as well as use the data from the projects for research have been useful in training students in practical problem-solving using design methodology, testing design methods and tools, and demonstrating to industry the power of design methodology ("Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA", ibid).

According to Riitahuhta and Oja ("Successful Industrial and Academia Cooperation in Technology Industry", ibid), it is *useful to have industrial components at all levels of training*: problem-based learning with real industrial problems at the undergraduate level; Masters theses with a theory framework and an industrial solution; or Doctoral theses with a novel theory validated with industrial examples.

In Ph.D. theses, Finland ("Successful Industrial and Academia Cooperation in Technology Industry", ibid) emphasises that validation must be scientific, but also industrially significant. However it was also found that industrially-related research agenda prevents scientific proficiency. It seems that research should remain relevant to industry, rather than solving the problems that pertain to only one company.

Ph.D. in collaboration with a company is a route in which data and expert opinion availability, often faces serious hurdles in research into industrial practice, are much easier. The same route makes it easier to translate the outcomes of the research into practice. (Salehi in "Development and Application of an Integrated Approach to CAD Design in an Industrial Context", ibid)

An educational route in the UK ("Industrial, and Innovation Design Engineering ", ibid) that has impacted practice significantly is based on three key principles: *diversity, design and engineering mix, and making it real*. The programme embraces a wide range of disciplinary entrants, and guides them on a journey through various areas of innovation enabled by diverse skills and experience. A highlight of the course is the *industrial embeddingof* some of its *student projects*. This provides both a contextual exposure to students to industrial problems, and demonstrates to practice the value of what is learnt in design courses.

Education and training activities provide direct bottom-up influence, though *tracing the impacts caused by newly trained engineers is challenging* ("Impacts of Function-Related Research on Education and Industry", ibid)

The Finnish experience has been that *industrial co-operation enabled researchers to successfully identify, understand and solve real problems*. The deep co-operation and discussion between industry and academy enabled design groups *use real industrial problems in teaching* ("Successful Industrial and Academia Cooperation in Technology Industry", ibid).

Industry-academia collaborative projects provide a context to embed students in industrial work, mostly through theses that are supervised from both ends as part of a common research project. These theses provide enough time and resources to adapt a scientific concept to an industrial context; in a way, the students bridge both worlds thereby ("Implementing Product Architecture in Industry: Impact of Engineering Design Research", ibid).

Engagement and Understanding

Design research aims to contribute to both design practice and science. One key implication of this is that *bridging research and industrial, commercial or* *entrepreneurial applications is a two-way relationship*. Very often new systems, products and processes spur, support or enable new fundamental questions that reveal new and valuable understandings and further new systems ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid).

Ponn ("Understanding the Gaps and Building Bridges for Synergy—How to Promote a Dialogue between Design Research and Design Practice" ibid) argues that while *academic research focuses on method development*, with resulting products as illustration of their efficacy, *industry focuses on developing successful products* for the market at right quality and cost; methods are deployed to achieve good products within an efficient process. While researchers operate at a high level, top-down manner to seek the big picture and holistic view, building generic methodologies, practitioners are often engaged in specific details at an operational level, working with a bottom-up perspective. In the process practitioners sometimes miss the big picture.

Yeh et al. (2010) quoted in Blessing and Seering ("Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics", ibid) observed that design methods often fail to deliver because *companies under-utilise design support or do not utilise it effectively*. According to Birkhofer (2011), some of the key problems are *wrong or inappropriate use of methods due to conceptual misunderstanding of key concepts*. Further, Araujo et al. (1996) found that there is *lack of awareness in companies about the potential quality benefits of available methods*. This is echoed in "Executing Distributed Development in Industry and the Influence of Design Research" (ibid) which finds as a major barrier for designers in practice the lack of knowledge about possible tools and methods in academia that could be helpful in practice.

Cohen (Cohen 2002 in Mowery 2011) also quoted in ("Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics", ibid) found that for most companies, patents and licenses involving inventions from university or public laboratories were of little importance, *compared to publications, conferences, information interaction with university researchers, and consulting*. More specifically, as pointed by Lindemann ("Impact of Design Research on Practitioners in Industry"), books, book chapters, reports or handbooks written for practitioners or for teaching Bachelor- or Master-level students have some impact, at least to motivate further exchange with researchers. A similar impact is generated when doing workshop, training or simple consultancy. When switching to joint projects and joint work within projects, the chances for impact are higher.

As Grieb and Quandt ("Executing Distributed Development in Industry and the Influence of Design Research", ibid) also point out, it is not common among designers from product design to read scientific publications or participate at conferences to obtain exposure to academic knowledge. As a result, as Telenko et al. ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid) argue, *valuable research findings may exist and yet may not have not been applied or are applied poorly*.

This highlights the *importance of addressing transfer and implementation in academic publications*, which Cantamessa (2003) found to be often lacking. As Kreimeyer ("Implementing Product Architecture in Industry: Impact of Engineering

Design Research", ibid) notes, *research publications are often too abstract* and found lacking in the following: many papers only showed ideas and *very few examples of implementation*; often, accessing the right results from research proves to be too difficult to be undertaken; *research context is often far more simplified than industrial context*; often pragmatic approaches that still need to be implemented in industry are little regarded in research, and there is a *wide gap from the common problems to the solutions published*.

This is further stressed by Lindemann ("Impact of Design Research on Practitioners in Industry") who sees the direct impact of scientifically oriented papers in industry as moderate, as practitioners rarely participate in academic conferences or read such papers. Reasons are: the efforts in time, the "scientific language" that is hard for practitioners to understand, and findings from research need adaptation to industry-specific needs and problems. Researchers from academia may have to be able to *formulate their content in a way that practitioners are able to understand and are willing to accept*.

However, *awareness of new thoughts and solutions emerging in academia is potentially useful for practice*, which is the first step to transfer ("Impact of Design Research on Practice: The IISc Experience", "Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid). Similarly, the *evolving patterns of problems that are faced in industry are essential for academia to be aware of* on an on-going basis (Chakrabarti, "Impact of Design Research on Practice: The IISc Experience", ibid).

A major barrier, however, is that the *goals of academia and practice are substantially different from one another*. According to Lindemann ("Impact of Design Research on Practitioners in Industry" ibid), academia aims to create sustainable impact on teaching, research and practice. The last one requires an intensive exchange with industry and practitioners.

Further, while researchers tend to create sophisticated and comprehensive methodologies, placing value in good documentation and clear, reproducible argumentation, practitioners prefer pragmatic solutions, based on implicit knowledge and experience, and often neglecting documentation. In terms of magnitude of changes, researchers tend to focus on revolution, creating innovations that lead to significant improvement. Practitioners rather focus on evolution, based on existing designs and procedures that are optimised through step-by-step adaptations ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry" ibid). Overall, while research is primarily novelty-driven with focus on scientific value, practice is profit-driven with practical value being the main goal ("Understanding the Gaps and Building Bridges for Synergy—How to Promote a Dialogue Between Design Research and Design Practice" ibid).

Therefore, an ongoing dialogue between industry and research is necessary to ensure mutual understanding. This needs effort, especially to overcome the mismatch of abstraction needed on the academic front but that makes immediate transfer in a company difficult ("Implementing Product Architecture in Industry: Impact of Engineering Design Research" ibid). Both industry and academia must understand and accept the difference in their goals and cultures.

Kreimeyer ("Implementing Product Architecture in Industry: Impact of Engineering Design Research" ibid) feels that researchers need to understand the need for pragmatism in industry. The distinct characteristics and challenges of industrial product development process and the product itself need to be understood in detail by the academic partner in order to enable the transfer of research into practice ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry" ibid). A basic training in industrial practice, and close discussion between research and industry to ensure its relevance, would be useful. In order to deliver solutions that are "practically worthwhile" (Blessing and Chakrabarti 2009), a deeper understanding of the details of industrial practice would be helpful ("Understanding the Gaps and Building Bridges for Synergy—How to Promote a Dialogue between Design Research and Design Practice" ibid). On the other hand, practitioners need not only to be aware of appropriate methods but also to be trained in these before they can apply them ("Understanding the Gaps and Building Bridges for Synergy—How to Promote a Dialogue Between Design Research and Design Practice" ibid).

Very often the general awareness in people in practice goes back to their university education or research in design; a good knowledge of the field of application is a cornerstone for success of transfer of methods ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry" ibid). Ideal links between academia and practice are via such "bridge people" (Perttula, "Verification Upstream Process, a Quality Assurance Method for Product Development in ODM Mode", ibid) who understand both academic and practical issues. As Umeda and Tomiyama ("Development of Function Modeling and Its Application to Self-maintenance Machine", ibid) also experienced, the project leader of the company, who also belonged to the academia, played a very important role in understanding the difference of missions and objectives between academia and industry, understanding the basic concept, the framework, and the methodology, and translating them into practice ("Development of Function Modeling and Its Application to Self-maintenance Machine", ibid). Designers or design managers with a Ph.D. degree, for instance, often keep in touch with their institute and get information about current research results, an information channel that is very important for the initiation of transfer processes; the other information channels are consultants and partners such as suppliers or competitors ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid).

Research into Practice

The overall goal of a design department in industry is to develop good solutions in a short time. This demand is easy to understand, but for the targets "good" and "short" designers have to struggle all the time ("When and How Do Designers in Practice Use Methods?", ibid). Thia et al. (2005) call the characteristics of design tools that are responsible for their non-adoption in practice as "internal reasons".

These are: user-friendliness, usefulness, time, monetary cost, flexibility and popularity. Most of these are reflected in the guidelines below.

Despite the benefits of many methods and strong support by qualification engineers, *application of methods is often experienced to be arduous and time consuming*; this lack of ease of use leads to resistance to use methods ("When and How Do Designers in Practice Use Methods?", ibid).

Methods for improving products (e.g., simulation and calculation) are more readily accepted by designers than those for improving processes, as designers see the results more directly on products and are supported by specialist departments who apply these methods for them ("When and How Do Designers in Practice Use Methods?", ibid). This is further supported by the study reported by Hicks ("Patterns and Paths for Realising Design-Led Impact: A Study of UK REF Cases Studies", ibid), who found that in the UK universities, product-led research gave rise to greater international academic impact. Product-led research also had a more significant measured economic impact in the timescale considered than process-led research. This does not necessarily mean process-led research has less impact on practice, but that *assessing impact of process-led research is harder*. This latter point is also raised in "When and How Do Designers in Practice Use Methods?".

To apply research findings in practice, *companies need to perceive the competitive advantage of new knowledge*. There must be a value proposition for industry ("Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA", ibid), as well as for academia ("Impact of Design Research on Practice: The IISc Experience", ibid). One step towards getting commitment in the VUP work in "Verification Upstream Process, a Quality Assurance Method for Product Development in ODM Mode" (ibid) was to clarify what kind of problems product development with suppliers had at that time and explain in what areas VUP could help. For design methods to be relevant, the company must be one that is interested in product development; studies show that relatively few companies tend to introduce new products or services ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid).

With respect to the research content, the method developed by Georgiev et al. ("Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA", ibid) was applied to an underdeveloped area of research. In all successful cases academic research transfer to GKN, the *novel methods or tools developed were demonstrated on real design cases—demonstrating their practical value* ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid). Same point is made in "Impacts of Function-Related Research on Education and Industry" and "Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA" (ibid), adding that demonstrable utility constitutes *direct, easy-to-use solutions to practical problems*. *Establishment of relevant use cases* is important—relevant enough to address industrial problems and specific enough to address research questions. Ability to pursue research with a long term vision, while finding mutual short term gains is also important ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid).

Simplicity and flexibility of core research contributions are critical to facilitate transition into practice, such that interested stakeholders can adopt and adapt the research outcomes with *low effort* ("Impacts of Function-Related Research on Education and Industry", ibid). *It is useful to transfer academic insights into a tool* ("Executing Distributed Development in Industry and the Influence of Design Research", ibid). In the case of development of self-maintenance machine ("Development of Function Modeling and Its Application to Self-maintenance Machine"), demonstration of research results and *machine prototypes were effective* in transferring the concept of the machine from academia to industry. In MAN, a demonstrator for the process (comparable to what often is generated in research projects and doctoral theses) was built to validate and illustrate the approach and obtain concrete feedback. In another case ("Executing Distributed Development in Industry and the Influence of Design Research", ibid), the knowledge to be transferred needed to be contextualised to the organisation and appropriate use case by an expert of design research.

It is harder to deploy a method that requires large initial investment. At the beginning the greatest challenge in VUP deployment was to get full commitment from the management of ODM customer because a lot of investments were needed to create full set of requirements for the product including its modules and components. ("Executing Distributed Development in Industry and the Influence of Design Research", ibid). If a company wants to implement a new method or tool, it is important that the benefit is considerably greater than the effort and that this is clearly recognisable in advance ("Executing Distributed Development in Industry and the Influence of Design Research", ibid).

It is important to *assess the goodness of the outcomes of design research through intensive tests* before their dissemination to a bigger audience. A reliable assessment should consider the effectiveness of the proposed methods and tools by validating them with statistical significance and on the field with companies to evaluate their industrial impact ("A Framework for the Dissemination of Design Research Focused on Innovation", ibid). *Using a systematic research methodology such as DRM helps streamline the process and defend outcomes* ("Development and Application of an Integrated Approach to CAD Design in an Industrial Context", ibid).

The drive for competitiveness (process improvement) which followed productivity (automation) have led to methods and measures for benchmarking production systems. Such measures enable the impact of interventions to be more objectively evaluated. A challenge is that *such measures are more complex in design research and a generalisable and universally accepted set has yet to be developed* ("Patterns and Paths for Realising Design-Led Impact: A Study of UK REF Cases Studies", ibid). For an offering to be successfully transferred to practice, it should be evident that the solution on offer works. In other words, approach to validation should be clear and convincing, and results from validation should be clear and significant ("Impact of Design Research on Practice: The IISc Experience", ibid).

However, according to Garvey and Childs ("Design as an Unstructured Problem: New Methods to Help Reduce Uncertainty—A Practitioner Perspective", ibid) relevance of use and application of design methods is sometimes less to do with the efficacy of the methods but more to do with *awareness* and *ease of use* and *operational resource constraints*.

Design Research can *learn from an examination of methodologies, methods and frameworks used in other disciplines*, such as Operations Research ("Design as an Unstructured Problem: New Methods to Help Reduce Uncertainty—A Practitioner Perspective", ibid) and Management ("Faceted Browsing: The Convoluted Journey from Idea to Application", ibid).

The survey conducted by Graner ("Are Methods the Key to Product Development Success? An Empirical Analysis of Method Application in New Product Development", ibid) revealed that *companies that use a combination of methods to consider the aspects of customer demand and willingness to pay, technical feasibility, product cost and project management together, will meet with an overall higher product success*. Similar findings were reported by Garvey and Childs ("Design as an Unstructured Problem: New Methods to Help Reduce Uncertainty—A Practitioner Perspective", ibid), who found that complex decision support issues would be better served by integration of methods, which will enhance both execution and end-user acceptance. (Garvey)

Isaksson ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid) found that it was *useful to combine related research initiatives in achieving interesting results*. Blessing and Seering in their survey found that a large concentration of successful applications of research results are in the area of support for a specific design task that is applicable in multiple settings ("Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics", ibid).

The three heuristics that were considered applicable in most cases studied in "Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics" (ibid) were: *The question being addressed will be of substantial interest to practitioners; Research results will be evaluated by practitioners; Tools will improve process effectiveness and/or efficiency measurably*.

Implementation and Use in Practice

Use of *design methods increased chances of product success* in New Product Development projects. Use of methods also *enhanced time to market*, *cross functional collaboration*, and *innovativeness*—all factors influencing product success. Product development teams should therefore foster adoption of methods in their design process. Further, companies that have *formally defined the new product development process*, which split this process into individual process steps that evaluate the status of development at the end of each step, and that decide whether to continue the development project at defined gates in the process, *tend to use more methods* in new product development (Graner, "Are Methods the Key to Product Development Success? An Empirical Analysis of Method Application in New Product Development", ibid).

Thia et al. (2005) found three major external reasons for non-adoption of design tools: *project nature, organisation, industries and culture*. Arlitt et al. ("Impacts of Function-Related Research on Education and Industry", ibid) also found that cultural inertia within established organisations can present barriers to acceptance of new design techniques.

Arlitt et al. also found that direct collaboration with industry provides top-down influence, but requires *buy-in from key people* in the organisation. Isaksson ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid) stresses that for adoption of research results that impact the mindset of people, research must be seen from a change management perspective. Strategies, methods and tools need an extremely high acceptance level by the designers so that they might have the possibility to convince a new department manager ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid). In MAN, documentation from other companies, especially case studies from industrial conferences and from academically documented case studies, served as important input. This helped create 'buy-in' into the company ("Implementing Product Architecture in Industry: Impact of Engineering Design Research", ibid).

Common to all cases is the *long term and deep relationship* between the academic research team and the company's key stakeholders (Fadel et al., "Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA", ibid). Transfer of research into practice requires a high level of trust on both sides ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid), which takes time and sustained effort. None of the success stories narrated by Isaksson ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid) delivered results through a single research study. Once a long term relation was established between universities and companies, it allowed the partners to act quickly once the timing was right and an appropriate understanding of opportunities and needs was achieved.

Engineering design research must therefore be seen as an *integral part of a strategic and tactic change management process* within companies. In the experience of Fadel et al. ("Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA", ibid) *close collaboration between academia and industry* is a key to achieving this. This includes several site visits, teleconferences, meetings, and workshops during the projects to have a true impact on industry.

Fadel et al. speak about the *importance of multiple projects* in building a long-term relationship. During the completion of their projects, the PIs and students have been intimately involved with industry—often through interns or extended work periods. The research themes continued from project to project with a particular focus on information and knowledge representation and methods to support conceptual design, which gave ample time to mature the research and showed its efficacy to practice.

Based on GKN (earlier Volvo Aero) experience, similar sentiment is echoed by Isaksson ("A Collaborative Engineering Design Research Model—An Aerospace

Manufacturer's View", ibid). Work matured through multiple linked projects. Researchers progressed in their expertise, Ph.D. students learnt and developed new ways of working, and industrialists were stimulated by new ideas from research. Allowing people to develop experience together from both the university side and the industrial side was important, ranging from student projects to researchers and professors. It is important to have a portfolio of work from short-term to more speculative, and to use each type of work to inform the other.

Building long-term relationship takes time. Changing design practices in industry require time, effort, competence and deliberate ways to overcome contextual barriers between industry and academia ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid). Successful transfer of research results does not happen overnight ("Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics", ibid). It is not surprising that despite notable exceptions, knowledge transfer can take up to 20 years ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid).

Transfer of design methods and tools to practice can be seen as a four-stage process: initiation of transfer process, analysis of design system, choice and adaptation of research findings, implementation of research findings, and evaluation of its impact ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid).

As already discussed in the last part, a *high level of trust* between academia and practice is needed for successful collaboration ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid). Misalignment in expectations between different stakeholders are common obstacles in industry-academia collaboration, and it is worth the effort to overcome these barriers. Projects need to have a *clear value proposition for industry* ("Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA", ibid). A *common understanding of the challenges whilst ensuring mutual benefit* in research initiatives is a key prerequisite for successful introduction of Engineering Design research results ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid). The actual contents and results obtained at research institutions, mostly as published work is useful as basic ideas and as a starting point. However, they are too high level to be implemented directly. Availability of tools, templates and demonstrators from research projects would be a good step to illustrate research results and make them more accessible for practice. *Topic maps on research solutions and industrial problems would be a positive way to help the dialogue and mutual understanding* ("Implementing Product Architecture in Industry: Impact of Engineering Design Research", ibid).

In the successful transfer of the self-maintenance photocopier machine in Japan ("Development of Function Modeling and Its Application to Self-maintenance Machine", ibid), a clear and agreed target was set early on in the project that was important for the business of the company as well as for demonstrating academic work. The expected output, the time required, and other resources were well defined at the beginning of the research carried out by Georgiev et al. ("Evaluating Tactual Experience with Products", ibid). This *early consensus was important as a common win-win ground for progress of the project.* As summarised by Kozlinska (2012), "mutual trust, commitment and shared goals" are essential drivers of university-industry relationships. It is critical to have the right collaborator as industrial partner, one who, on one hand understands the problems in the industry and its time scale, and on the other hand the problems in the academia and its time scale ("Impact of Design Research on Practice: The IISc Experience", ibid).

(Mis-)match in timing with business was another major (barrier)enabler in transfer of research results to practice ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid). Another major problem is the *issue of confidentiality* and other legal and organisational issues ("Executing Distributed Development in Industry and the Influence of Design Research", ibid) while allowing publication of results ("Impact of Design Research on Practice: The IISc Experience", ibid). Collaboration on interesting—and therefore confidential—projects needs confidence among the people involved ("When and How Do Designers in Practice Use Methods?", ibid). Another is technical maturity of the research. The research team should *continually monitor the technical maturity of the research outputs*, for example using 'technology readiness level' ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid).

According to Lindemann ("Impact of Design Research on Practitioners in Industry", ibid), based on types of actors on the management and on the operational level in industry, five different levels of success in transferring research into practice are possible: there is a good chance for successful transfer via PhDs or MScs if management and operation both see the necessity; there is a small chance for a successful transfer via PhDs and MScs, if management is not interested but operation sees the necessity; in case of transfer via MScs there is a small chance, and in case of PhDs and joint projects there is a realistic chance, if management sees the necessity and operation is at least interested; in case of transfer via MScs there is no chance, and in case of PhDs and joint projects there is a small chance, if management has at least some interest and operation sees no necessity; if neither management nor operation sees the necessity, there is no chance for successful transfer.

Once convinced, successful transfer depends on the company's key stakeholders being decisive in efficiently transitioning research results into practice ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid). This requires *support of the management*, as stressed by several authors. For instance, according to Wolf ("When and How Do Designers in Practice Use Methods?", ibid), strict demand of the management and the *company's documentation system* proved to be the most important drivers for explicit use of methods. Stetter too found that demand from management was the single crucial factor in changing design practices in automotive industry ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid). Graner ("Are Methods the Key to Product Development Success? An Empirical Analysis of Method Application in New Product Development", ibid) found from his survey that product development teams that received greater support from the management adopted substantially more methods.

Research in method implementation indicates that not only the choice of the right method and a sensible adaptation is necessary, but also a conscious implementation ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid). As found by Fricke ("Experience with Development Methods at Three Innovative Hidden Champions", ibid), for implementing design methods in practice, it is helpful to *employ at least a critical number of methodically educated engineers*; having at least one of the directors educated and practically experienced in applying those methods was found useful where no methodical expert was available. In MAN, establishing a steering committee consisting of line executives and project managers to oversee the implementation provided a shared concept and multipliers from early on in the project across the company ("Implementing Product Architecture in Industry: Impact of Engineering Design Research", ibid).

Rigorous project management are also needed if new products are to be developed quickly and with efficient use of resources ("Are Methods the Key to Product Development Success? An Empirical Analysis of Method Application in New Product Development", ibid). As found in the MAN experience ("Implementing Product Architecture in Industry: Impact of Engineering Design Research", ibid), *strong social bond and team spirit among team members*—partly due to common educational and institutional background—were the most important drivers at the people level. The *continuity of external partners*, some of whom had a similar background as the team in engineering design research, provided stability. *Running several projects with academia to have continuous input and reflection* helped progress of implementation. The *scientific network*, gained through conferences and comparable events, was helpful *to obtain insights* into companies with similar issues. *Integration of the new tool within the existing design process is important* and may need many supporting methods ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid).

An introduction strategy is needed. In MAN ("Implementing Product Architecture in Industry: Impact of Engineering Design Research", ibid), the introduction strategy was mostly driven by common approaches from organisational change management. *All methods and tools were documented* such that the individual engineer would either have a click-by-click manual for the tools or an instruction leaflet similar to a lecture note. *An operational support was used to introduce the tool* in the company. This allowed to identify gaps, to integrate criticism, to train staff, to build experience, and to better understand the problems associated in practice. The *ability of the team to document and teach*, as learnt in academic lectures and seminars, helped introduce the new tool to a large section of the member of the staff.

Typical reasons for not using methods are *perception that methods aretime-consuming, learning needed time, and situations were not critica*l enough to warrant their application. However, often engineers spend a long time "muddling through trial and error" and meet with failure. Junior design engineers should be *advised to a systematic approach using simple methods in critical situations or collaborate closely with a senior expert* ("Experience with Development Methods at Three Innovative Hidden Champions", ibid)

It is useful to convince designers to *use*, at the beginning, simple methods at management-, project- and product-level for solving low-hanging fruit problems. This encourages application of other methods next time ("Experience with Development Methods at Three Innovative Hidden Champions", ibid). It is useful to provide procedural *guidance to the designer as to how to use a design method or tool* ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry", ibid). Keeping a *core team as an expert support* helps since the organisation requires undergoing a mindset change process in aligning with the new method/tool ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid).

Development of New Practice

One way of impacting practice is to take the research outcomes and create new practice—start-ups ("Facing Complex Challenges—Project Observations", ibid). *Small start-ups represent a compromise* between receptiveness to new ideas and capacity to impact practice ("Impacts of Function-Related Research on Education and Industry", ibid).

Academics need a good understanding of the organisational and financial constraints for taking their research to practice, as well as an appropriate support mechanism ("Faceted Browsing: The Convoluted Journey from Idea to Application" ibid).

Research teams also need a very good understanding of the mechanisms for commercial development of research through venture capital, seed-corn and other early stage funding ("Faceted Browsing: The Convoluted Journey from Idea to Application" ibid).

Industrial partners and users of the research outputs need to be aware of the influence that they can have with early-stage funders and especially the benefits to the research team of targeted support for commercialisation efforts ("Faceted Browsing: The Convoluted Journey from Idea to Application" ibid).

Carrying out an industrial project provides a reliable test-bed for demonstrating design research results and builds confidence to transition into a start-up ("Facing Complex Challenges—Project Observations", ibid).

Platforms

A matchmaking of the needs of industry and offerings from academia should happen somewhere in the middle, where scientific needs of the academia and practical needs of the industry must be met. *The platform should act as a conduit for intense and permanent exchange between academia and practice*, and encourage exchange of a variety of problems that the two sides think are important to solve, and the timescale associated with them. It should also encourage 'tweeting' on the emerging trends in the solutions being explored in academia ("Impact of Design Research on Practice: The IISc Experience", "Executing Distributed Development in Industry and the Influence of Design Research", ibid). Industry and academia must be in continuous engagement through the following: Academia: findings (practice as sample or data source) → development (practice as sounding board) → verification (practice as test bed) ("Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics", ibid).

For designers in industry, *a platform for discussion and exchange with people from other companies* is also meaningful. Design researchers could chair such a platform. They can help to open the minds and question the frequently continued and hardened convictions and habits in design practice. The common aim is to find out the most relevant and promising results of research that make design practice more efficient and attractive ("When and How Do Designers in Practice Use Methods?", ibid).

Design researchers can accompany important design projects from outside the company. With such an approach one can analyse relevant design projects—even crucial ones—instead of studies ("When and How Do Designers in Practice Use Methods?", ibid).

A platform to support exchange between industry and academia should include three roles: academia, industry partner (who support the development process) and industry consumer (who develop products) ("Executing Distributed Development in Industry and the Influence of Design Research", ibid).

The key to developing academically and practically worthwhile knowledge is an exchange that is bidirectional, a give-and-take for academia and practice. This requires: a change in mindset: being open to other's perspective; bridging the gap: reaching a 'common ground' for discussion where researchers explain their work using "cookbooks" and examples and practitioners describe their problems at a general level and create 'stories'; and platforms that set-up suitable formats of dialogue and exchange, e.g., people as binding links, joint projects, common knowledge bases and so on ("Understanding the Gaps and Building Bridges for Synergy—How to Promote a Dialogue Between Design Research and Design Practice", ibid).

One possible structure that links together academia and industry is *a center of competence, with mutual exchanges on research objectives, best practices on design methods and punctual assessment of the related impact*; one such structure involves students, innovators and early adopters to work in collaboration within a design research-centre of competence to generate interesting research results, develop new methods, apply these on practical case studies, and generate a culture of design research ("A Framework for the Dissemination of Design Research Focused on Innovation", ibid).

Given the large variety of decision support methods and tools already available, design and business academics have an important methodological role in formulating paradigms that can be readily applied by the practitioner community. *Such frameworks must encourage practitioners to become both more aware of the availability and relevance of methods, and more crucially how their introduction and application can enhance business performance* ("Design as an Unstructured Problem: New Methods to Help Reduce Uncertainty—A Practitioner Perspective", ibid).

The most common mechanisms for achieving impact in the UK were Technology Strategy Board (TSB) funding, Knowledge Transfer Partnerships and consultancy activities. Spin-outs were the key mechanism for product-led impact while consultancy was the key mechanism for tool/method-led impact ("Patterns And Paths For Realising Design-Led Impact: A Study of UK REF Cases Studies", ibid).

Finally, to reiterate, university-based research and running industrial operations have different objectives. *To use this difference there needs to be a mutual understanding of these differences in objectives.* This requires being interactive and engaged in explaining effects and implications of research or needs in as many ways as possible. The use of demonstrators and prototypes, the use of TRL scales and the use of dedicated platforms, collaborative workshops and events are all examples of mechanisms that enable alignment of expectations and innovation ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View", ibid).

Conclusions and Further Work

Overall, the content in the chapters show that design research, in its relatively short existence as an academic discipline, has already made a significant impact on practice. The impact is made via a variety of transfer routes, and at various levels of directness and significance. The book provides a number of guidelines that may be useful to follow in increasing the chances of successful transfer of research into design to its practice.

People, trained in design and its research, seem to be the single most significant influence on practice of design and its education. Long-term collaboration, which requires building of trust and mutual understanding seems a key recipe for success. The significance of bridge people as collaborators and research champions seems to be very high. Lack of awareness of existence of methods and tools and their relevance seems to be a major barrier to their use in practice. A platform for promoting ongoing dialogue between academia and practice has been emphasised by both academics and practitioners.

This does not mean, however, that all is well and there is no scope for improvement. There indeed is significant scope for improvement, as many more methods and tools have been developed than are used in practice. Having said that, this situation is not special to design research; similar complaints have been raised in other disciplines such as medicine, management and so on. The following are some of the areas where further work is needed.

More investigations of product development in industry on project and on management levels are needed for understanding and supporting better the processes to transform a fuzzy set of ideas into a successful product within a complex, dynamic and real-life environment ("Experience with Development Methods at Three Innovative Hidden Champions", ibid).

The mixing and linking of methods, although part of a logical sequence to narrow down decision choices, are rare. Little evidence is available in either the academic or practitioner domains of integration of methods to create a decision path process ("Design as an Unstructured Problem: New Methods to Help Reduce Uncertainty—A Practitioner Perspective", ibid). This also calls for further research.

There may be a conflict between academic research looking for scientific rigour and high levels of empirical research, while practitioners seeking ease of use and visible functionality when addressing complex problematical issues ("Design as an Unstructured Problem: New Methods to Help Reduce Uncertainty—A Practitioner Perspective", ibid), requiring further research to seek possible resolutions.

A wider range of models and guidelines are needed to cover the varied conditions in the design research-practice relationship. Strategic policies and incentives are also needed to build bridges between design research and practice ("Changing Conversations and Perceptions: The Research and Practice of Design Science", ibid).

Investing efforts in attempts and activities for transfer of research outcomes to practice requires possibilities of measuring the real impact or at least identification of indicators. Reliable ways of measuring impact requires long-term analyses of changes; this is hard because of a large number of influences that are difficult to control ("Impact of Design Research on Practitioners in Industry", ibid). Further research is needed in developing composite metrics for assessing impacts of design research.

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Part I
Surveys and Summaries

Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics

Lucienne Blessing and Warren Seering

Abstract Although the development of methods and tools was for many decades the main focus of design research, transfer of research results to practice has been fragmented and limited and, hence, had a low impact. Various studies into the problems involved in transfer have been undertaken the uptake of the recommended improvements has been limited. One of the reasons, in our opinion, is the lack of a coherent, and agreed upon set of heuristics. This is where we intend to contribute. In this chapter we focus on the transfer of design research results into practice as experienced by those who have been involved in their development. Our aim is to propose a preliminary set of best practice heuristics for researchers to enhance the chances of successful transfer of research results into practice as a starting point for discussion and further research.

1 Introduction

People have undertaken and attempted to improve design processes for centuries, but it was not until well into the second half of the twentieth century that researchers became interested in designing as a topic of research, with its own body of knowledge, related but not identical to other sciences (including engineering science) (Blessing and Chakrabarti 2009). General agreement seems to exist that design research integrates two aims: the development of *understanding* and the

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development of *support*[1] based on this understanding. These aims are closely linked and should therefore be considered together to achieve the overall aim of design research: to make design more effective and efficient, in order to enable design practice to develop more successful products (Blessing and Chakrabarti 2009). In the terms used by Horváth, design research is "generating knowledge *about* design and *for* design" (Horvath 2001).

Even though the development of support was for many decades the main focus of design research, transfer of research results into practice has been fragmented and limited and, hence, had a low impact. Since the mid 1980s the design research community has expressed their dissatisfaction and worry about this situation (e.g., Andreasen 1987). Most results end up in scientific publications rather than being transferred into practice. This has several reasons (Blessing 2002). Many guidelines, methods, and tools have weak foundations: empirical data are hardly used. Evaluation is poor and implementation issues are rarely addressed (as, e.g., pointed out by Cantamessa 2003). If the aim of design research, as a discipline, is to improve design, and if this research is to be successful, it should have some effect in practice (Blessing 2002). This does not imply that each individual research project has to have an effect in practice. There are still important contributions to be made to our basic understanding of the design phenomena.

Various studies into the problems involved in transfer and implementation of research results have been undertaken and recommendations for improvement proposed. Benefits of using design tools have been reported if they are fully implemented (Booker 2012; Cantamessa 1999), but overall the uptake and impact is still considered insufficient. What has changed is that politicians and funding agencies increasingly focus on transfer and impact of research results (see, e.g., the European Commission's Horizon 2020 program). Innovation is heralded as the main factor for economic growth and the expected economic and/or social benefits have become important—if not the most important—criteria for investment in a research project. The issue of transfer has thus become more relevant than ever before.

In our opinion, there is a need for a coherent and agreed upon set of heuristics to enhance the chances of successful transfer of research results into practice. This is where we intend to contribute.

Our focus is on academic engagement not commercialization, although commercialization may follow (Perkmann et al. 2013). Our interest is the transfer processes, rather than the outcomes, in line with the findings of Ankrah et al. (2013), who found that "the immediate outputs of relationships between university and industry actors might not necessarily take a tangible form, such as inventions, patents, prototypes or products, but could be 'intermediate outcomes.' These could be bits of knowledge, hints, clues, ideas for new projects, opportunities, or even

[1]The term *support* refers to "the possible means, aids and measures that can be used to improve design. This includes strategies, methodologies, procedures, methods, techniques, software tools, guidelines, information sources, etc., addressing one or more aspects of design" (Blessing and Chakrabarti 2009).

negative findings. They found that "the majority of benefits were less-tangible" and concluded that "It could well be that evaluating the transfer process by looking for tangible outcomes such as cost-effectiveness is looking in the wrong place."

We concentrate here on the work of individuals rather than institutions, as we consider individual contacts between academic and industrial actors as essential for starting collaboration and for long-term engagement.

The organization of the paper is as follows. After a short overview of studies into the uptake of design support and university–industry collaboration in Sect. 2, the chapter focuses on the results of two, day-long workshops intended to develop an initial set of heuristics to guide the transfer of research results into practice (Sects. 3–5). This chapter concludes with the main contributions and an outline of further research.

2 Current State-of-the-Art

Various research areas, whether applied or not, involve interaction with industry or society. "Researchers in these areas are more likely to be engaged on real-world problems and interacting with industry, and their status is likely to be codetermined by their reputation among their peers and their standing in industry. This is especially true in the case of engineering" (Bruneel et al. 2010). It is therefore surprising that in the area of engineering design, despite close collaboration, uptake of design support (methods, tools, systematic procedures, etc.) by industry is still slow. This has been discussed in the 1980s, e.g., by (Gregory[2] 1984; Andreasen 1987; and Gill 1990). Gill points at the lack of insight of researchers into practice and the fact that practitioners do not necessarily understand the process of design as an intellectual endeavor. Publications, he continues, "serve, collectively, to impede progress toward acceptance by practitioners because of their apparent dissimilarity and the consequent confusion this creates." He calls for "a period of consolidation" and for "field trials." The importance of consolidation has been repeatedly mentioned (e.g., Blessing 2003), and is still considered a very important issue (e.g., Birkhofer 2011).

Over the years a large number of empirical studies aimed to shed light on the issue of poor uptake of design support in practice (e.g., Gregory 1984; Araujo et al. 1996; Sheldon 2004; Booker 2012). In general the authors are convinced of the improvements that can be realized when design support is implemented, either based on their own experiences or on reports of successful implementation. Araujo et al. (1996) concluded that "many companies are unaware of the potential quality benefits of available methods." Nearly a decade later, Sheldon (2004) saw, "encouraging signs that academic design research in specific areas … are producing

[2]Gregory (1984) speaks of Design Technology comprising "general design technology and broadly applicable techniques, domain specific procedures and techniques, and CAD systems and processes" "It includes all the essentials for the execution of design work."

intellectually challenging outputs that are being adopted by industry." Booker (2012) lists very impressive measurable improvements made by design teams employing some well-known design support methods, such as FMEA or DFA.

The expected impact of the proposed design support will be an important criterion in deciding on an investment in its transfer, even if only for testing. Cantamessa (1999) shows that at operational level "design techniques are not important because of their objective value but, rather, because of the combined impact they may have upon the design capability of the firm." He found a positive impact of what he called best practice techniques (IT tools and engineering methods) on the design process and its outcome, if these are fully implemented (see also Booker 2012). The main finding is that "they do not deliver linear effects upon the design process, but interact in a complex manner with one another," so that "when considering their adoption or assessing their impact, it is necessary to consider them altogether and never in isolation." He suggests that it is the design capability of the firm that links adaptation and effects. "It is the endogenous evolution of routines which may lead to learning, while an exogenous injection of knowledge may not be as effective, at least on its own." The concept of design capabilities may lead to "sounder and more coherent plans concerning the adoption of widely publicized best practice." López-Mesa and Bylund (2011) confirm this in their study. "Measuring the impact of methods in terms of methods applied by the book may not yield a fair measure of the impact design methodology has had in the practical world." Researchers should expect an "incorporation of some features of the academic methods in their already working methods, or an influence in their way of thinking." The principles of a method should therefore "match that used in engineering thinking and should give the engineer the feeling that they own the engineering value judgments and decisions."

Yeh et al. (2010) observed that implementation fails because companies under-utilize design support or do not utilize it effectively. Companies also adapt design support in order to make them more appropriate for their own processes and products, sometimes with success (e.g., O'Hare et al. 2010), but sometimes leading to unreliable results (López-Mesa and Bylund 2011). According to Birkhofer (2011) the key problems are wrong or inappropriate use of methods due to conceptual misunderstanding of some of the key concepts, or "degeneration of design methods" when methods are applied "mechanically without gaining additional insights […] or a better understanding of the problems to be solved." "Development methods and tools may truly sustain sound design practice, but cannot be considered as surrogates to it" (Cantamessa 1999).

Thia et al. (2005) distinguish between internal reasons for non-adoption of design tools (user-friendliness, usefulness, time, monetary cost, flexibility, and popularity) and external reasons (project nature, organization, industries, and culture).

All these findings suggest that transfer cannot be addressed without taking into account the wider context, and that transfer requires collaboration over time and the building of trust. According to Bruneel (2010), trust in university–industrial collaboration is one of the strongest mechanisms to further collaboration, but "requires long-term investment in interactions, based on mutual understanding about different incentive systems and goals. It also necessitates a focus on face-to-face contacts between industry and academia, initiated through personal referrals and sustained by repeated interactions, involving a wide range of interaction channels and overlapping personal and professional relationships."

Literature on university–industry collaboration provides indications of areas to improve in order to facilitate the transfer. A distinction is made between academic engagement and commercialization (Intellectual Property creation and academic entrepreneurship) (e.g., Perkmann et al. 2013). Commercialization is the "prime example for generating academic impact," but academic engagement is considered the most important channel. Academic engagement is "knowledge-related collaboration," which includes "formal activities such as collaborative research, contract research, and consulting as well as informal activities like providing ad hoc advice and networking with practitioners." In addition a third type of interaction is frequently mentioned (e.g., Bodas Freitas et al. 2012): Employment-based interactions such as joint training and supervision of graduates, graduate recruitment, and personnel exchanges.

Studies suggest that "the effects of many of these 'technology commercialization' policies remain controversial" (Mowery 2011) and that "Universities income from academic engagement is usually a high multiple of the income derived from intellectual property," even though results are not conclusive (Perkmann et al. 2013). "For most industries, patents and licenses involving inventions from university or public laboratories were reported to be of little importance, compared with publications, conferences, information interaction with university researchers, and consulting" (Cohen et al. 2002 in Mowery 2011). This highlights the importance of addressing transfer and implementation in our publications, which is often found to be lacking (Cantamessa 2003).

Bodas Freitas et al. (2012) conclude that "personal contractual interactions with individual academics, which do not directly involve the university, appear to be more effective in facilitating the transfer of knowledge, especially to small firms, and in providing firms with knowledge relevant to their business, technology and production needs." According to Ramos-Vielba and Fernández-Esquinas (2012) "For the majority of universities the thrust of their collaborative experiences is devoted to tacit knowledge rather than to intellectual property rights." Their survey also showed that "It is important to recognize that a variety of different types of interactions contribute to increased absorptive capacity in specific industries because they generate long-term relations of trust that are associated with a variety of different collaborative experiences." Kozilsnka (2012) observed that "Mutual trust, commitment and shared goals are the most essential drivers" of university–industry relationships.

As early as 1984, Gregory (1984) suggested nine "aspects which seemed to be significant in helping adoption" based on the 12 procedures he analyzed in terms of what are believed to be important aspects of design technologies and their transfer. These 12 procedures played a significant part in the buildup of design technology and had relevance to both industry and academia, and include brainstorming, systems engineering, functional analysis and costing for design. The nine aspects are:

- Presentation of the item in a well-defined package, including a clear title;
- Specificity in nature, rather than abstract in presentation or use;
- Potential relevance to immediate tasks rather than acting as an infrastructure for design;
- Track record of success within reason;
- Potentiality for competitive advantage and legal or contractual compliance;
- Ease of application;
- Ease of acquisition;
- Ready identifiability;
- Quality or research work, argument, presentation.

Unfortunately, the generic value of these aspects as guidelines is not clear from Gregory's article, as the procedures he discusses only partially reflect instances of these aspects.

Booker (2012) provides an extensive overview of design tools and classifies their attributes and implementation issues he found in literature in "a set of questions that a manager or engineer would naturally ask in the context of design tool implementation in their business." Although a very useful and comprehensive starting point, the set seems to need further consolidation and reformulation in order to provide guidelines for researchers developing design support. The question also remains in how far the statements of the different authors are based on their experiences or their expectations.

As starting point of knowledge transfer, Kelli et al. (2013) suggest technical verification (proof of concept, scalability, robustness, production quality, cost, and yield) and business verification (SWOT or NABC: Needs, Approach, Benefits, Competition: a business verification method developed by the Stanford Research Institute).

This short study of the literature suggests that the transfer of design support not only depends on the quality of the support but on individual contact, long-term relationships based on mutual trust and commitment, and shared expectations. Any set of heuristics to support the transfer and implementation of design support should thus consider not only the qualities of the support, but a wide range of issues that concern both the researcher and the industrial partners and require development over time.

3 Approach

The findings presented here are the result of a comparison of the outcomes of two, day-long discussions on heuristics for guiding the transfer of research results into practice. The participants were the members of the Management and Advisory

Boards, as well as the leaders of the Special Interest Groups, of the Design Society (www.designsociety.org). The majority of participants took part in both meetings.

3.1 First Meeting 2012

The starting point of the first meeting in March 2012 were the experiences of the 35 participants with research results they knew had been successfully transferred into practice. Details of these results were distributed among the participants. They also received a set of 16 heuristics for transfer of research into practice prepared by the second author. Based on a discussion about their experiences with successfully transferred results, the participants had to assess the applicability of the 16 heuristics, and reformulate or add where they deemed necessary.

3.2 Second Meeting 2013

The seeding for the second meeting in March 2013 was a summary of exploratory interviews with people from industry, who are responsible for, or regularly involved in, contacts with universities. The participants were divided into five groups to discuss the results of the interviews, and to formulate statements on how to improve transfer of research results into industry. The statements were brought together and clustered into sets of thematically related statements. Each group of participants was given one set from which to derive heuristics.

3.3 Formulation of Heuristics

After the two meetings the authors analyzed and compared the two sets of heuristics and brought these together into a preliminary set of best practice heuristics for researchers to enhance the chances of successful transfer of research results into practice, as well as for further discussion and research.

4 Findings

Section 4.1 presents the findings from the first meeting, which comprised the review of the set of methods and tools based on research results and successfully transferred to practice. This is followed in Sect. 4.2 by the findings from the best practice heuristics discussions in the second meeting.

4.1 Heuristics Derived from Academic Experience

During the first meeting, two triggers were used: a set of cards summarizing successfully transferred research results and a set of 16 heuristics for successful transfer preformulated by the second author.

4.1.1 Successfully Transferred Research Results

Prior to the first meeting the participants were asked to provide the following information about research results they knew had been implemented in practice: the name and aim of the result, the research team, the companies using the product, and the value to the user. The participants were divided into 5 groups, each discussing the summaries produced by the participants in the group. A sample of the cards can be seen in Fig. 1.

Of the 54 entries, 51 concerned methods and tools and 3 entries concerned products that had been successfully transferred to practice. In 38 of the 54 entries, at least one of the participants had been involved (see "own" in Table 1). For further processing only 45 of the methods and tools were considered, as none of the participants were familiar with the details of the transfer of 6 established methods and tools.

Table 1 shows that the majority of the research results that were discussed are generally applicable. Many of these had been demonstrated in multiple application areas (last column). Those that were characterized as generally applicable, but had only been applied in one area, were recent developments.

Fig. 1 Input for first meeting: summary cards of successfully transferred research results

Table 1 Range of successfully transferred research results

n = 54 (38 own)	Specific application area	Generally applicable, applied in one area	Generally applicable
Support for a specific task	3 (2 own)	6 (6 own)	19 (13 own)
Support for multiple tasks	3 (3 own)	5 (5 own)	9 (6 own)
Not further considered	Products 3 (3 own)		Established 6 (0 own)

The research results were further divided into support for a specific task and support for multiple tasks. The latter usually offered a set of methods and tools or a methodology.

The largest cluster of transferred research results fell into the category of 'generally applicable and task specific support.'

One factor usually mentioned as key to success is the value created by the support in practice. This value is often expressed in terms of time, and cost savings, and quality improvement. Although important for the 45 analyzed research results, other values were equally important, as shown in Fig. 2.

A total of 74 values that were mentioned by the participants were grouped by the authors into the 8 categories as shown in Fig. 2. The grouping of values into categories is shown in the appendix. The variety in values mentioned is interesting, even the highest ranking value 'design' was only mentioned for 16 of the 45 research results.

Among the most frequently mentioned values are the direct support for the design activity (e.g., to support exploring solutions spaces or evaluation), i.e., the task at hand, and for collaboration (e.g., to support knowledge management, design rationale capturing, or multidisciplinarity). The value 'organization' includes support for changing organizations, lean product development, and stage-gate process

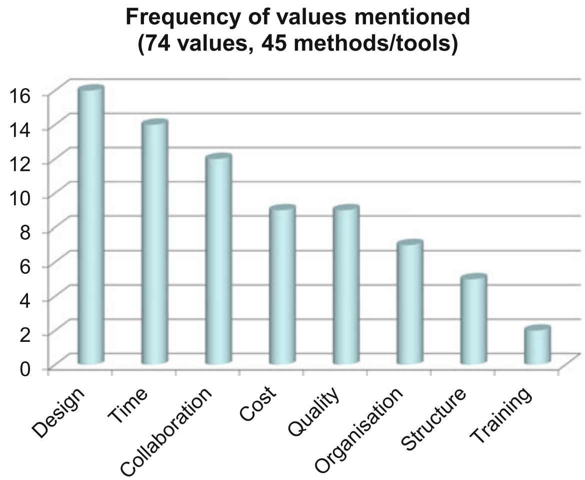

Fig. 2 Values for the user

Table 2 Dependency of values on type of support (*v*/*n* = number of values/number of transferred methods and tools)

	Specific application area	Generally applicable, applied in one area	Generally applicable
v/*n* = 74/45	*v*/*n* = 15/6	*v*/*n* = 23/11	*v*/*n* = 36/28
Support for a specific task (*n* = 28)	TCQ > DCO 6:2	TCQ > DCO 7:3	TCQ = DCO 11:11
Support for multiple tasks (*n* = 17)	TCQ < DCO 2:4	TCQ < DCO 4:7	TCQ < DCO 2:8

management. The value 'structure' refers to the product structure and includes support for modularization and robust architecture. 'Training' refers to results that are used for training purposes.

Grouping the values Time, Cost, and Quality (total frequency TCQ: 32) and the values Design, Collaboration, and Organization (total frequency DCO: 35) suggest that the values depend on the type of support (see Table 2). The numbers are small and the values mentioned for each research result may not have been exhaustive, but the findings are interesting. The more 'external' values cost, time, and quality were far more often mentioned for task-specific support, even though these values relate to the development process as a whole. Support covering multiple tasks seems to have a more 'internal' value, contributing to the designer, the team, and the organization.

4.1.2 Heuristics for Successful Transfer

After first discussions in the group about the successfully transferred research results, the participants received a set of 16 heuristics for transfer of research into practice, which had been prepared by the second author. The heuristics were divided into five categories: generally applicable, designer related, design artifact related, method related, software tool related. These categories reflected the set of design research areas defined in a meeting of the participants a year earlier in March 2011 (Seering and Oehmen 2012).

Based on their experiences with successful transfer, the 35 participants identified each of the 16 heuristics as

- Applicable in most cases (>90 % agreed[3]) → 3 heuristics
- Applicable in many cases (>70 % agreed) → 6 heuristics
- Applicable in some cases (>50 % agreed) → 7 heuristics

[3]The percentage indicates the percentage of participants who agreed that a particular heuristic applies to the successfully transferred research result.

In the emerging discussions 16 additional heuristics were formulated and existing ones reformulated. Of the 16 additional heuristics, 6 related to the research process. The final set of heuristics can be found in the Appendix.

The three heuristics that were considered applicable in most cases are:

- The question being addressed will be of substantial interest to practitioners
- Research results will be evaluated by practitioners
- Tools will improve process effectiveness and/or efficiency measurably

Interestingly, heuristics concerning the study of designers or artifacts were considered only relevant in some cases. The same was found for the heuristics on compatibility of tools with those already in use by practitioners and the quality of the user interfaces.

4.1.3 Conclusions

Many of the participants had been involved in successful transfer of research results. Whether this is exceptional or not, we cannot say. All participants are experienced researchers from a variety of countries, but their number is small compared to the size of the research community as a whole. In other words, we are likely to have only seen the tip of the iceberg, many more results are likely to have been transferred successfully.

It is promising to see that so many managed to bridge the gap between academia and practice, but we are of the opinion that this bridge is narrow and fragile as it seems very much dependent on personal connections and luck in timing. An incubation time is needed, as well as product champions within the company. In some cases publications seem to lead to wide spread use, in other cases consultants pick up the results and ensure their distribution. The trigger can differ: industrial need or academic interest (industrial pull or academic push), although the heuristics seem to suggest that ultimately, industrial need is essential.

Unfortunately, very little is published about results that were transferred, apart from some methods that have become widely known in industry, such as QFD or FMEA. In fact, many of the 45 mentioned methods were not known to the other participants.

Our aim was to extract the lessons that were learnt in order to formulate heuristics that can be shared and that will improve the likelihood of successful transfer. For that purpose, we started a series of interviews with practitioners and used preliminary results as input for a second round of discussions.

4.2 Heuristics Derived from Industrial Input

The seeding for the second meeting came from outside academia. Our view as researchers on what makes transfer into industry successful will only provide a one-sided perspective, which may be strongly colored by the fact that we are the developers of the support. The first author, kindly supported by Tim McAloone (TU Denmark) conducted a set of exploratory interviews with people from 12 companies in 5 different countries, who are responsible for or regularly involved in contacts with universities. The interviews were based on the same set of questions:

- What makes a particular research result (method/methodology/tool) interesting for your company?
- What are the reasons to accept or at least try out such results?
- What are the reasons to be skeptical or not even wishing to try out such results?
- Do you have procedures for testing, adapting, implementing of such results in your company?
- When would a research result be interesting enough to really implement, after having tried it?
- What are your personal good and bad experiences?

The interviews, even though only exploratory, revealed viewpoints that had not been taken into account in the heuristics derived during the first meeting in 2012. The interviews are still ongoing and will result in a separate publication.

In the second meeting, the preliminary findings of the interviews were presented. The participants were then divided into five groups and asked to discuss the findings, and to come up with statements on how to improve transfer of research results into industry, and on factors that play a role in this transfer. The statements (63 in total) were placed on the wall of the meeting room and then jointly clustered into related statements. The authors, as facilitators of the meeting, grouped the clusters into 5 sets. Each group of participants was given a set of statements and asked to bring these together in a set of heuristics for successful transfer.

Table 3 shows the themes identified by each group in the received statements, the number of statements, and the number of heuristics derived from these statements.

This second set of heuristics covered a wider range of heuristics than the first set. The role of education became explicit, and considerable emphasis was put on the need for continuous multilevel and multidirectional interaction between academia and industry in particular in order to understand industry. The heuristics also emphasized the careful preparation of the transfer and the importance of understanding the readiness level of the research results with respect to the company (the so-called methodological readiness level). All heuristics can be found in the appendix.

Table 3 Themes, received statements and derived heuristics

Group	Theme	Statements	Heuristics
G1	Education	9	3
G2	Understanding and addressing company needs, selling	12	8
G3	Relationships, champion, understanding the company, presentation	15	4
G4	Planning, mutual benefits, stepwise approach	17	5
G5	Methodological readiness, understanding of industry	10	6

Table 4 Themes covered by the two sets of heuristics

Trigger: own experiences and predefined set of heuristics (2012)	Trigger: experiences from industry (2013)
Generally applicable heuristics	Understanding and addressing company needs
Heuristics on studying designers	Relationships, understanding the company
Heuristics on studying artifacts	Planning, mutual benefits, stepwise approach
Method-related heuristics	Methodological readiness
Tool-related heuristics	Visibility, presentation
Research-related heuristics	Education

5 Comparison of Derived Heuristics

Table 4 shows the different themes covered by the two sets of heuristics. While processing the heuristics of the second meeting, the heuristics concerning visibility and presentation were put in a separate category.

The two sets of heuristics show some overlap, but, overall are surprisingly different, despite the fact that the majority of participants were involved in the formulation of both sets. It seems that the trigger (own experiences versus interpretation of industrial input) determined the focus and hence the themes covered, even though the interview results were only used as a trigger; the statements and heuristics were formulated by the researchers and thus included their personal and group view (as they did in the first meeting).

As discussed in Sect. 4.2, the input from industry in the form of a set of preliminary interviews about their experiences certainly added important additional points of view that had not been considered in the first meeting.

The first meeting was very much an inward looking, academic push model; when we have done our job well, industry will be happy to use the results. The focus of this first set of heuristics is on what academia needs to do, such as more realistic evaluations, and better understanding of industry.

The second meeting focused much more on what academia and industry need to do together, and on the fact that there is no quick fix: transfer takes time and requires continuous interaction that is professionally executed (see the heuristics on presentation). Furthermore, the university's educational role was introduced as a strong contributor to the successful transfer of research results.

6 Conclusions and Further Research

The two meetings, the analysis of the collected data and the initial interviews resulted in characteristics of research results that have been successfully transferred into practice, characteristics of the processes involved, and a draft set of best practice heuristics for enhancing the chances of successful transfer of research results into practice.

We found that a large concentration of successful applications of research results are in the area of support for a specific design task that is applicable in multiple settings. Our analysis also revealed that support for a specific task is more likely to affect the ‘external’ values of cost, schedule, and quality while support for a collection of tasks is more likely to be perceived as of value to internal stakeholders; designers, design teams, and organizations.

Concerning the process of transfer, the set of reviewed methods and tools and the stories of their development make clear that successful transfer of research results does not happen overnight. Those that were successful generally involved a vision, many years of development, the input of multiple researchers who worked together and built upon each other’s work, as well as a personal contact with a company willing to collaborate. This is in line with the literature on university–industry relationships, discussed in Sect. 2.

One of the main messages is that researchers have to engage practitioners in their research. As illustrated in Fig. 3, their involvement should be continuous but requires different input, depending on the stage of the research.

We have achieved our aim to propose a preliminary set of best practice heuristics for researchers to enhance the chances of successful transfer of research results into practice, which could be used as a starting point for discussion and further research.

The study has its limitations. Even though the input for the second discussion came from industry and many participants have industrial experience or frequent contact with industry, the heuristics were formulated by the academic actors. The input from industry was based on a limited set of interviews and industrial actors were not involved in the discussions.

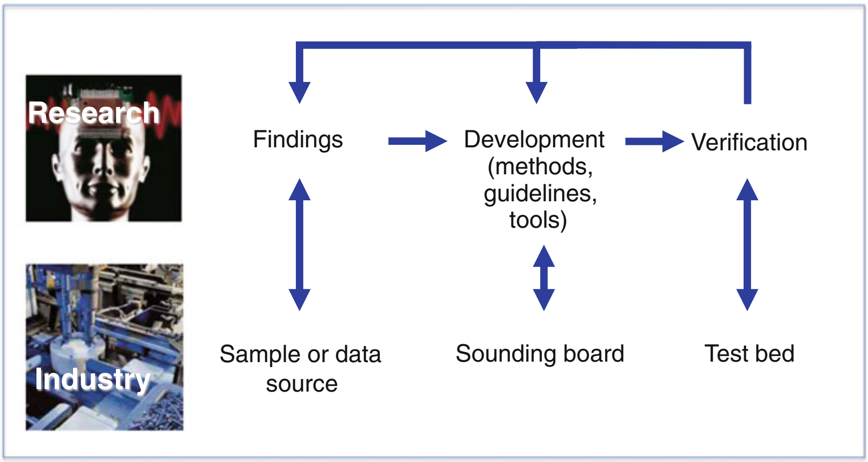

Fig. 3 Roles of industry in design research

The set of heuristics is therefore not yet suitable for practical use: refinement is required. A further input will be the results of the ongoing interviews with industrial actors involved in the transfer of research results into practice, and the results of the breakout session at the IDRP workshop at which this paper has been presented (see Blessing, Results of Breakout Sessions of Group A, Chap. 4).

The heuristics, though preliminary, are presented here to encourage the research community as a whole to address the issue of transfer of our research results into practice. If understanding and improving design is the purpose of our research, the currently not very successful transfer of our research results should be of major concern and, in the light of external pressures from funding agencies and politicians, be addressed as priority and joint responsibility.

Acknowledgments We are indebted to Tim McAloone for undertaking some of the interviews, and to the Design Society's Advisory Board members and Leaders of the Special Interest Groups for their active involvement in the meetings. Without them, there would be nothing to report. We also wish to thank the National Research Fund Luxembourg (FNR) and the School of Engineering, Massachusetts Institute of Technology (MIT) for their financial contribution toward the first author's sabbatical stay at MIT, which allowed her to do the research described in this paper.

Appendix: Draft Set of Heuristics

Table 5 contains the categorized heuristics resulting from the two meetings. The first column indicates from which meeting the heuristic results. The second column contains the heuristics. The last column shows the applicability of each of the heuristics to the successfully transferred research results that were discussed in the 2012 meeting. No frequencies are available for the new heuristics that were proposed by the participants in 2012 and those that were proposed in 2013.

Table 5 Heuristics and their applicability (applicable in most/many/some cases) (blank: new heuristic which is at least applicable to some of the research results in one of the groups)

Generally applicable heuristics		
2012	The questions being addressed will be of substantial interest to practitioners	Most cases
2012	Practitioners will participate in setting objectives for the research	Many cases
2012	Research results will be evaluated by practitioners	Most cases
2012	Practitioners will be in frequent communication with the research team	Many cases
2012	Value should increase over time	–
2012	Results should have long-term impact in industry	–
2013	Concentrate on people: collaborate with the right people	–
2013	Apply exciting process goals and deliverables for research and project	–
2013	Design the research, plan with measurable deliverables	–

(continued)

Table 5 (continued)

Generally applicable heuristics		
2013	Balance the work: Problem Solving versus Research Vision	–
2013	Have a long-term goal and produce spin offs and continuous quick wins	–
2013	Understand the culture of company, the company's process, and the competition	–
Designer-related heuristics		
2012	Research will be conducted with practicing designers as the subjects	Some cases
2012	Activities being studied will be actual/representative design tasks	Some cases
2012	Studies will be conducted in settings emulating those of practice	Some cases
Artefact-related heuristics		
2012	The artifacts being studied will be professionally designed products or components	Some cases
2012	Artifacts/Product models will be sufficient in scope to address the problem	Some cases
Method-related heuristics		
2012	Methods will apply seamlessly to situations in design practice	Many cases
2012	Methods will be easy to understand and implement	Many cases
2012	Methods will yield benefits (early in the process of implementation)	Many cases
2012	Methods will be robust in the presence of differences in standard work process	Many cases
2012	Methods will be credible	–
2012	Methods need to be rational and self-consistent	–
2012	Methods should be novel	–
2012	Methods should be petty, feel good	–
2012	Long term maintenance should be guaranteed	–
2013	The readiness level of the method with respect to the company should be understood and related to the company's needs in communication	–
2013	Make a strategic plan and acquire expertise to bring the method to the next level readiness level	–
Tool-related heuristics		
2012	Tools will be compatible with those already in use by practitioners	Some cases
2012	User interfaces will be well designed	Some cases
2012	Tools will improve process effectiveness and/or efficiency measurably	Most cases
2012	Tools will improve satisfaction	–
2012	Tools should maintain data integrity	–
2012	Long term maintenance should be guaranteed	–
Research-related heuristics		
2012	The result should be relevant and provide input for further research	–
2012	The result should provide benefit for researchers	–
2012	Ethics of the research work should be considered	–
2012	Design research should be socially responsible	–

(continued)

Table 5 (continued)

Generally applicable heuristics		
2012	Research is capable of being done rigorously/scholarly	–
2012	The research should promote further collaboration in academia and industry	–
Education-related heuristics		
2013	Understand education as an ecosystem (educational institution, industry, alumni), dreams of researchers transferred via students into industry, and feedback from industry. You have to advertise the integrated ecosystem.	–
2013	Internships in industry for students	–
2013	Enhance collaboration by exchanging students	–
2013	Be systematic on how students work with industry	–
2013	Enhance educational system to better expose our undergraduate students and Masters students to design	–
2013	Two levels: bottom up—students to industry, Top-down—policy making (SIG?)	–
Interaction enhancement heuristics		
2013	Internships in industry for faculty	–
2013	Trust building—Enable bidirectional movement of industrialists and academic—Win-win situation	–
2013	Better communicate with industry—know client	–
2013	Offering continuing education	–
2013	Two levels: bottom up—students to industry, Top-down—policy making (SIG?)	–
2013	Start with consulting projects and build relationships before engaging the formal university process	–
2013	Understand the “customer”, i.e. the company, and what the business case is for them if they use your ideas	–
2013	Inspire confidence!	–
Visibility-related heuristics		
2013	Publish/expose more in trade journals and non-academic journals (economist, HBR,…), tv, … to show our work	–
2013	Have journals add case studies/success stories section	–
2013	Build on a “crowd”. Use the DS as testimony of competence. But, we rarely use or promote each other’s work…	–
2013	Is it possible to create some “open source” platforms, documents, methods via the DS that can support the above?	–

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Are Methods the Key to Product Development Success? An Empirical Analysis of Method Application in New Product Development

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Abstract This article analyzes method application in the context of new product development. Based on a study of 410 new product development projects, it is shown that applying methods in new product development leads directly to superior financial performance of the developed product (by reducing product costs, for example) and also leads indirectly to a greater degree of innovativeness, better cross-functional collaboration, and shorter time to market. The optimal combination of different method categories is examined and two key determinants of the successful adoption of new product development methods are analyzed, showing how firms can actively improve on what in some cases are very high failure rates of new products.

1 Introduction: Method Application in New Product Development

New product development (NPD) is one of the most important determinants of sustained company performance and therefore represents a key challenge for many firms. Accordingly, numerous authors have focused their research on improving new product development and identified several success factors, including cross-functional collaboration during product development, fast times to market, and product innovativeness. Ernst (2002) and Poolton and Barclay (1998), for example, provide sound overviews of success factors for new product development. Compared to these factors, all of which have already been studied very intensively, relatively little research has so far been conducted into the use of methods in new product development (Nijssen and Frambach 2000). Notwithstanding, studies in this field clearly show that precisely the adoption of product development methods is crucial to the performance of development projects (see Graner and Mißler-Behr 2012).

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In summing up the findings of the extensive innovation study conducted by the Product Development & Management Association in the USA, Barczak et al. (2009), for example, note that: “In terms of aspects of NPD management that differentiate the ‘best from the rest,’ the findings indicate that the best firms […] use numerous kinds of new methods and techniques to support NPD.” The structured use of methods can indeed be a very effective way to help generate new ideas and improve companies’ ability to innovate (Fernandes et al. 2009).

This article aims at analyzing method application in the context of new product development projects. To consider both key determinants and direct and indirect effects of method application, a comprehensive research model is required. Based on a structural equation modeling (SEM) approach and on a large empirical sample of 410 product development projects the individual effects of those factors are analyzed in detail. Methods used by several corporate functions involved in new product development such as Engineering/R&D, Market Research, Purchasing, Quality Management or Logistics are considered. The methods investigated are selected using a systematic process based on defined selection criteria. By doing so, this article seeks to answer the following questions:

- What are key determinants of successful method application?
- What are the direct effects of method application in new product development on the success of the product?
- How does method application affect cross-functional collaboration, time to market and product innovativeness, and thereby influence product success?
- Which combination of methods from different categories can help to develop particularly successful products?

2 Research Framework and Key Hypothesis

Based on existing research, a comprehensive research model was developed which is displayed in Fig. 1. It contains key frame conditions for the adoption of methods in the context of new product development (left side of the model) and both the direct impact of method application on NPD success and the indirect impact of method application via time to market, cross-functional collaboration and product innovativeness (right side of model).[1]

[1]A detailed description of the research model, the statistical analysis and the results can be found in Graner and Mißler-Behr 2013 (isolated analysis of key determinants of method application); Graner and Mißler-Behr 2014 (impact of method application specifically on cross-functional collaboration on product success) and Graner 2013 (comprehensive model, in German language).

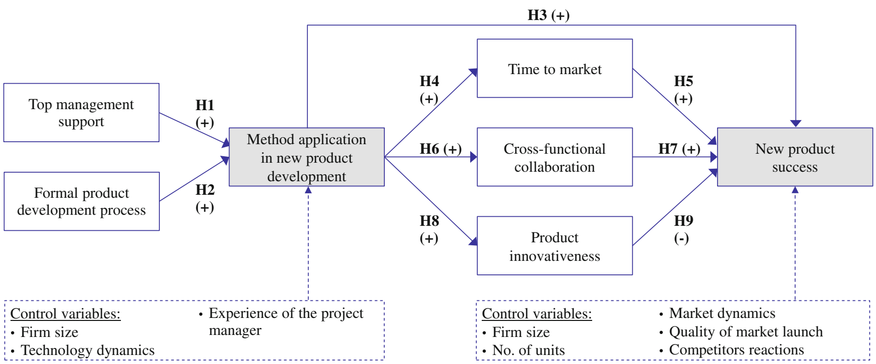

Fig. 1 Conceptual model (see Graner 2013). The hypnosis's are explained in the following paragraph. (+/-: A positive/negative influence is postulated)

2.1 *Frame Conditions of the Successful Adoption of New Product Development Methods*

Little research has so far been conducted into frame conditions of successful method application in the context of new product development and especially analyzing frame conditions together with the effects of method application in a comprehensive research model (see Graner and Mißler-Behr 2013). Nijssen and Frambach (2000), for example, focus mainly on requirements for the successful adoption of methods in new product development. They point out that the degree to which a company formalizes the new product development process and the support given by top management to NPD projects have a material influence on the use of methods in new product development. Based on this study and supplemented by the results of Ettlie and Elsenbach (2007), Thieme et al. (2003), and Geschka and Dahlem (1996) two key determinants for successful method application were analyzed: *Top management support* and the *formalization of the product development process.*

2.1.1 Top Management Support

Several studies (see Ernst 2002; Henard and Szymanski 2001) confirm the role of top management support as an important success factor in new product development. Top management has a crucial influence on both the wider culture of innovation in firms (Poolton and Barclay 1998) as on individual development projects. For example, the use of methods in new product development often requires financial and human resources that must first be made available by the appropriate management level (Ernst 2002). Nijssen and Frambach (2000) show that the degree of top management support has a significant influence on the application of methods in new development projects. The results of Thia et al. (2005) support this conclusion. Geschka and Dahlem (1996) too point out that a supportive attitude on the part of management is a precondition, in particular if methods are to be applied successfully. Thieme et al. (2003) demonstrate that top management support for new product development projects is key to the quality of project planning and the use of certain methods, such as quality function deployment (QFD). In light of these research findings, the following link is postulated: Top management support has a positive impact on the application of methods in new product development projects (hypothesis 1).

2.1.2 Formal Product Development Process

The impact of a formal product development process on new product success has also been confirmed by previous research (Ernst 2002; Henard and Szymanski 2001). Where a company's new product development process is split into several phases with defined decision gates, it is also to be expected that financial or technical evaluation methods, for example, will be used as the basis for decision-making. Nijssen and Frambach (2000) show that the more heavily the development process is formalized, the more methods are used in new product development. Ettlie and Elsenbach (2007) likewise prove that firms that operate a structured development process deploy more new product development methods. Indeed, at some firms, the new product development process is formalized to such an extent that the application of certain methods (such as specific quality or market research methods) is actually prescribed. In such cases, the decision whether to use a method is no longer made solely by the individuals involved in the project. This explains why the degree to which the process is formalized might influence whether methods are applied in new product development projects. The second hypothesis is therefore: The existence of a formal, structured new product development process has a positive impact on the application of methods in new product development (H2).

2.2 Direct Impact of Method Application on NPD Success

The correlation between the *use of methods in new product development* and the *success of the developed product* has been substantiated in a number of studies (see Graner and Mißler-Behr 2012). Market research methods (such as conjoint analysis) can be used to gain a better understanding of specific customer needs (and their willingness to pay) and, based on these insights, to develop the product or individual product components in a way that improves the benefit to the customer and maximizes the financial success of the product. The adoption of purchasing methods at an early stage can help to reduce the cost of materials for the product. Design methods and approaches such as concurrent engineering and design for manufacturing can help to find better technological solutions and to cut the cost of product development, thereby also reducing the subsequent cost of production.

A whole series of methods can therefore be applied in new product development in a way that increases the financial performance of the product. The following central hypothesis is thus proposed: The use of methods in new product development has a positive impact on the financial performance of the product (H3).

2.3 Indirect Impact of Method Application via Time to Market, Cross-Functional Collaboration, and Product Innovativeness

The duration of the development project too is an important success factor in new product development (see Henard and Szymanski 2001). Development projects that are completed quickly tie up fewer resources and enable a faster *time to market*. In many cases, fast new product development also gives firms a head start relative to the market launch of competitor products. This can favor deeper market penetration and a longer product life cycle overall, both of which lead to higher revenues. At the same time, the cost of development can be spread across a larger number of products. For these reasons, a raft of studies and meta-analysis confirm the positive impact of a short development process on the success of innovation (see Graner 2013). Evans (1990) and Dumaine (1989) investigate the cost of slow times to market and determine that delaying market launch by 6 months can cost a firm up to a third of profits in the first 5 years.

Research findings vary regarding the impact of the use of methods on the *time to market*. Some authors argue that applying certain methods costs extra time and thus slows development projects down (Thia et al. 2005; Eisenhardt and Tabrizi 1995). Contrary to this view, however, project staff often saves time if methods are adopted. Cordero (1991) demonstrates this with regard to the use of computer-aided design/manufacturing/engineering. Sun and Zhao (2010) identify a positive correlation between the use of multiple methods (including TQM, QFD, and value analysis) and the speed of new product development. Griffin (1993) and Barczak et al. (2009) likewise confirm that certain methods can help to reduce product development cycle time. Thus the following hypotheses are proposed: The use of methods shortens the development runtime and improves time to market (H4). Projects with faster time to market meet with greater financial success (H5).

Cross-functional collaboration of new product development teams is another key success factor for NPD, substantiated by several studies (e.g., Slotegraaf and Atuahene-Gima 2011). The more closely the people from different functions (such as R&D, production, marketing, purchasing, and logistics) coordinate their activities and the more they share relevant information, the more successful the development project will be.

Precisely, the application of methods often requires all kinds of information from a variety of functions (Nijssen and Frambach 2000). For example, technical specifications and/or product samples are sometimes needed before market research methods can be applied. On top, most methods are often used in combination and require or provide input from or for other methods that are applied from other corporate functions (Lindemann 2003). Therefore, the use of more methods often leads to closer collaboration between the people and functions involved in the project. Thus the following hypotheses were developed: The use of methods has a positive impact on cross-functional collaboration (H6). Cross-functional collaboration during product development has a positive impact on product success (H7).

A third key factor influencing the success of the newly developed product is its *degree of innovativeness*. A wide range of studies confirm this assertion (Danneels and Kleinschmidt 2001; Henard and Szymanski 2001; Song and Montoya-Weiss 1998). Heated debate nevertheless rages regarding the specific impact of innovativeness. To date, different studies have thus identified both positive correlations between innovativeness and NPD (e.g., Gatignon et al. 2002; Song and Montoya-Weiss 1998) and negative ones (e.g., Horsch 2003). On the one hand, more innovative products that satisfy customers' needs better than existing products are attractive to customers and therefore often enjoy substantial market potential. In addition, firms that pioneer innovation often attract considerable attention. On the other hand, however, products that are *too* innovative are sometimes ahead of their time. Moreover, pioneers often struggle with the product's "teething troubles" and shoulder most of the burden of development. Followers can learn from mistakes made by the pioneers and develop mature products at better prices (or at better cost). A majority of research work thus concludes that innovativeness tends rather to have a negative impact on the financial performance of a product (see the overview provided by Schlaak 1999).

The use of methods can materially influence the innovativeness of the product. Market research methods, for instance, can help a firm to better understand the needs and areas of application that are of interest to the end customer. This knowledge allows them to develop more innovative products with new and better features (Song and Xie 2000). At the same time, the adoption of research and development methods can help the new product development team to develop alternative technological solutions. Thus the following hypotheses are proposed: The use of methods leads to more innovative products (H8). Overall, a high degree of innovativeness has a negative impact on the success of the newly developed product (H9).

2.4 Control Variables

Variations in the factors "technology dynamics," "market dynamics," "quality of market launch," "reaction of competitors," "number of units produced," "firm size," and "experience of the project manager" were controlled in order to be able to quantify the influence of the described determinants and effect of method application in isolation. A detailed argumentation including a description of all items can be found in Graner (2013).

3 Method Selection and Measure Development

The analyzed methods were selected in a systematic process. First, an exhaustive literature review evaluated existing studies of the use of methods in new product development, focusing on the methods examined by these studies. A survey of 50 product developers and experts was then used to select the most relevant methods (see Graner 2013). The survey covered individuals from 17 companies (including mechanical, automotive, process and medical engineering firms), each of whom had several years' experience of new product development, and scientists representing various engineering disciplines, quality management, and economics. These experts were asked to select those methods that are adopted especially frequently in the context of new product development or that are especially important to new product development and that, for this reason, should be included in the main investigation. The methods regarded as important by at least 50 % of the respondent experts were selected. In this way, 29 methods of particular relevance were identified. During a questionnaire pretest, very similar methods were then combined. As a result, a total of 26 methods were selected. The full list of methods can be found in the appendix. In the main investigation, the same questions were asked for each method: 1. Was the method used in the development project? (Yes/No). 2. How intensively or thoroughly was it used? (Five-point scale with anchor points: 1 = very low intensity and 5 = very high intensity/method applied very thoroughly). Additionally, the participants were asked whether other methods were also used in the project. Where this was the case, these extra methods too were evaluated. The measurement scale for method application was than calculated as the product of the frequency and intensity of application (see Graner 2013).

New product success (Cronbachs's $\alpha = 0.94$) was measured with six items, such as "market share relative to the firm's stated objectives," "product revenues relative to stated objectives," and "return on investment relative to stated objectives."

Cross-functional collaboration ($\alpha = 0.88$) was measured with four items, such as "in the product development project, different departments fully cooperated in generating and screening new ideas," "… fully cooperated in establishing goals and priorities," and "…were adequately represented and involved in the project teams."

Product innovativeness (Cronbachs's $\alpha = 0.74$) was measured with three items, such as "the technology of the product was new to the firm" and "the product reflects radical differences from industry norms."

Time to market (Cronbachs's $\alpha = 0.82$) was measured with four items, such as "speed of the development project compared to the project time goals and plans," "…compared to industry norms," "…compared to initial expectations" and "…compared to a typical product development project in your firm."

Top management support (Cronbachs's $\alpha = 0.83$) was measured with four items, such as "top management authorized all required resources for the development project," "top management supported the development project throughout the entire development process" and "top management was very actively involved in the project throughout the entire development process."

The degree to which a company formalizes the new product development process ($\alpha = 0.83$) was measured with five items, such as "our firm uses a formal NPD process with a standardized set of stages and defined decision gates," "our NPD process has clearly defined go/no-go decision gates for each stage in the process" and "our NPD process lists and defines which methods (e.g., FMEA, QFD) must be applied at each stage of the process."

See Graner (2013) for a full list and exhaustive wording of all items.

4 Survey of 410 Product Development Projects

The data for the investigation of method application in new product development was collected between April and August 2011 via computer-assisted telephone interviews. A team of specially trained interviewers was assembled to conduct the interviews in order to guarantee a constant, high data quality and to do justice to both the target group and the complexity of the subject matter. The telephone interviews were conducted with manufacturing companies that operate their own new product development from bases in Germany, Austria, and Switzerland. The methods described by Frohlich (2002) were used to increase the response rate, including advance telephone contact with respondents (to arouse their interest in the survey and arrange an appointment for the interview), focused approaches to R&D managers, preliminary questionnaire testing during several conversations, and the use of existing, proven scales. Respondents had to be able to make informed statements about two completed new product development projects. Accordingly, the target group for the survey (as in the case of Chai and Yan 2006 and Langerak and Hultink 2006) included experienced product development managers and project managers who had been involved in the relevant new product development projects. In total, the data from 201 companies could be used without restriction and the data from 8 companies could be used for one project each. This is equivalent to a response rate of 17 %. A total of 410 new product development projects were assessed in this way.

The companies surveyed represent a broad spectrum of manufacturing firms. The majority come from the mechanical engineering and metalworking industries (35 % of the respondents), automotive and vehicle engineering (26 %), electrical/measurement/control system engineering and optics (14 %), and plant engineering (13 %). The interviews also covered a balanced mix of large, medium-sized, and smaller firms in revenue terms. The sample thus comprises companies with annual revenues of between EUR 6 million and more than EUR 1 billion. In terms of the number of employees too, the respondent companies reflected a balanced spread. Smaller enterprises with up to 500 employees accounted for 37 % of the sample, while medium-sized to large companies with up

Table 1 Core data for the respondent companies

Industry sector	%	Company size in terms of revenue (EUR m)		Company size in terms of full-time employees	
Mechanical engineering and metalworking	35	<50	18 %	<250	15 %
Automotive and vehicle engineering	26	50 to <100	16 %	250 to <500	22 %
Electrical/measurement/control systems engineering, optics	14	100 to <250	24 %	500 to <1000	17 %
Plant engineering	13	250 to <1000	28 %	1000 to <5000	26 %
Other (building materials, aviation, plastics,…)	12	>1000	14 %	>5000	20 %
Year of market launch	%	Project duration		Annual production volume (units)	
2011	15	1 year	29 %	<10	19 %
2010	27	2 years	33 %	10 to <100	15 %
2009	16	3 years	22 %	100 to <1000	12 %
2008	12	4 years	8 %	1000 to <10,000	15 %
2007	11	> 4 years	8 %	10,000 to <100,000	12 %
Before 2007	19			>100,000	27 %

to 5,000 employees accounted for 43 % and very large companies with more than 5,000 employees for 20 % of the sample. The detailed breakdown is shown in Table 1:

The analyzed projects were very recent. More than 80 % of the newly developed products had been launched on the market no more than 4 years before the data was collected (2007–2011). In terms of project duration, around one-third of the projects surveyed had runtimes of less than 1 year. Another third ran for between 1 and 2 years, while longer running projects that lasted three or more years accounted (approximately) for the final third. This breakdown is peculiar to manufacturing industries, which tend to have relatively long average development runtimes. The average duration of new product development was just over 2 years. The volume of units produced again reflects a balanced distribution. The sample thus contains single and very small batches (with less than 10 units per year), small batch series (with less than 100 units per year), and large batch series (with more than 100,000 units per year).

5 Analysis and Statistical Results

To test the hypothesis, a structural equation modeling (SEM) approach was employed. The analysis was conducted using the partial least square (PLS)-based SmartPLS software (Version 2.0.M3, Ringle et al. 2011). The validity and reliability of the variables and the constructs were assessed according to the criteria proposed by Hair et al. (2012) and Chin (1998) including indicator reliability (indicator loadings ≥0.7), internal consistency reliability (composite reliability ≥0.7), convergent validity (average variance extracted, AVE ≥ 0.7) and discriminant validity (Fornell–Larcker criterion).

According to Hair et al. (2012), the primary criterion for inner model assessment is the coefficient of determination (R^2), which represents the amount of explained variance. Our total R^2 for product success is 0.45, which is fairly good considering the broad range of influencing factors on new product performance. In addition, the substantial explanatory contribution made by the factors and the forecasting relevance of the model were tested and confirmed based on the strength of the f^2 effect and based on Stone-Geisser's Q^2 (Chin 1998). The stability of constructs was assessed through bootstrapping (n = 410), which estimates the t-values of the path coefficients. All constructs passed these tests. A detailed description of all construct-specific criteria can be found in Graner (2013). The results of the tests performed on the hypothesis are displayed in Fig. 2 and will be explained below.

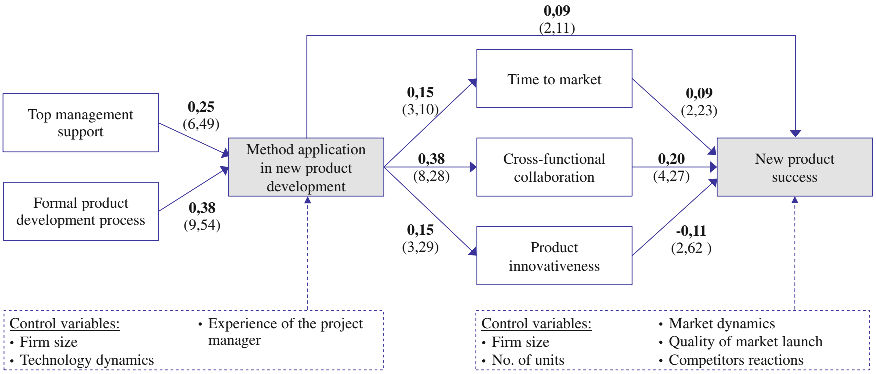

Fig. 2 Key determinants and impact of method application in new product development (path coefficients and t-values)

5.1 *Frame Conditions of the Successful Adoption of New Product Development Methods*

In accordance with prior research into method application in NPD, Hypothesis 1 regarding the positive impact of *top management support* was fully corroborated. A coefficient of 0.25 and a *t*-value of 6.49 (see Fig. 2) indicate that top management support does indeed have a positive impact on the use of methods in new product development.

The existence of a *formal, structured new product development process* likewise positively affects the adoption of methods in new product development, with a coefficient of 0.38. A *t*-value of 9.54 makes this correlation too significant. Hypothesis 2 is therefore also clearly confirmed.

Comparison of both factors shows that the development process has a greater influence on the application of methods than does the support of top management. The path coefficient for the factor "formal product development process" is approximately 50 % higher.

5.2 *Direct Impact of Method Application on NPD Success*

Hypothesis 3 regarding the correlation between the *use of methods in new product development* and the *success of the developed product* could also be also confirmed (path coefficient = 0.09, $p < 0.05$, see Fig. 2). Product development projects, that adopt more methods and use them particularly thoroughly meet with an overall higher product success.

5.3 *Indirect Impact of Method Application on NPD Success via Time to Market, Cross-Functional Collaboration, and Product Innovativeness*

In terms of *time to market*, it was first postulated that the use of methods has a positive influence on the speed of product development and thereby shortens time to market (Hypothesis 4). In line with this reasoning, the results display a positive correlation ($b = 0.15$, $p < 0.01$). Second, a positive influence of short time to market on NPD success could be identified ($b = 0.09$, $p < 0.05$), thereby also confirming Hypothesis 5.

In terms of *cross-functional collaboration*, it was postulated that the use of methods has a positive influence (Hypothesis 6). In line with the above explained reasoning, the results display a strong and positive correlation ($b = 0.38$, $p < 0.01$). Second, a significant positive influence of cross-functional collaboration on NPD success was identified ($b = 0.20$, $p < 0.01$), thereby also confirming Hypothesis 7.

Regarding Hypothesis 8, the results reveal a positive effect of method application on *product innovativeness* ($b = 0.15$, $p < 0.01$) but a significant negative influence of product innovativeness on NPD success ($b = -0.11$, $p < 0.01$), thereby also confirming Hypothesis 9 (see Fig. 2).

5.4 Influence of Control Variables

All the control variables that were taken into account were likewise significant. *Technology dynamics* and firm size both had a positive impact on method application, although the influence of technology dynamics was stronger. Markets characterized by fast technology dynamics experience frequent shifts in technology and are open to a wide variety of possible technologies. Firms that operate in such a context use more methods and apply them more intensively.

As expected, large companies (control variable *firm size*) that have both commensurate financial and human resources also adopt more methods. By contrast, the *experience of the project manager* had a slight negative influence on the use of methods. Very experienced project managers use less methodological support in order to make decisions and achieve outcomes, while in experienced project managers apply more methods in their new product development projects.

Out of the control variables for product success investigated, the *quality of market launch* and the reaction of competitors to the new product have the most powerful effect. While the firm is in a position to directly influence the quality of market launch as an important success factor, the *reaction of competitors* can at best be influenced indirectly (for example, due to the timing of market launch). Interestingly, however, a positive correlation between competitor reaction and the success of the product was identified. Competitors react especially vigorously to successful new products in particular. Seen from this angle, a forceful reaction on the part of competitors (such as price cuts) should not be regarded solely as disadvantageous, but rather as a sign that the developed product is particularly promising.

The *number of product units made* likewise correlates positively to the success of the product. On average, mass-produced products generate greater financial success than single batch series or very small batch series. Similarly, *market dynamics* also has a slightly positive effect on product success, and hence a mild stimulant effect in the sense that this factor forces companies to develop “better” products. By contrast, *firm size* exhibits a slightly negative correlation to financial performance. While larger companies tend to use more methods, they are still less successful than smaller firms.

5.5 The Optimal Combination of New Product Development Methods

Besides investigating method application in the above-described SEM model, the study also assessed the impact of combining methods from different categories (such as market research and purchasing methods). Based on a t-test for two independent samples, it was examined whether statistically significant differences occur between the success of those projects that use methods from several categories (such as market research and purchasing methods) and those that do not.

To do so, the combination of marketing research methods (which provide information about what customers want and thus primarily influence revenue) and purchasing methods (which affect product costs) were investigated (A). The underlying hypothesis is: If methods are used that take account of both the *customer demand* (and willingness to pay) dimension and the p*roduct cost* dimension during new product development, this should, on balance, lead to higher product margins.

In addition (B), a combination of methods that focused, respectively, on *customer demand* (such as marketing research methods), *technological feasibility* (research and development methods and quality and logistics methods), *product cost* (purchasing methods), and *project management* were investigated.

Several groups of projects were compared. The first comparison concerned those projects in which *at least one method* was used from each of the two categories A/B (1). In light of the generally considerable use made of methods in the overall sample, few firms did not satisfy this criterion. For this reason, a comparison of those groups that used *at least two of the methods* (2) and those that used an *above-average number of methods in each category* (3) was also made.

All in all, differences in financial success were examined for six different combinations:

- A.1: At least one method in the marketing research category and at least one purchasing method
- A.2: At least two methods in the marketing research category and at least two purchasing methods
- A.3: An above-average number of methods in the marketing research category and in the purchasing category
- B.1: At least one method each in the categories marketing research, research and development, quality and logistics, purchasing and project management
- B.2: At least two methods each in the categories marketing research, research and development, quality and logistics, purchasing and project management
- B.3: An above-average number of methods in the categories marketing research, research and development, quality and logistics, purchasing and project management

Table 2 Additional product success when multiple methods are combined

Criteria	No. of projects		Mean success		Delta[a]	Std. dev.	T	Df	Sig. (2-sided)
Criteria met?	No	Yes	No	Yes					
A.1: At least one method each from purchasing and marketing research applied	54	352	**–0.34**	**0.05**	0.40	0.14	2.74	404	**0.006****
A.2: At least two methods each from purchasing and marketing research applied	140	266	**–0.15**	**0.08**	0.23	0.10	2.20	404	**0.028***
A.3: Above-average number of methods from purchasing and marketing research applied	238	168	**–0.12**	**0.18**	0.30	0.10	3.01	404	**0.003****
B.1: At least one method each from all categories applied	88	318	**–0.28**	**0.08**	0.36	0.12	3.08	404	**0.003****
B.2: At least two methods each from all categories applied	208	198	**–0.10**	**0.11**	0.21	0.10	2.14	404	**0.033***
B.3: Above-average number of methods from all categories applied	302	104	**–0.09**	**0.26**	0.35	0.11	3.13	404	**0.002****

[a]The average difference in the mean financial success between projects that satisfy the criteria (e.g. that used at least one purchasing method and market research method) and projects that does not
$^{*}p \leq 0.05$; $^{**}p \leq 0.01$

Table 2 shows that those projects that satisfied the relevant criteria in each case (e.g., at least one method from all categories in the case of B.1) experienced substantially higher financial success than those projects that did not satisfy these criteria.

For all combinations, the difference in the mean success displays a high level of statistical significance. It can therefore be stated that projects that use a combination of multiple methods covering customer demand (and willingness to pay), product cost, technological solutions, and efficient project management are significantly more successful than projects that take account only of isolated dimensions.

Accordingly, a balanced combination of different methods appears to be of particular importance to the success of a development project. This assertion is reflected in the notable success of those development projects that use a lot of methods from all categories (Table 2).

6 Discussion of Results and Implications for Practice

The outcomes of this study of 410 new product development projects yield to a series of interesting insights both for scholars as well as for product development managers. It became evident that companies that make greater *use of methods* in new product development achieve significantly greater success in innovation.

Besides the direct effect on product success (e.g., better price levels or reduce material cost) also indirect effects on product success via time to market, cross-functional collaboration, and product innovativeness were revealed in this study.

The statistical results clearly depict that development projects that adopt more methods and use them particularly thoroughly and intensively are executed faster. The resultant products can thus be launched on the market more quickly. Moreover, a faster *time to market* also often gives the firm a head start relative to the market launch of competitor products. This can favor deeper market penetration and a longer product life cycle overall. The analysis of the 410 product development projects clearly showed that products with a shorter development cycle generally meet with greater financial success.

The factor *cross-functional collaboration* in product development projects provides a particular strong link between method application and product success. In projects in which more methods are adopted, staff involved in the project engage in more dialog across functions and generally work better together. Further, the more closely employees from the various functions (such as R&D, production, marketing, purchasing, and logistics) collaborate and the more they share relevant information, the more successful the development project will be.

The analysis also shows that companies that use more methods in new product development ultimately develop more innovative products. Market research methods, for instance, can help a firm to better understand the needs of the end customer and develop more innovative products to satisfy these needs. In light of these findings, the project owners must reconsider the targeted degree of innovativeness in the developed product. The findings show that excessive innovativeness has a negative impact on the success of the product. However, since a high degree of innovativeness is not an inevitable consequence of using methods, it is up to the project owners to actively choose a degree of innovativeness that is not excessive and consciously to avoid launching radically new products on the market. At this point, it must be pointed out that this suppressor effect exerted by the mediator innovativeness is by no means inevitable. Using methods in new product development will not necessarily lead to more innovative products. The degree of innovativeness can be consciously controlled in the course of new product development. Furthermore, the statistical method adopted delivered the mean of 410 projects. In isolated cases, highly innovative products can indeed be very successful.

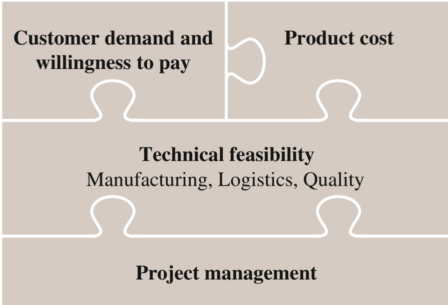

Fig. 3 Recommendations matrix for the use of methods

All in all, the empirical findings clearly confirm the overall positive *impact of method application on the success of new product development*. The managerial implication is therefore that product development teams should foster the adoption of existing methods. Especially the revenue components, cost considerations, and technical feasibility should all be carefully considered and weighed against each other in the context of any given project. Rigorous project management is also needed if new products are to be developed quickly and with the efficient use of resources. Companies that use methods to consider all those aspects, that are displayed in Fig. 3, will meet with an overall higher product success.

To foster method application companies should set the right *frame conditions* for their development projects. Especially, the *design of the development process* has a powerful influence. Companies that have formally defined the new product development process, which split this process into individual process steps, that evaluate the status of development at the end of each step and that decide whether to continue the development project at defined gates in the process tend to use more methods in new product development. The existence of decision gates with clearly defined deliverables thus demands concrete outcomes even while new products are still being developed (such as a technical concept or an economic feasibility assessment, for example). Supported by the individual methods, better outcomes can be achieved with a clearer focus.

Top management support is a second determinant for successful method application in development projects. Product development teams that receive greater support from the management (by having adequate human and financial resources approved, for example) adopt substantially more methods. By conducting more systematic market research, for example, they are able to develop products that fit customer needs more closely and are therefore more successful. Firms that are seeking a more methodical approach to new product development can choose the right combination of methods to increase the success rate of their new product development activities.

Consequently, the same attention must be given to the speed of the development project, a profound cross-functional collaboration in the development project and the degree of innovativeness of the developed product.

Notwithstanding, the results of this study also show that, even when taken together, the use of methods, time to market, cross-functional collaboration, and product innovativeness are unable to fully explain the success of a new product, which depends on a large number of factors of influence (such as the quality of market launch and the reaction of competitors). Despite this constraint, however, they remain important aspects of new product development success—aspects that firms can influence directly, thereby consciously increasing the success rate for the development of new products.

7 Three Most Important Messages for the Transfer of Research into Practice

- The use of methods in new product development has a positive impact on the financial performance of the developed product. Companies should therefor set the right frame conditions and foster method application in product development projects.
- Product development projects that use a combination of multiple methods covering customer demand, product cost, technological solutions, and efficient project management are significantly more successful than projects that take account only of isolated dimensions. Accordingly, a balanced combination of different methods appears to be of particular importance to the success of the developed product.
- Besides the direct effects on product success (e.g., better price levels or reduce material cost), also indirect effects on product success via time to market, cross-functional collaboration and product innovativeness were revealed.

Appendix: Investigated Methods

Method/approach	Description
Research and development	
Simultaneous/concurrent engineering	Simultaneous, distributed development, e.g., involving different development teams and/or locations
Design for manufacturing/assembly (DFM/DFA)	Attention to or improvements in the "manufacturability" of the product (or of product costs) during the development phase
Computer-aided engineering/design (CAE/CAD)	Use of computers as new product development tools, e.g., for design and technical drawing activities

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Method/approach	Description
Quality function deployment (QFD)/house of quality	Method of identifying and evaluating product components that affects customer benefits (what does the customer want and how can it be realized on a technological level?). To this end, the benefit that a product component yields for customers (e.g., long standby times for mobile phones) is translated into technological and quality requirements (e.g., requirements placed on the battery and the display)
Standardization/modular design	Standardization of product components and, where appropriate, use of modular building blocks to increase the number of identical parts (with the aim of reducing complexity and cutting costs)
Collaborative supplier integration in product development	Active involvement of suppliers in product development, e.g., by running ideas competitions
(Rapid) prototyping	Various manufacturing methods for the rapid production of prototype parts (e.g., 3D printing or laser deposit welding)
Marketing research	
Customer interviews and observations (e.g., monitored test markets)	Structured observation of customers (e.g., in the context of a video-monitored test market) or the conduct of interviews with customers (e.g., personal, on-site interviews or questionnaire-based telephone interviews) with the aim of identifying and better understanding what customers need/want
Product (design) test (e.g., home-use tests)	Getting customers to try out products, e.g., in the context of home-use tests (where a product is supplied to customers who subject it to everyday use and provide feedback on their experience of the product) or product design tests (e.g., by demonstrating and evaluating different product designs)
Price test/price sensitivity analysis	Method of determining the ideal price or price range
Conjoint analysis	Market research method to identify the importance of individual product functions. To this end, several different combinations of products are showed to the test person and evaluated (comparison of pairs)
Purchasing	
Target costing	Calculation of the maximum cost of a product or component in light of its market price or target price (or how much the customer has been found to be willing to pay)

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Method/approach	Description
Specified tenders	Eliciting of tenders from several suppliers based on detailed product specifications for each component that adds value and that must be purchased in order to manufacture the new product
Total cost of ownership (TCO)	Calculation of all costs, from the development of a product to its withdrawal from the market (e.g., including downstream costs for the spare parts provisioning)
Low-cost/best-cost country sourcing (L/BCCS)	Systematic sourcing in countries with low labor costs (e.g., in Eastern Europe)
Quality and logistics	
Supplier management and development	Direct intervention in the activities of suppliers and/or direct support for suppliers' operations with the aim of improving suppliers' skills and performance
Design for six sigma (DFSS)	Quality management method with the aim of achieving zero-defect products and processes wherever possible
Failure mode and effect analysis (FMEA)	Analytical method used in reliability engineering with the aim of identifying and evaluating potential weaknesses in a product at an early stage. To this end, potential sources of defects are weighted and assessed. This form of risk analysis is intended to identify and eliminate potential defects before they materialize
Project management	
Critical path analysis	Project milestone planning ("who is to do what by when?") in which individual steps are coordinated and the "critical path" is defined (delays in these project steps lead to delays in the overall project)
Product value/profitability analysis (break-even analysis, net present value, return on investment)	Structured project feasibility analysis, e.g., based on a break-even analysis or on the return on investment
Project controlling (time and budget)	Regular project controlling to ensure that deadlines and budget targets are met and to monitor compliance with project milestones (e.g., by designated project controllers)
Project risk controlling/project risk matrix	Visualization and monitoring of project risks (e.g., delays and quality considerations)
Common methods	
Creativity techniques (brainstorming, brainwriting, mind mapping, synectics, etc.)	Methods deployed to find creative solutions, e.g., intuitive methods (such as brainstorming) and discursive methods (based

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Method/approach	Description
	on logical reasoning sequences, such as morphological boxes)
Benchmarking (competitive intelligence)	Structured comparison with both in-house products and products (or solutions) made by competitors
SWOT analysis (strengths, weaknesses, opportunities, and threats)	Structured juxtaposition and analysis of the strengths, weaknesses, opportunities, and risks associated with a product or a possible
Scenario planning and analysis	A method of strategic planning designed to analyze the scope of potential events and their impacts (e.g., best-case, worst-case, and typical-case scenarios)

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Patterns and Paths for Realising Design-Led Impact: A Study of UK REF Cases Studies

Ben Hicks

Engineering research is by its definition concerned with not so much an exhaustive investigation of fundamental principles but generating sufficient understanding so as to be able to reliably predict behaviour for the purpose of improving design. Thus, much engineering research can be considered per se to have been undertaken with the aim of influencing design practice. With this in mind, the focus of this chapter is on the impact of more general engineering research on design practice and product[1] designs. In particular, this chapter examines 22 case studies taken from two of the UK's leading Mechanical Engineering Departments. The case studies were all prepared in 2013 for the purpose of the UK's Research Excellence Framework assessment. The cases are categorised and grouped according to the dimension of impact, sector, timescale and core mechanisms employed, with the aim of eliciting common paths/routes to influencing practice, product design and policy. The data is also analysed for patterns or trends. Although the small sample size necessarily limits the generality of the findings it provides some indication of typical timescale, and reach and significance of impact with respect to the structure and interrelationship of the UK's government funding bodies. Finally, observations pertaining to design process research and the challenges associated with achieving and monitoring impact are highlighted.

1 Introduction

Since the turn of the millennium the impact of research and in particular, the impact of government-funded research, has come under increased scrutiny. This is driven by a combination of an economic downturn, the desire for government funding

[1]In this chapter machines and high value systems are considered as products.

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bodies to protect their budgets and thus demonstrate value for money, the need to stimulate the UK economy through innovation, and the long-term desire to redress the relative contribution of manufacturing to the UK's GDP (Gross Domestic Product).

While impact has always been a consideration it is only recently that the need to more explicitly monitor and measure impact has emerged. This requirement has filtered down through government funding agencies and is now an integral part of the assessment of research quality for UK universities. The challenges of monitoring and measuring impact are not straightforward and include:

- Type—Impact in terms of economic, political, societal, environment and health all pose different challenges for measurement, and in particular, quantification of reach (range of beneficiaries) and significance (level/value of benefit).
- Reach (locality)—It is generally only possible to measure directly impact in areas where impact is known to have been made, e.g. within a particular organisation, supply chain or region.
- Reach (partiality)—Any account of impact may only be part of the total impact, and in extreme cases may vastly underestimate the impact, which may for example have been applied elsewhere by company staff who have moved on.
- Timescale—A further complication lies in the timescale for impact which can span many decades. Here the original researchers may well have moved both institutes and research areas at the point in time of measurement of impact.
- Significance (dilution)—Research output/findings generally impact on only a small part of a larger system—no matter whether it is product or process-led—in which many innovations may have been made. It therefore becomes difficult to isolate and quantify the magnitude of the impact of one specific research output/finding.
- Process versus product—Product-led research output/findings generally directly affect the performance of a product. Correspondingly, it is possible to measure more objectively the impact on the product itself and/or the market, e.g. improved performance or function, or business activity, market share and sales. In contrast, for process-led research it is more difficult to cite explicit measures, and researchers rely more on qualitative and subjective measures, such as time saving or improved working culture.

Despite these challenges and for the reasons previously mentioned, the requirement to assess impact; approaches for achieving, accelerating and maximising impact; and techniques for monitoring and measuring impact are becoming increasingly important. Given this, the study reported in this chapter presents an investigation of 22 case studies prepared for the UK Research Excellence Framework with the aim of exploring their similarities and differences and eliciting implications for realising impact from design research.

The chapter begins with background to the Research Excellence Framework and an overview of the guidelines and template for the preparation of impact case studies (described in detail in 2.1). The dataset is then described and key dimensions extracted and tabulated. The cases are categorised and grouped according to the dimensions of impact, sector, timescale and core mechanisms employed, with the aim of eliciting common paths/routes to influencing practice or policy. The data is also analysed for patterns or trends. Although the small sample size (<30) necessarily limits the generality of the findings it provides some indication of typical timescale, and reach and significance of impact with respect to the structure and interrelationship of the UK's government funding bodies. The chapter concludes with observations pertaining to design process research and the challenges associated with achieving and monitoring impact. These observations are based on the author's experiences from the process of synthesising, selecting and developing REF case studies, and 15 years' experience as a researcher in the engineering design field.

2 The Research Excellence Framework (REF)

The Research Assessment Exercise (RAE) is undertaken approximately every 5 years on behalf of the UK's four higher education funding councils (HEFCE,[2] SHEFC,[3] HEFCW,[4] DELNI[5]). The aim of the exercise is to assess the quality of research undertaken by UK universities. The process is undertaken by a specialist peer review panel for each subject area. A submission is made by universities for each subject area for which they are eligible (i.e. active in teaching and research). The submissions from each subject area (termed unit of assessment) are assigned a ranking. These rankings form the basis for the allocation of the quality-weighted research funding (QR) that each higher education institution receives from their national funding council. RAEs took place in 1986, 1989, 1992, 1996 and 2001. The most recent results were published in December 2008 (RAE 2013).

In June 2007, the Higher Education Funding Council for England (HEFCE) announced that a new framework for assessing research quality in UK universities would replace the Research Assessment Exercise (RAE) in 2013, 2014. The key aims of the new framework were (HEFCE 2007):

[2]HEFCE—Higher Education Funding Council for England.

[3]SHEFC—Scottish Higher Education Funding Council.

[4]HEFCW—Higher Education Funding Council for Wales.

[5]DELNI—Department for Employment and Learning of Northern Ireland.

- to produce robust UK-wide indicators of research excellence for all disciplines which can be used to benchmark quality against international standards and to drive the Council's funding for research;
- to provide a basis for distributing funding primarily by reference to research excellence, and to fund excellent research in all its forms wherever it is found;
- to reduce significantly the administrative burden on institutions in comparison to the RAE;
- to avoid creating any undesirable behavioural incentives;
- to promote equality and diversity; and
- to provide a stable framework for our continuing support of a world-leading research base within HE.

One of the main differences between the RAE and the new framework (termed Research Excellence Framework) was the inclusion of impact measures. These measures created significant controversy in the UK with the majority of the criticism focused on the areas of the REF that dealt with the "impact" of research. There were two main objections. The first concerned the way that "impact" was defined to mean impact outside academia, which thus constrains academic freedom—requiring a certain type of end goal. The second concerned the way that "impact" is currently construed and the fact that it is correspondingly hard to measure in any way that would be regarded as fair and impartial (Shepherd 2009; Oswald 2009; Fernandez-Armesto 2009). Notwithstanding this, HEFCE argued that their measure of "impact" was a broad one which encompasses impact upon the "economy, society, public policy, culture and the quality of life". Such was the concern and criticism over impact that in 2010 the Universities and Science Minister David Willetts announced that the REF exercise was to be delayed by a year in order to assess the efficacy of the impact measure (Baker 2010).

Submissions are assessed and graded according to the following criteria: (REFa 2011)

- Four star: Quality that is world-leading in terms of originality, significance and rigour.
- Three star: Quality that is internationally excellent in terms of originality, significance and rigour but which falls short of the highest standards of excellence.
- Two star: Quality that is recognised internationally in terms of originality, significance and rigour.
- One star: Quality that is recognised nationally in terms of originality, significance and rigour.
- Unclassified: Quality that falls below the standard of nationally recognised work, or work which does not meet the published definition of research for the purposes of this assessment.

2.1 Format of Research Excellence Framework Impact Case Studies

Research Excellence Framework (REF) case studies have to conform to a four page template that includes five sections (REFb 2011). While fixed word limits are not given for each section, indicative word counts are provided and these are restated. The five sections include:

1. A 100-word **summary of the impact** (i.e. the difference it has made) and the context (the significance of the difference).
2. A 500-word description of **underpinning research**. This describes the specific research findings/output that led to the impact. It can include research that was undertaken at any time over a 20 year period between 1993 and 2013. The section should demonstrate a clear pathway between the specific research findings/output and the stated impact.
3. **References to the research** (indicative maximum of 6). These should clearly reference the research publications that led to the impact and must be of at least two star quality (see aforementioned rankings).
4. A 750-word description of the **details of the impact**. This section describes the detail of the impact realised by the specific research findings/output between January 2008 and July 2013. The section focuses in detail on the reach (extent and breadth of the beneficiaries of the impact) and significance (the degree to which the impact has enabled, enriched, influenced, informed or changed the products, services, performance, practices, policies or understanding of commerce, industry or other organisations, governments, communities or individuals).
5. **Sources to corroborate the impact** (indicative maximum of 10 references). This section includes further information to support the details of the impact. These can include testimonials, formal reports or press articles. Each source must be made available to the panel upon request.

3 The REF Case Studies (Dataset)

The case studies reviewed in this chapter were obtained from two of the UK's leading Mechanical Engineering Departments. In total, 22 case studies were obtained: 8 from one university and 14 from the other. The key dimensions of the case studies are summarised in Table 1. This includes the date of first publication of the specific research findings that underpin the case study; the number of researchers contributing to each case study; the industry sector; the size and number of commercial organisations involved; the nature, type, magnitude and reach of impact (discussed in detail in Sect. 4) and the mechanism(s) by which impact was

Table 1 Summary of REF Case Studies and their key dimensions

Case study	Date of research	No of researchers	Sector	Organisation type	No of organisations	Nature of impact	Type of impact	Magnitude	Reach
1	2004	7	Processing	SME and Large	3	Process improvement, new products and new services	Economic	£8 M new product sales and £4.4 M savings	National
2	1994	5	Healthcare	SME and Large	2	New products	Economic	£180 M sales and £36 M sales	National and International
3	1994	6	Power systems	Large	2	Process improvement, new methods and standards	Economic	£4 M savings	National and International
4	2005	4	Manufacturing	SME and Large	3	Process improvement and new machinery	Economic and societal	£38 M sales	National
5	2000	4	Materials	Micro and SME	2	New product, new processes and patent	Economic and societal	New jobs	National and International
6	1995	6	Aerospace	Large	2	Improved products	Economic	Process improvement and fuel savings	National
7	2008	4	Automotive	Large	1	Improved products	Economic	25 M Euro savings for customers	National and International
8	2007	4	Automotive	Micro	1	New product	Economic	£340,000 savings for customers	National
9	1999	3		Large	2	New tool/method	Economic		National

(continued)

Table 1 (continued)

Case study	Date of research	No of researchers	Sector	Organisation type	No of organisations	Nature of impact	Type of impact	Magnitude	Reach
			Infrastructure and Engineering Service					Process and project improvement—cost and time savings	
10	1998	2	Aerospace, infrastructure and automotive	Micro	1	New tool/method and new product	Economic	£700 k sales	National and International
11	2003	5	Electronics	Micro	1	New product	Economic and societal	£5 M investment + 4 jobs	National
12	1997	2	Aerospace and marine	SME and Large	2	New products	Economic	£3.5 M sales	National and International
13	2008	1	Aerospace	Large	2	New tool	Economic	Improved product designs	National
14	2002	1	Defence	Large	1	New product	Economic	Fuel savings and new business ($50 M)	National and International
15	1998	2	Aerospace	SME	1	Improved/new product	Economic	Sales of £3.9 M and £2.4 M annual savings for customers	National International
16	2001	1	Infrastructure	Micro	2	New product/patent	Economic and societal	Sales of £1.18 M in 3 years	National and International

(continued)

Table 1 (continued)

Case study	Date of research	No of researchers	Sector	Organisation type	No of organisations	Nature of impact	Type of impact	Magnitude	Reach
17	1996	2	Infrastructure	Community	2	New method	Societal	Prevention of land slides in at risk areas	International
18	1997	2	Nuclear	Large	5	New tool	Societal	Prevention of failure (safety)	National
19	2003	1	Aerospace	Large	3	New tool	Economic	Weight savings	National and International
20	1995	1	Transport	SME	1	New product	Economic	£40 M sales	National
21	2000	2	Energy	Large	3	New method/service	Economic	11 jobs and £750 k turnover	National and International
22	1993	2	Electronics	SME	1	New method and standards	Economic	25 staff	National and International

achieved, i.e. the means by which the specific findings were transferred to, embedded in or exploited by government, society or commerce.

For the purpose of REF, the number of case studies submitted is dependent upon the size (number of academics) included in the submission. The current REF guidelines are two case studies for the first 15 staff and an additional case study for every 10 further fulltime staff (REFc 2011). The total contribution of the case studies to the overall assessment is 20 % (REFd 2011). The case studies are thus an important part of the assessment process and as such both institutions adopted an internal review, selection and refinement process in order to ensure the strongest case studies were submitted. The consequence of this process and the guidelines are two-fold. First, the case studies submitted are likely to only represent a small proportion of examples of research that have had impact and may only represent a small proportion of the total academics. Although as is seen in Table 1, for almost all case studies, multiple academics were involved with as many as six or seven in some cases. Second, the cases represent successful impact and hence pathways, rather than the learning generated from unsuccessful attempts, e.g. through trial-and-error.

Although the dataset comprises only 22 case studies the quality of the cases can be considered to be very high. The reasons for this are:

i. Case studies have been prepared in conjunction with the organisations, institutions and individuals who have been the beneficiaries of the impact. This helps to ensure that the stated impact is validated.
ii. The organisations and individuals involved have been required to formally corroborate the reach and significance of the impact knowing that both the case study and the source of corroboration will be made available in the public domain following the REF 2014 period. This helps to ensure that the magnitude and significance of the stated impact is representative and fair.
iii. The case studies describe impact between January 1, 2008 and July 31, 2013 but relate to research work undertaken between 1998 and 2013, and must be explicitly related to specific research findings/output (up to 6 publications). This helps to ensure that the stated impact is strongly related to the research findings/output.
iv. The mechanism(s) by which impact has been achieved has to be explicitly discussed. This again helps to elucidate the link between the specific research finding/output and the stated impact.
v. Case studies and their corroborating statements are to be reviewed by the REF 2014 panel. A proportion of submitted information from each institution will be verified as well as data identified by panel members during assessment (REFe, 2011). This transparency and auditing again helps to ensure that the stated impact and the influence/role of the specific research findings/output on the impact are true and fair accounts.

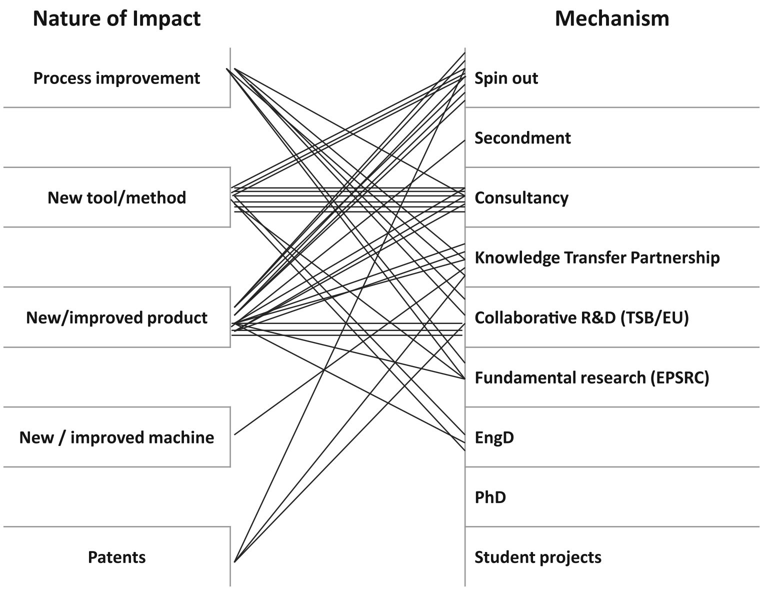

Fig. 1 Mapping of cases studies over key dimensions

4 Analysis of REF Case Studies

The case studies are analysed by grouping and classification, and mapping of pathways to impact across sector, mechanism, nature of impact and reach (national/international). The mapping is shown in Fig. 1. The sector (e.g. auto, aero, power) and reach (national/international) classifications are consistent with generally accepted terms, while the 'nature of impact' and 'mechanisms' were synthesised from REF case studies, REF documentation and the authors' experience of the mechanisms by which UK universities can work with industry and commerce. The 'nature of impact' spans internal impact (intra-organisation) such as processes, tools and infrastructure/equipment and extra-organisational such as new products, increased business activity and entry into new markets and patents. In terms of the mechanisms employed eight types were established, a number of which are UK specific. The mechanisms are thus defined in detail in Table 2.

In the case of nature of impact, the mechanism(s) and reach, the classification is not exclusive. That is to say, multiple mechanisms were cited and/or impacts of different natures, such as process improvement and a new product. The 22 case studies are classified in Table 3 and mapped in Fig. 1.

While, as previously stated, the sample size is relatively low (<30), the classification (Table 3.) and mapping in Fig. 1 suggest five emergent relations:

Table 2 Typical mechanisms for achieving impact research-led industrial impact

Mechanism		Description
1	Spin out	Researchers and/or their industrial collaborators setup a company to exploit the specific research findings/output.
2	Secondment	Researcher or industrialist spends time in industry or academia, respectively. These can be fully funded or partly funded by industry or government. Schemes are offered by organisations such as the Royal Academy of Engineering (RAEng 2013).
3	Consultancy	Projects undertaken directly with an external sponsor where researcher expertise/time, applied research activities or equipment is utilised. Normally, the project is fully funded by the external company or organisation.
4	Knowledge Transfer Partnership	UK government-funded initiative (typically 50:50 funding) to help UK businesses to improve competitiveness, productivity and performance by accessing the knowledge, technology and skills form universities, colleges and research organisations (TSBa 2013). The KTP is partnership with an academic institution to obtain knowledge and expertise to which they currently have no access, to address their business challenges and embed sustainable innovation. The knowledge sought is embedded into the company through a project or projects undertaken by a recently qualified person (known as the KTP associate) recruited specifically to work on that project.
5	Collaborative R&D	Jointly funded projects (typically 50:50) between either UK government or the European Commission and industry with the aim of accelerating economic growth by stimulating and supporting business-led innovation. In the UK, the majority of such collaborative R&D is funded by the Technology Strategy Board (TSBb 2013).
6	EngD	Engineering Doctorate (EngD) funded by government and industry. EngD is 4 years and includes approximately 1 year of taught components. EngD researcher works on a portfolio of industrial problems to produce a doctoral thesis
7	PhD	Government, university or industry-funded support for a 3–3.5-year doctoral researcher based predominantly at the university and working on issues of fundamental science (blue-skies).
8	Fundamental Research	Core scientific research funded by the UK government by UK Research Councils such as the Engineering and Physical Sciences Research Council (EPSRC 2013).

1. For the case studies considered there is, perhaps unsurprisingly given the applied nature of engineering research, a greater focus on new/improved products rather than process improvement. In total, there were 14 instances of new products from a total of 29 impacts cited within the 22 cases.
2. When considering reach, it is apparent that tools and methods and product-led research appear to offer greater opportunity for international impact and hence greater reach. For the cases considered, 75 % of tools/methods give rise to

Table 3 Nature of impact, mechanisms and reach

		Mechanism									Reach		
Nature	No	Spin out	Secondment	Consultancy	KTP	Collaborative R&D	Fundmental research	EngD	PhD	Student projects	National	International	Ratio
Process improvement	4	–	–	1	2	2	2		–	–	4	2	0.5
New tool/method	8	3	–	6	–	–	1	2	–	–	8	6	0.75
New/improved product	14	6	1	3	3	3	1	1	–	–	14	9	0.64
New /improved machine	1	–	–	–	1	–	–	–	–	–	1	–	0
Patent	2	1	–	–	1	1	–	–	–	–	2	2	1

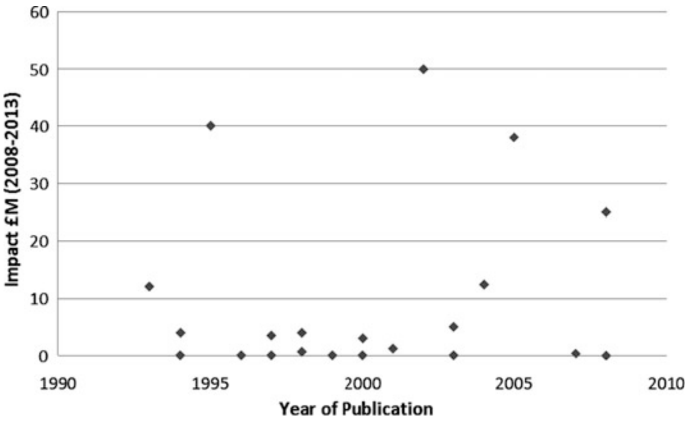

Fig. 2 Magnitude of impact against date of publication of specific research findings

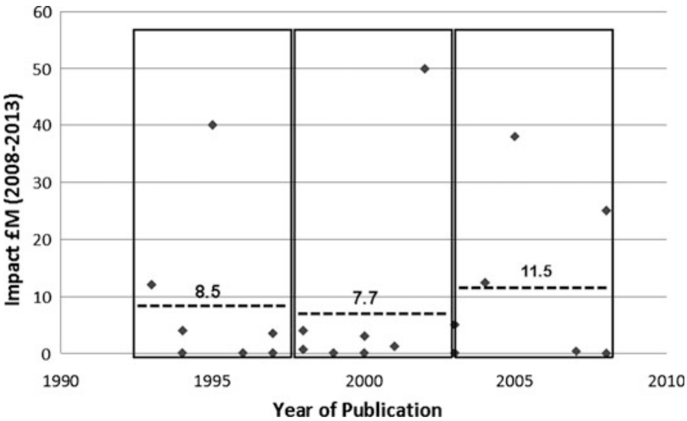

Fig. 3 Time-phased analysis of impact (£M)

international impact while 64 % of product-led impact gave rise to international impact.

3. In contrast to above (2), process-led research is generally more restricted to national/local impact although half of the four citations of process-led improvement have international reach (50 %). This is perhaps unsurprising given that process-led improvement is more commonly intra-organisational (improving quality and saving time/costs) and this is more likely to be regional as research teams will generally need to be accessible to the beneficiary organisation.
4. In the case studies considered, there were relatively few references to PhDs and fundamental research compared to collaborative R&D (e.g. TSB), Knowledge Transfer Partnership and consultancy activities. This would suggest that to have

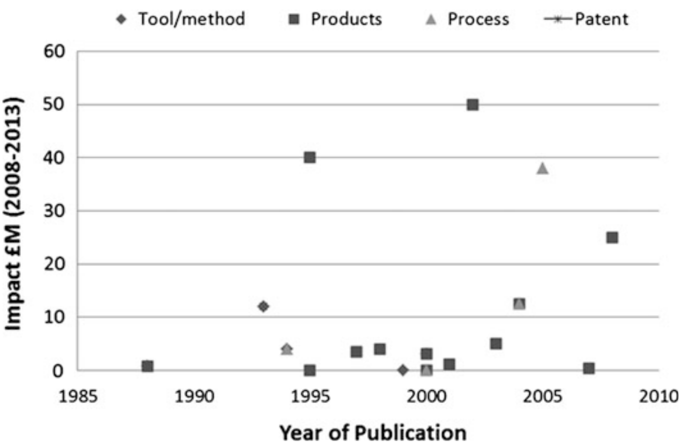

Fig. 4 Magnitude of impact for product and process-led research

impact or increase, the chances of impact academics should be involved in higher technology readiness level (TRL) research and consultancy.

5. Inspection of the mechanisms for achieving impact reveal that, although note exclusively, spin-outs is the key (most frequently occurring) mechanism for product-led impact while consultancy is the key mechanism for tool/method-led impact. Although spin-outs and consultancy are used also for tool/method-led impact and product-led, respectively.

In terms of examining the trends between timescale, reach and magnitude, a number of insights can be drawn. The first insight concerns the nature of impact. For the cases considered, there is little or no mention of wider societal benefits, such as quality of life, rather nearly all of the stated impacts centre on economic gains. While societal impacts are mentioned in six of the case studies, a detailed explanation is only given in 2 cases (17 and 18). The major focus of the other four case studies is on the economic measures such as sales values and increases in turnover with new jobs being mentioned in brief. This trend arguably reinforces the concerns highlighted in Sect. 2 about the limited/singular view of impact as being economic. Notwithstanding this, economic impacts can generally be considered to be easier to quantify and express both in the case studies themselves and when preparing corroborating statements, many of which are from commercial organisations. The stated economic impacts of the case studies are plotted in Figs. 2, 3 and 4 with respect to the date of publication. For the purpose of presenting the data, the product-led research resulting in a £216 M impact has been removed (case study 2).

The second insight concerns the relationship between published research and the time for impact (latency). For the case studies considered (Fig. 3), research undertaken within 5 years of the period of impact (2008–2013) has a magnitude of impact that is equal to or greater than research undertaken ten years or even 15 years prior to the period of impact. Although it is important to note that research

Table 4 Key emergent relations and insights

Relation/insight	Description
Relation 1—Focus	A greater focus on new/improved products rather than process improvement.
Relation 2—Product and tool/method reach	Product-led and tool/method research generally gives rise to greater international impact and hence greater reach.
Relation 3—Process reach	Process-led research is generally more restricted to national/local impact, although 50 % still has international reach.
Relation 4—Impact mechanism (a)	The most common mechanisms for achieving impact are Collaborative R&D (e.g. Technology Strategy Board) funding, Knowledge Transfer Partnerships and consultancy activities.
Relation 5—Impact mechanism (b)	Spin-outs are the key mechanism for product-led impact while consultancy is the key mechanism for tool/method-led impact.
Insight 1—Impact type	Almost all the stated impacts (20 out of 22 cases) concern economic gains with few if no explicit reference to societal gains such as quality of life, healthcare or environment.
Insight 2—Impact magnitude (significance)	Research undertaken within 5 years of the period of impact (2008–2013) has a magnitude of impact that is equal to or greater than research undertaken 10 years or even 15 years prior to the period of impact.
Insight 3—Product versus process	Product-led impact and research generally has a more significant measured economic impact in the timescale considered than process-led research.

undertaken 15 years prior to the period of impact may well have been delivering impact for a greater period, e.g. for 10 + years prior to the period of impact and will therefore have a cumulative total that is greater than given in the case studies. Notwithstanding this point, it is interesting to note that for over one-third of the case studies considered, impact has been realised within 5 years of publication of the specific scientific results/findings.

The third insight concerns the difference between product- and process-led impact and hence research. This is related in part to the emergent relations identified during mapping (c.f. Figure 1). This insight is that product-led impact and research generally has a more significant measured economic impact in the timescale considered. The term 'measured' is used here to acknowledge the factors of partiality and dilution discussed in Sect. 1. On average, the impact of product-led research was £25.7 M while process-led was £13.6 M (Fig. 4).

A further evaluation of the key dimensions (Table 1) with respect to magnitude (significance) of impact reveals that there is no observed correlation between whether the beneficiary is a small-to-medium enterprise or a large enterprise. The impacts of greater magnitude (economic) are associated with new products and machinery rather than process improvement.

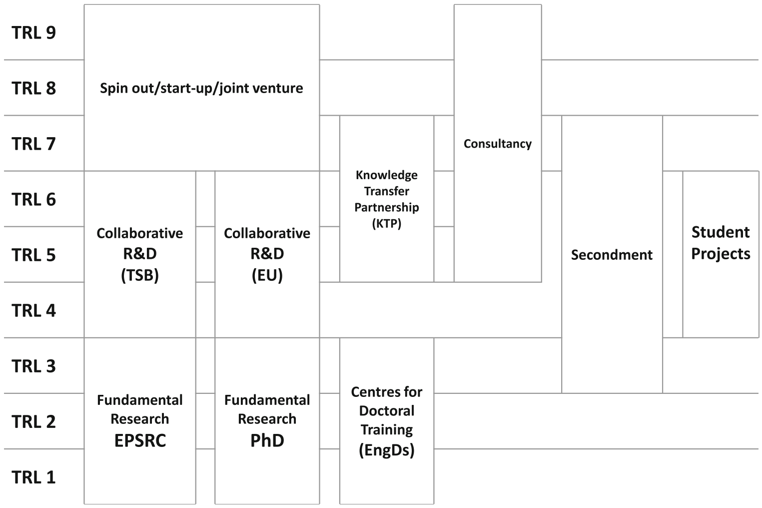

Fig. 5 Technology readiness levels and research mechanisms

5 Discussion

The key insights and relations established from the analysis are summarised in Table 4. The wider implications of these for delivering impact and the specific challenges for design research are now discussed. While the relations are elicited directly from the text of the case study data, relation 4 can be considered to imply that very little impact arises from fundamental research supported by UK government/funding agencies, such as the Engineering and Physical Sciences Research Council. One possible reason for this is that support for the specific research findings/outputs is acknowledged in the research publications rather than the case studies themselves. To explore this further, the first (seminal) paper for each case study was reviewed to elicit any acknowledgement of financial support for the research. This supplementary analysis revealed that of the 22 case studies, six acknowledge the Engineering and Physical Sciences Research Council, eight contain no acknowledgements and six cite sources from the Health and Safety Executive, Department for Trade and Industry (now Department for Business, Innovation and Skills (BIS)), Nuclear Research Laboratory and British Energy (now EDF). Of the eight that do not acknowledge any financial support, two mention doctoral researchers, which are likely to be funded by UK government agencies/funding councils. Thus, a fairer estimate of the number of case studies, and hence resulting impact arising from specific research findings supported by UK government funding bodies, is one-third to two fifths. These findings allude to the importance of a range of mechanisms to support the translation of specific research findings through the technology readiness levels.

5.1 Research and the Technology Readiness Levels

One of the most interesting findings from the analysis of the cases studies concerns the mechanism for realising impact from specific research findings/outputs. The examination of cases reveals the important (central) role of collaborative R&D funding, Knowledge Transfer Partnerships and industry-funded consultancy. While the latter is directly undertaken by academics and fully funded by the external organisation, the first two are both funded largely by UK government and in particular the Technology Strategy Board (c.f. Table 2). Further, these two mechanisms are explicit in their role to progress research through the technology readiness levels.

The technology readiness level (TRL) framework was first introduced by NASA (Mankins 2002; Hicks 2009) and is now widely used to represent the transformation and translation of research into technologies and new products. The TRLs are shown on the left-hand side of Fig. 5 which shows the position of the TRL 'ladder' typically supported by collaborative R&D (e.g. TSB). In addition, the mechanisms synthesised from the case studies and the author's own experience (c.f. Table 2), are mapped onto the TRL framework. A spin-out/start-up will typically follow collaborative R&D projects and are very often cited in grant applications as one of the key exploitation methods.

This shows that the entire TRL framework is supported, in part or full, by UK government, although securing funding at each stage is a competitive process. In the context of engineering, one of the most important interfaces is that between fundamental research (EPSRC) and collaborative R&D (TSB) which has been considerably enhanced since 2010 with initiatives such as the Manufacturing Futures[6] challenge theme and targeted research calls such as manufacturing fellows that work within the UK's "Catapult" (TSBc 2013). The UK's HVM Catapult is again funded largely by the UK government through the TSB. It currently comprises seven Catapults in the areas of High value manufacturing; Cell therapy; Offshore renewable energy; Satellite applications; Connected digital economy; Future cities; and Transport systems. Each Catapult is a physical centre where the very best of the UK's businesses, scientists and engineers work side by side on late-stage research and development—transforming "high potential" ideas into new products and services to generate economic growth. The Catapult network represents over £1bn of investment.

[6]"Manufacturing the Future" is a research theme for the Engineering and Physical Sciences Research Council (EPSRC) and sponsors researchers and research institutions to help solve some of the most serious challenges facing the UK today and in the future.

5.2 Challenges for Design Research

Based on the author's experiences from the process of synthesising, selecting and developing case studies for REF and 15 years' experience as a researcher in the engineering design field, a number of challenges for design research are now proposed.

i. **Studying 'what is' rather than 'what should be' is limiting**. Much design research is centred on understanding current practice which is very often more interpretive (descriptive) and less likely to be prescriptive unless it seeks to optimise the current. Thus there is very often little or no industrial impact, although there might be significant academic impact arising from the work. Furthermore, in many cases it may be difficult to acquire data from practitioners and all but impossible to test new ideas other than with trainee engineers such as students. These factors will again limit impact.

ii. **Lack of verification of practice-led research**. In general, much design research concerns practice rather than product-led research and while some new tools/methods are applied in industrial studies these are very often selected only for the purpose of demonstrating the principles of the new approach rather than realising an improvement in an industrial context. In addition, impact is less obvious with much of the process/practice-led research, unless benchmarking studies are completed pre- and post-intervention as is commonly done in manufacturing research (see vii).

iii. **Balancing generality and specificity.** Where impact has been realised through design research it is very often the case that the tool/method/approach has been developed for a particular domain. This focussing of a method/approach is necessary to contextualise a tool, and increase/reveal utility and usability for engineers. In contrast, the higher level more abstract theories, while more generalisable, may offer little utility in their application to a particular class of problem unless they are customised (tailored) or fully developed for that class of problem.

iv. **Proliferation of tools/approaches**. For reasons stated in the introduction to this chapter, almost all engineering research can be considered to have been undertaken with the aim of influencing design practice and products. As a consequence, there exists a proliferation of tools/approaches. Further, the drive to increase number of publications encourages the continual creation of new/modified tools/methods. The consequence of this is that there is a focus on new tools/methods rather than improving existing ones. The latter of which necessarily demands application in an industrial context which would be more likely to increase impact. Thus, many tools/methods have had apparently little or no impact or at least the research team is unaware of any impact.

v. **Practice and training**. While product-led research is directly relevant to engineering teams, process-led is more closely aligned to Continuing Professional Development (CPD) and training activities of companies. As such there is a need to engage engineering organisations and relevant departments in these activities. This demands that the research output/findings be explicitly packaged as an industrial training course or similar. One way to achieve this is to partner engineering service providers, trade bodies, professional institutions and advisory groups that can both disseminate and co-deliver courses. This may require significant additional resources beyond the core research funding itself.

vi. **Integrated funding**. While the UK has a complementary range of funding mechanisms across the technology readiness levels, the drive to deliver impact and the extensive involvement of manufacturers in projects and the advisory boards of government funding agencies means that the technology-centric research, which is of direct relevance to the products of the manufacturers is generally favoured. This poses a challenge for design researchers attempting to secure funding for process-centred research.

vii. **Benchmarking and performance measurement**. As previously noted, in the production field the drive for competitiveness (process improvement) which followed productivity (automation) have given rise to methods and measures for benchmarking production systems, e.g. Overall Equipment Effectiveness, productivity and reliability (Hicks, 2012). These measures enable the impact of interventions to be more objectively evaluated. Such measures are more complex in the design field and a generalisable and universally accepted set has yet to be developed.

6 Conclusion

This chapter has considered the pathways to realising impact from engineering (engineering design) research. In order to explore the pathways, 22 case studies have been examined. The case studies were prepared by two of the UK's leading Mechanical Engineering Departments for the Research Excellence Framework (REF) 2014 assessment. The cases report impact occurring between 2008 and 2013 that has arisen from specific research findings/output over the period 1993–2013. The background to the REF assessment and the format of the case studies has been described and an overview of the dataset given. The cases were classified and grouped according to the dimensions of impact, sector, timescale and core mechanisms employed. This suggested five emergent relations:

1. There is a greater focus on new/improved products rather than process improvement.
2. Product-led research gives rise to greater international impact and hence reach.
3. Process-led research is generally restricted to more national/local impact.
4. The most common mechanisms for achieving impact are Technology Strategy Board (TSB) funding, Knowledge Transfer Partnerships and consultancy activities.

5. Spin-outs are the key mechanism for product-led impact while consultancy is the key mechanism for tool/method-led impact.

The data was also analysed for patterns or trends which gave rise to three insights:

i. All the stated impacts concern economic gains.
ii. Research undertaken within 5 years of the period of impact (2008–2013) has a magnitude of impact that is equal to or greater than research undertaken 10 years or even 15 years prior to the period of impact.
iii. Product-led impact and research generally has a more significant measured economic impact in the timescale considered than process-led research.

Further consideration of the case studies and the results was undertaken to elicit more general insights for realising impact from design process research. This revealed seven challenges concerning: the limitations of studying 'what is' rather than 'what should be'; the general lack of verification of practice-led research; the difficulty of balancing generality and specificity; the proliferation of tools/approaches; the need to directly support practice and training; the need for integrated funding and the need for benchmarking and performance measurement.

The analysis also highlighted the importance of access to government/collaborative funding (government and industry) across the technology readiness levels, and in particular, TRLs 1–6 and at the interface of the valley of death which occurs at the transition between TRL 3/4–5/6. The central role of the UK's government-funded initiatives such as the Knowledge Transfer Partnership and Catapult Centres are also highlighted in terms of bridging the valley as well as, in the case of the Catapult, providing the mechanisms for accelerating the creation of communities of practice in emerging high-tech areas such as Stem Cells and Composites.

The limitations of the study were also highlighted and include the relatively small sample size, the timescale, and the implicit approach/form of measuring and reporting impact associated with the UK's Research Excellence Framework.

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Results From the Breakout Sessions of Group A

Luciënne Blessing, Alessandro Baldussu, Gaetano Casini, Georgi V. Gerogiev, Jöran Grieb, Josef Ponn, Maik Maurer and Ralf Stetter

Guidelines for successful transition of design research results into practice based on the experiences of the participants.

Relationships: During the research phase acknowledge and include experience and knowledge of practitioners. Distinguish between industry customers and industry partners. Plan the application of research outcomes in practice as a joint activity of researchers and practitioners. Take time to build up trust and sustainable relationships and include confidentiality issues (it is the long-term relationships that at the end bear fruits). Quick fixes do not exist: research results that have been successfully transferred are built on years of research and collaboration involving various researchers. Learn from other research institutions, whose focus is on research in collaboration with industry.

Benefits: Show the practical value: the benefits of using the results should be larger than the required resources. Research results should not be too complicated or at least not seem to be complicated for the practitioner. Consider different types of benefit: resources, sales, risk reduction, politics, etc. For the first transition, convince practice about the expected benefits: build on relationships (it is all about

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belief), include the company's other products into the story, focus on the innovation and not on the method, realize that newness of research results is less important for practice than the practical value they bring. Use successful transfers to convince.

Research: Choose hot problems as case studies, and not trivial ones to simplify the task. Reduce the unnecessary variety of research results: industry is interested in contributions, many research results differ too little. Undertake research into measuring impact and results. Start publications with the main message to be of interest for practitioners, with a one page executive summary for industry, write "in the most non-bothering way", and allow practitioners to compare the results with other results. Establish a "normalization" of results to support comparison.

Results: Include a sequence of actions to be taken (max. 4 steps), make use of industrial buzz words (not academic ones), address a hot industrial problem, focus on a clearly underdeveloped aspect (which should be made visible), aim at broad applicability. Do not make the description too generic but convince by providing concrete examples and use cases and by filling any framework with content. Develop a flexible method/tool to allow customization and interpretation by the company. Make it fun to use, only as complex as needed, and as simple as possible. Consider modern technologies, e.g. apps, as medium.

Transfer: Consider implementation processes: e.g., 1. create the right mindset (making it or linking to their problem/need); 2. introduce the support (guidelines, rules, templates, procedures); 3. introduce the related IT tools. Choose a stepwise integration strategy.

Platforms needed for supporting ongoing interactions between academia and practice for carrying out academically worthwhile yet practically relevant research.

Collaboration forms: Collaboration to transfer ideas and solutions into practice can be at different levels and of different duration. At organizational level: Centres of Competence (see, e.g. Cascini in this book) where academic and industrial partners can meet, or framework agreements between specific academic institutions and industrial organizations. At project level: joint research projects, PhD/Master/Bachelor projects. Industrial PhDs can provide a particularly strong link. At topic level: working groups to enhance the dialogue between academia and practice, or between practitioners with academics as moderators. At individual level: mentoring of academics by practitioners, exchange through secondments and stays of academics in practice or of practitioners in academia, employment of graduates in industry.

Training/Certification: Research results can be transferred through workshops like this IDRP workshop, but also through summer schools for practitioners or lifelong learning programs. Participation of practitioners in workshops/conferences organized by academics could be increased by: clearly showing the benefits for the practitioners, having a central organization accrediting workshops (e.g. through evaluation), providing certificates of participation, linking to existing events for practice (e.g. fairs) and asking for a proper fee.

Presentation skills: Training to explain one's research in a few words, and for a non-academic audience can help transfer results or raise interest for their topic. Media training can also be useful.

Sustainability: Ongoing interaction requires considering long-term interests. Sustainable relationships require a practitioner as contact person, who is interested and has experience in the topic of research, and who is specifically assigned to support exchange (and not as additional task). Researchers need access to the company's practices to obtain the necessary insight. This takes time but will improve the transfer of results. The above centres of competence can also play a role in sustainable relationships.

Funding: Governments, the European Commission and national funding agencies increasingly provide initiatives to stimulate collaboration. Continuity of funding is required. Competence Centres need business models and funding. Industry may directly fund research, but this depends on country and may hamper independence.

Visibility: Academia needs to show what is on offer: overviews of who is working on which topic and what the results are, i.e. catalogue of academic "method/tool suppliers", or a method roadshow (like suppliers do), or a "fun to read" journal.

Knowledge base: Researchers can benefit of an overview of the types of practice problems that exist (using a stringent classification of problems), and of a database with industry cases to support benchmarking. This will help to speak the language of practice and target the research.

Benchmarks/standards: The creation of standards and structures in the field of design research can make the research more tangible. Workshops are proposed: (i) to develop across-product process benchmarks amongst practitioners and moderated by academia; (ii) to develop benchmarks comparing academia and moderated by practitioners; (iii) to consolidate our field.

Role of consultancies: Consultancies can be proactively included in the dialogue with practitioners: they have insight in a multitude of companies, can act as brokers and may fill the gap between academia and practice (they will do so, whether we want it or not).

After-transfer support: When results are implemented and rolled-out continuous support is required (e.g. a hotline). Academia is not geared for after-sales support, which makes the offer unattractive. A third party, e.g. a competence centre, is required.

Results From the Breakout Sessions of Group B

Chris McMahon, Niccolò Becattini, Amaresh Chakrabarti, Udo Lindemann, Benoit Weil, Burkhard Wolf and Kris Wood

Based on the experience of the participants, what guidelines can be formulated for successful transition of design research into practice?

Understanding the method user The discussion on the translation of design research to practice concentrated largely on development of new design methods. In this context it is very important for the design researcher to understand the needs and aspirations of the user or potential user of a method. For some designers the very idea of using a method is anathema, others may have little knowledge of formal methods (and perhaps think that methods are not important to them) but nevertheless they may work in a very systematic fashion and apply their own methods. Many designers may seek methods to make their lives easier: for these ease of use of the methods may be paramount (and we should always be conscious that method use may become intrusive). Nevertheless, designers should nevertheless be challenged to come out of their comfort zones: methods may allow them to be more radical.

Understanding the context There is no "one-size fits all" design method. Different contexts require different methods. Even in the same industry, companies

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that have different histories will produce the same type of artefact with different processes and methodologies. It is thus important to understand the full socio-technical context in which methods (and indeed tools and processes) are to be applied. The needs, motivations and roles of all of the stakeholders in a design process—from different members of the design team to company directors—need to be understood. The historical and application contexts of the work also need to be understood, including the political, economic and financial as well as the engineering contexts. It is important to establish this context through discussion with potential users of a research team's methods. Often a 'champion' in a company will be helpful to aid such discussion. More broadly, through understanding context, researchers and students of design can develop a world view of the design activity that will help them in their interpretation of their research results and what they learn from their design activities.

The need for a common language A common language is needed to support discussion on theory, process, method, model and organisation. Especially, the difference between methods, methodology, processes and tools needs to be understood. Industry develops processes, often over many years, and needs to feel that the processes are 'owned'. Process will depend very much on the socio-technical context (see above). While industry is sometimes not so overtly interested in methods, most industries are very interested in tools, and spend a good deal of money and effort purchasing, adopting and adapting tools such as computer-aided design (CAD), product lifecycle management (PLM) and so on.

The importance of support Researchers should support method users in various ways: they should provide examples and illustrations of how methods can assist; they should design with companies rather than simply handing methods over; they should support designers in their use of methods, especially when it encourages them to think in different ways.

The need for reflective practice Designers and students of design should be encouraged to be reflective practitioners—to reflect on the success of the methods that they use, and on the match of the methods and tools to the context in which they are being applied. It was noted, however, that it may be difficult to be reflective when working in a large team. The need for reflection extends from individuals to groups and companies. Research needs feedback from application, in all its forms, on what works well and what does not.

Confidentiality and intellectual property Design is mainly carried out in industry for commercial benefit. This has two important consequences. First, most design knowledge is not in the public domain: it is only partly accessible to researchers or to students. Second, companies today are very sensitive to the possibility of leaking or losing their intellectual property (although in practice secrecy may be very difficult to achieve in complex projects). This poses all sorts of restrictions on the conduct of design activities, and potential barriers to the development of new ideas.

Research should think long-term and should challenge the status quo Many companies are strongly motivated to seek short-term improvements, and to use methods and tools that support such objectives. While design research can and should support this, it is important for research to think long-term, to seek radical solutions and to challenge conventional wisdom, especially in view of the societal challenges faced today.

What kind of platform is needed for supporting on-going interactions between academia and practice for carrying out academically worthwhile yet practically relevant research?

A common platform A common platform can be achieved in many ways. The ‘training model’ was considered a good one, in which a company’s design staff learn new approaches and methods with an academic team via training exercises. Other approaches reported included co-location—locating a company’s designers at the academic institution (with design being done in partnership), ‘beacon projects’ between small and medium-sized enterprises in a region and one or two universities, and larger cluster projects joining a number of companies and academic institutions. The use of open innovation/social networking/open source is developing very rapidly just now, and the competition model is also considered a good one. In design learning, massive open on-line courses (MOOCs) can be used for knowledge transfer, but mechanisms are needed for experimentation and practice, for example supported by ‘maker groups’ with prototyping facilities. The common platform is most fruitful when a company is convinced that an outside view would help. C-K theory may point to the sort of exercises that are suitable for the platform: for example, design involving a lot of company-specific knowledge (i.e. working in the K-space) is not likely to be appropriate. Exercises involving new knowledge may well be, and exercises largely in the concept (C) space are most appropriate to open innovation approaches.

Approaches to studying design A number of different approaches to interaction were considered. It was noted that ‘management researchers’ widely use the approach of observing and interpreting—studying practice and observing what works well and what less so—and this can be powerful in a design context, especially when studying design processes in an industrial context. But design research can also be more active, for example when new methods are developed and experiments are done to explore how successful these are in practice. Examples in this latter case include the development of computer-aided design (CAD). It was noted that historically new design tools and methods have been developed in order to address the challenges of each age—for example multi-view drawing allowing teams to work on the design of ships in the 17th century, detail drawing allowing interchangeable parts in the 19th century, CAD allowing complex faired shapes in the 20th century and so on. The design of complex systems is a challenge today that needs the development of new techniques.

Confidentiality, IPR and contracts With regard to sharing of intellectual property rights (IPR), there was some enthusiasm expressed for giving it away (or perhaps allowing the industrial partner free use in their own business context, with the academic partner allowed to use it in others). Other contract models included differential pricing according to who retains the IPR. In all cases, in order for a common platform to succeed it is important that issues of confidentiality are resolved, and it is also essential that the academic partner has rights to publish (there was no enthusiasm expressed for modes of operation without publication). It is also important that an atmosphere of mutual trust is developed between the partners in the activity and that it is understood that research does not guarantee results. A lot of research will come to nothing: there must be an opportunity for exploration, experiment and play. Researchers are not suppliers. Industry is a partner and also a consumer.

Culture It is important always to bear in mind cultural differences among the participants. Academia is novelty-driven; industry is value-driven. Different companies, even in the same industry, can have very different cultures, and of course there are big differences between countries.

Part II
Experience from Academia

Impacts of Function-Related Research on Education and Industry

Ryan M. Arlitt, Robert B. Stone and Irem Y. Tumer

Abstract Designers have long understood that a device must function well in order to satisfy its users, but only relatively recently has function been studied formally and extensively. The corresponding function-based paradigm focuses on abstracting what a system *does* separately from what it *is*. Within this paradigm, it is important to communicate abstract functions in a consistent manner, without binding them to their embodiments. This chapter discusses two recent outcomes in function-based design research, their impacts on education and industry, and the authors' observations regarding their adoption into practice. The first of these outcomes is an information schema for capturing design artifact knowledge, which includes a standardized function taxonomy. The information schema provides guidance for teaching functional thinking, and also supports basic computational design techniques during conceptual design. The second research outcome is a conceptual linking between functions and failure modes, enabling new types of failure analysis techniques in early design. Both research outcomes are likely still in the early stages of impacting practice, but evidence points toward the most immediate impacts occurring during education. While the industry is typically more reserved regarding the details of their design practices, the chapter also presents several instances of practical interest in function-based design approaches.

1 Historical Context

The Internet boom of the 1990s improved the feasibility of engineering partnerships across large distances. As a result, designing of complex engineering systems became an increasingly collaborative task among designers or design teams that were physically, geographically, and temporally distributed. The complexity of these products meant that a single designer or design team could no longer manage

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the complete product development effort. Additionally, developing products without sufficient expertise in a broad set of disciplines resulted in extended product development cycles, higher development costs, and quality problems. This shift toward increasingly knowledge-intensive and collaborative design increased the importance of computational design frameworks to support the representation and use of general knowledge among distributed designers (Ullman 1997).

Around this time, Product Data Management (PDM) systems hit their stride as an effective way to manage engineering data, such as computer-aided design (CAD) drawings. By organizing product component data, PDM systems improved communication, shortened production times, and reduced costs. However, designers were no longer merely exchanging geometric data (as supported by these PDM systems), but more general knowledge about design and design process, including specifications, design rules, constraints, rationale, etc. As such, merely providing access to schematics and CAD models was no longer sufficient. In order to support reuse of engineering knowledge, a representation was needed to convey additional information that answers not only "what?" questions about a design, but also "how?" and "why?" questions. Mappings from form to function had often been pointed to as an example of the kind of information that is needed for effective reuse of design knowledge, but were absent from traditional CAD models.

Early attempts at cataloging function were not entirely suitable for design repositories, being either extremely domain specific or extremely general. For example, Collins et al. (1976) developed a helicopter-specific list of 105 unique mechanical functions to accurately archive helicopter failure information. This approach is useful for cataloging and retrieving helicopter failure information, but is not generalizable to other types of systems. More generally, Pahl and Beitz (1984) provide a highly abstracted vocabulary containing five functions and three flows (function operands), and Hundal (1990) develops six abstract function classes, each containing more specific functions. The Theory of Inventive Problem Solving (TIPS or TRIZ), published by Altshuller (1984), describes all mechanical design with a set of 30 functions. TRIZ was developed through a survey of over 2 million patents, pointing to a high level of validity. Malmqvist et al. (1996) noted that the TRIZ vocabulary would benefit from a structured function hierarchy using the Pahl and Beitz functions. A further review of function classification at the time can be found in Hubka and Eder (1984).

To address the functional issues in PDM systems, the National Institute of Standards and Technology (NIST) held a workshop to identify basic research and industry needs for their Design Repository Project. This emerging research area of design repositories was aimed at making use of research in knowledge-based design to facilitate the representation, capture, sharing, and reuse (search and retrieval) of corporate design knowledge (Szykman et al. 1996). Importantly, while there was widespread use of functional decomposition at this time, there was no standard language for describing function (Szykman et al. 1996). Within such decompositions, whether for function or architecture, no standard existed concerning levels of abstraction. Specific needs identified at the workshop included: (1) a need for representation of function in CAD, in addition to geometry, (2) a need for a fixed representation scheme for modeling function, (3) a need for a commonly agreed set of functions performed by mechanical systems, and (4) a need for representations that are both human-interpretable and machine-interpretable (Szykman et al. 1996). To meet these needs, a collaborative research effort between NIST and academia was formulated to investigate the underlying framework for creating design repositories, including representation of design function, product architectures, and form; and notably lead to the development of a design repository data schema containing generalized function and component abstractions.

The remainder of this chapter will discuss two related research outcomes. The first is the aforementioned design repository information schema designed to address the needs identified by NIST, and the second is a relationship between functions and system failures. Each outcome is summarized, and followed by a discussion of their impacts in practice.

2 Research Outcome: A Design Repository Information Schema

The first research outcome, an information schema for describing artifacts in a design repository system, was formulated to enable designers to store and retrieve design knowledge at various levels of abstraction, from form (components, sub-assemblies, and assemblies) to architecture description to function. The different levels of abstraction provide innovative ways to approach design. This information schema includes a function description language called The Functional Basis, a taxonomy of electromechanical components, and basic matrix representations that afford computational concept generation.

2.1 The Functional Basis

A systematic approach to functional modeling (e.g. Ullman 1997; Pahl and Beitz 1984; Hubka and Ernst Eder 1984) generally has the designer decomposing a product's overall function into subfunctions until each subfunction is small and easily solved. Unfortunately, knowing when a function is *small and easily solved* can be quite ambiguous. As such, one of the key issues motivating the development of a consistent functional vocabulary was to provide guidance on when to stop decomposition. General function vocabularies (e.g. Pahl and Beitz 1984; Hundal 1990; Altshuller 1984), while applicable to a wide variety of domains, lack the detail to provide guidance on decomposition depth. In contrast, domain-specific function taxonomies (like Collins' helicopter-specific taxonomy (Collins et al. 1976)) are not useful outside of their fields.

The NIST Function Taxonomy and the Functional Basis were separate parallel efforts undertaken to address this disconnect between function abstraction layers. Both projects sought to create a general function taxonomy with high validity by unifying past research. To support this goal, the taxonomies were unified into a single reconciled Functional Basis (Tables 1, 2). The reconciled Functional Basis represents a general standard function taxonomy that describes the electromechanical design space at multiple levels of abstraction. This reconciled Functional Basis contains a set of functions (action verbs) and flows (nouns), to be used together as verb-noun pairs in a functional model. The function and flow sets both provide three levels of decomposition guidance. These levels are called primary, secondary, and tertiary; and they correspond to the level's degree of abstraction. A fourth column called *correspondents* offers synonyms to define and contextualize each function and flow. *Italicized correspondents* occur in multiple functions, indicating slightly different usages or senses of the word.

In forward design, a designer can use the Functional Basis to iteratively decompose a functional model from a single black box function. To maximize form-independence and promote a wide search of the solution space, the first iteration is generally performed at the primary level. Subsequent iterations contain increasingly specific functions at the secondary and tertiary levels, until the designer shifts to component selection or domain-specific terminology. In general, decomposition to the secondary level is a good target due to its high information content (Sen et al. 2010). In reverse engineering, the Functional Basis offers a way to consistently catalog products based on functions performed by those products, subassemblies, components, etc.

For example, a vise grip (Fig. 1) can be described with the black box model in Fig. 2. The black box model captures incoming and outgoing material, energy, and signal flows. Here, the vise grip's overall function is to *secure material*. *Mechanical* energy, *Hand* and *Object* materials, and a *Not Clamped* signal flow into the system. The same flows also exit the system after operation, except the system visually signals that the object is now *Clamped*. The functional model in Fig. 3 provides a higher resolution functional view of the same system using Functional Basis terminology. As with natural language functional models, there are multiple correct ways to describe the system's function (e.g. the signal flow could be treated differently or omitted entirely), but the standard terminology enables meaningful comparison between multiple models.

Several studies point to high validity of the Functional Basis. On grounds of theoretical validity, the Functional Basis is built upon extensive past work, subsuming the function taxonomies of Pahl and Beitz, Hundal, and Altshuller, as shown in Fig. 4. More pragmatically, a study by Ahmed and Wallace (2003) found that 90 % of the functions described by a group of practicing aerospace engineering designers could be described by the Functional Basis, with two thirds of those function descriptions matching a Functional Basis term exactly. This study suggests that the Functional Basis has good validity in an industry engineering design context. Further, a study by Kurfman et al. (2003) found that a directed approach to functional model creation using functional basis terminology produced more

Table 1 Functional basis flows (Hirtz et al. 2002)

Class (Primary)	Secondary	Tertiary	Correspondents
Material	Human		Hand, foot, head
	Gas		Homogeneous
	Liquid		Incompressible, compressible, homogeneous,
	Solid	Object	Rigid-body, elastic-body, widget
		Particulate	
		Composite	
	Plasma		
	Mixture	Gas–gas	
		Liquid–liquid	
		Solid–solid	Aggregate
		Solid–Liquid	
		Liquid–Gas	
		Solid–Gas	
		Solid–Liquid–Gas	
		Colloidal	Aerosol
Signal	Status	Auditory	Tone, word
		Olfactory	
		Tactile	Temperature, pressure, roughness
		Taste	
	Control	Visual	Position, displacement
		Analog	Oscillatory
		Discrete	Binary
Energy	Human		
	Acoustic		
	Biological		
	Chemical		
	Electrical		
	Electromagnetic	Optical	
		Solar	
	Hydraulic		
	Magnetic		
	Mechanical	Rotational	
		Translational	
	Pneumatic		
	Radioactive/Nuclear		
	Thermal		

Overall increasing degree of specification →

Table 2 Functional basis functions (Hirtz et al. 2002)

Class (Primary)	Secondary	Tertiary	Correspondents
Branch	Separate	Divide	Isolate, sever, disjoin
			Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, *allow*, input, *capture*
	Export		Dispose, eject, *emit*, empty, *remove*, destroy, eliminate
	Transfer	Transport	Carry, deliver
			Advance, lift, move
		Transmit	Conduct, convey
			Direct, shift, steer, straighten, switch
	Guide	Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	*Constrain*, unfasten, unlock
Connect	Couple	Join	Associate, connect
			Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack
Control	Actuate		Enable, initiate, start, turn-on
Magnitude	Regulate	Increase	Control, equalize, limit, maintain
			Allow, open
		Decrease	Close, delay, interrupt
	Change	Increment	Adjust, modulate, *clear*, demodulate, invert, normalize, rectify, reset, scale, vary, modify
			Amplify, enhance, magnify, multiply
		Decrement	Attenuate, dampen, reduce
		Shape	Compact, compress, crush, pierce, deform, form
		Condition	Prepare, adapt, treat
	Stop	Prevent	End, halt, pause, interrupt, restrain
			Disable, turn-off
		Inhibit	Shield, insulate, protect, resist
Convert	Convert		Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, *process*, solidify, transform
Provision	Store	Contain	Accumulate
			Capture, enclose
	Supply	Collect	Absorb, consume, fill, reserve
			Provide, replenish, retrieve
Signal	Sense	Detect	Feel, determine

(continued)

Table 2 (continued)

Class (Primary)	Secondary	Tertiary	Correspondents
			Discern, perceive, recognize
		Measure	Identify, *locate*
	Indicate	Track	Announce, show, denote, record, register
			Mark, time
		Display	*Emit*, expose, select
	Process		Compare, calculate, check
Support	Stabilize		Steady
	Secure		*Constrain*, hold, place, fix
	Position		Align, *locate*, orient

Overall increasing degree of specification →

Fig. 1 Vise grip

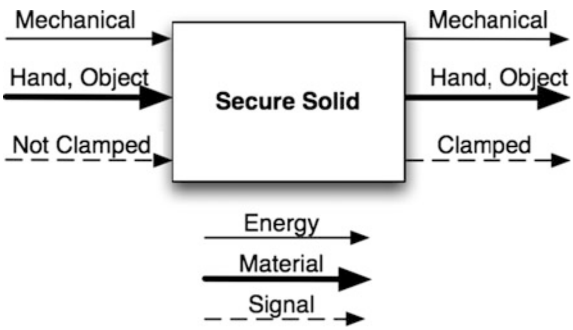

Fig. 2 Vise grip black box model

uniform functional models than an undirected approach. Finally, an information-theoretic study of the Functional Basis demonstrates that the information content of function terms increases from primary to secondary levels, while the jump from secondary to tertiary provides marginal benefits (Sen et al. 2010).

This function terminology is the first of several standard vocabularies and representations that are embodied in a design repository. Combined with these other

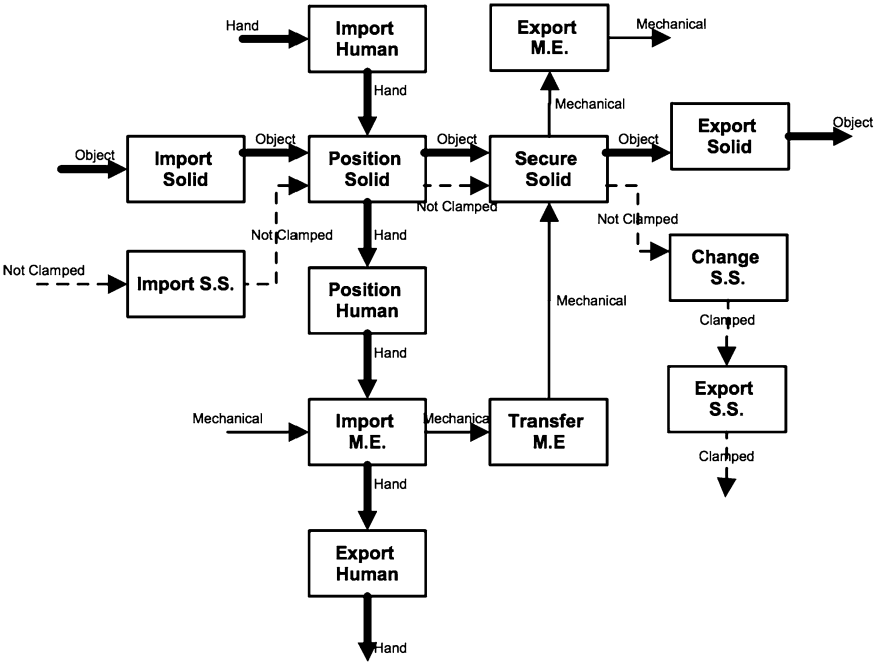

Fig. 3 Vise grip functional model

standard vocabularies, the Functional Basis facilitates forward design activities including automated concept generation and early detection of potential failure modes.

2.2 The Component Taxonomy

Similarly to the Functional Basis, the electromechanical component taxonomy provides abstract categories for components in order to support a consistent knowledge vocabulary. General component terms are accompanied by synonyms and definitions, and are organized according to the functions that the components generally perform (Table 3). As was the case with function, this taxonomy was formulated with the goals of standardizing electromechanical component terminology and enabling automated design tools (Kurtoglu et al. 2005), while being as complete and exclusive (i.e. low redundancy between terms) as possible. Because components are more concrete than functions, the component taxonomy is easier to use as a framework for domain-specific adaptation. Unlike function, technological progress results in new types of components. As a consequence, a general

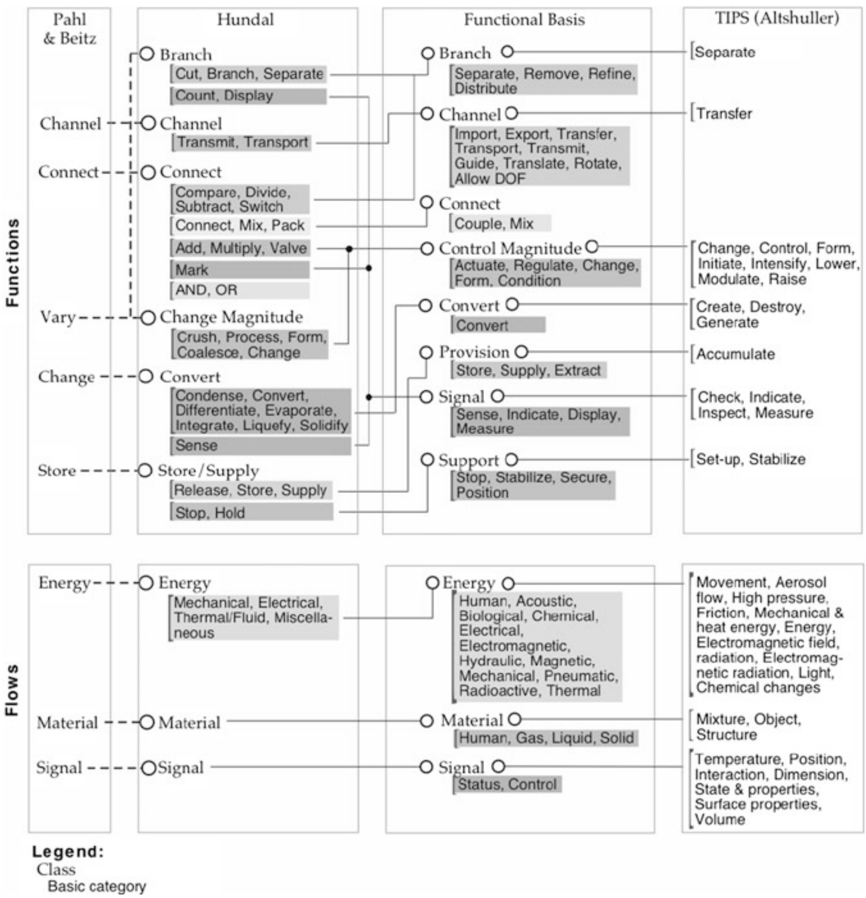

Fig. 4 The functional basis compared to other function taxonomies (Stone and Wood 2000)

classification of components can always be updated, but the vast majority of components in the taxonomy form a stable core capable of describing most products.

2.3 *Matrix Representations*

Given these consistent abstractions for functions and components, several types of matrix representations are possible. These matrices reveal interesting similarities (functions) between apparently dissimilar physical solutions, and enable automated design tools. The matrix representations support simple mechanisms for propagating abstract functions forward into more physical domains.

Table 3 Component Taxonomy Excerpt

Primary component classification	Secondary component classification	Component term	Component subset	Synonyms	Definition
Branchers	Separators	…			
	Distributors	…			
Channelers	Importers/exporters	…			
	Transferors	Carousel			A device used to move material in a continuous circular path
		Conveyor			A device used to move material in a linear path
		Electric conductor		*lead*	A device used to transmit electrical energy from one component to another
			Electric wire		An electric conductor in the form of a thin, flexible thread or rod
			Electric plate		An electric conductor in the form of a thin, flat sheet or strip
		Electric Socket			A device in the form of a receptacle that transmits electrical energy via a detachable connection with an electric plug
		Electric Plug			A device in the form of a plug that transmits electrical energy via a detachable connection with an electric socket
		Belt		*strap, girdle, band, restraint*	A device shaped as an endless loop of flexible material between two rotating shafts or pulleys used to transmit mechanical energy
		…			
	Guiders	Hinge		*pivot, axis, pin,*	A device that allows rigidly

(continued)

Table 3 (continued)

Primary component classification	Secondary component classification	Component term	Component subset	Synonyms	Definition
				hold down, jam, post, peg, dowel	connected materials to rotate relative to each other about an axis, such as the revolution of a lid, valve, gate or door, etc.
		Diode			A semiconductor device which allows current to flow in only one direction
		…			
Connectors	Couplers				
	Mixers				
…	…	…			

The first of these, called the Function Component Matrix (FCM), relates a product's subfunctions to the components that perform those functions. One axis lists functions, and the other axis lists components. Each matrix cell contains an integer representing the number of times a component has solved a given function, and FCMs can be created for an individual product or a set of products. Individual product FCMs can be combined via matrix addition. Consistent FCMs are made possible by the standardized terminologies of the Functional Basis and Component Taxonomy.

The Design Structure Matrix (DSM) catalogs the internal physical connectivity of a design. Several types of DSM exist, but a simple variety catalogs binary yes/no connections between components in a system. Both axes in this 2D matrix contain a row/column for each component, allowing pairwise comparisons between every pair of components in a system. A DSM can represent connections between specific individual artifacts inside a product or connections between components. Again, the standardized component terminology enables meaningful comparison and combination of separate DSMs.

Broadly, these representations enable tools that provide guidance from general abstract function description to domain-specific component selection. For instance, after aggregating a large number of FCMs representing historical product data, a designer can query the matrix for the desired functions to generate a large number of potential component solution candidates. These solution candidates take the form of morphological matrices wherein multiple potential solutions are given for each subfunction. This enables designers without expert knowledge to examine alternatives that they may not have otherwise considered.

2.4 Impacts of Design Repository Information Schema

The initial driver behind much of this work was to enable design repositories, and many of these results are appropriately embodied in a design repository (hereafter referred to as "The Design Repository"). The Design Repository represents an influential research outcome in that it broadly demonstrates the value of capturing and reusing product knowledge according its function. These vocabularies and techniques are used to capture knowledge about (at the time of writing) 184 reverse engineered electromechanical products. Products in the repository are decomposed to multiple levels of abstraction, including function data for components, subassemblies, and assemblies. Key artifact information, including function and component data, is stored using standard vocabulary. Figure 5 shows a typical artifact entry in The Design Repository. The rotation plate in the figure is a *housing* component in the Dyson Air Multiplier system, and it performs the function *transfer mechanical energy* from the *base motor* artifact to the *base* artifact.

Using The Design Repository, designers can store and retrieve design knowledge at these various abstraction levels, providing innovative ways to approach design. However, in addition to supporting a repository of design knowledge, the repository information schema has also had less tangible (but no less significant) impacts in both education and industry.

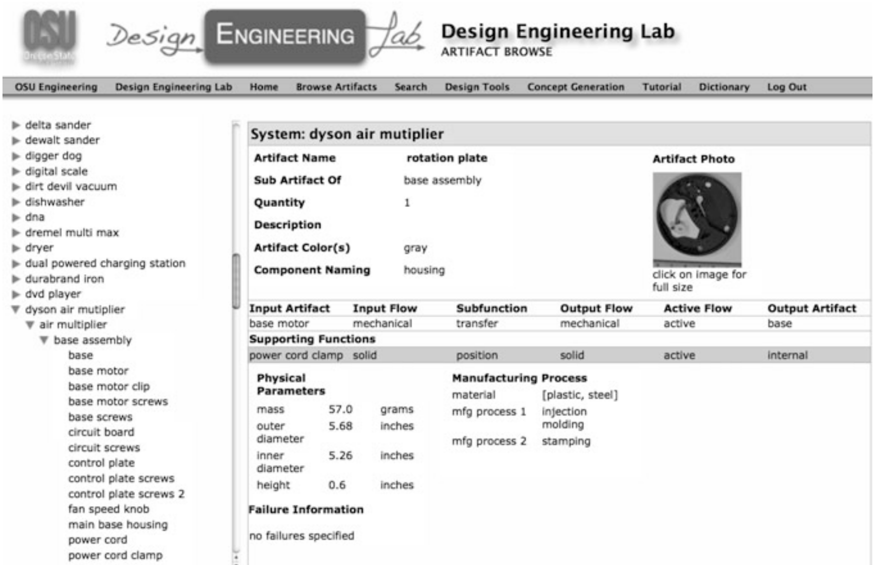

Fig. 5 Rotation plate artifact in the design repository

3 Education Impacts

To date, dozens of medium and large engineering schools in the U.S. introduce functional modeling in their undergraduate and graduate curriculum and use the Functional Basis as a language for expressing functionality. Owing to its small vocabulary, the Functional Basis guides students around common pitfalls associated with learning to create functional models. Some common pitfalls include references to specific components or forms, modeling the product as a flow through itself, or violating verb-object norms. Invalid functions (e.g. function descriptions that imply an embodiment) are more difficult to express when using Functional Basis terminology as opposed to natural language, which leads students to identify more product subfunctions (Kurfman et al. 2000) and increases repeatability in functional model creation (Kurfman et al. 2003). For instance, the function-flow format of the Functional Basis encourages verb-object function descriptions (e.g. "rotate" becomes "transfer rotational energy"), and solution-centric function descriptions must be reconsidered to exclude references to form (e.g. "unlatch spring" becomes "actuate mechanical energy").

In a separate but related effort, the Biomimicry 3.8 Institute has recognized function as valuable tool for organizing biological strategies in their AskNature database, which is used in classrooms around the world to teach and promote biologically inspired design (BID). The group has developed a biology-specific function taxonomy in order to help designers easily answer the question "How would nature do X?" Easily interpretable function categories in this taxonomy are the key to supporting the search process.

While the design repository research discussed prior did not directly influence these efforts, they illustrate an important parallel. The topic of biologically inspired design is widely studied in universities, but its application in practice remains limited. A series of BID workshops have brought together a community of researchers in order to address this issue by investigating ways to facilitate BID in a practical context. Function-based taxonomies represent a promising framework for mining and cataloging biological strategies, as seen in AskNature, to increase the ease of applying BID techniques. Progress in this area is still early, but several industry representatives have expressed interest in the outcomes of these workshops. More generally, such workshops may serve the dual roles of addressing research challenges and gaining critical industry support.

4 Industry Impacts

In industrial practice, Ford Motor Company participated in efforts to utilize the functional basis in its design efforts dating back to the late 1990s and early 2000s. A new program in Design for Six Sigma uses the functional basis as a method of developing critical and repeatable "transfer functions" to create robust designs.

Informal reports indicate that functional modeling has been received with great enthusiasm, and the results show that the functional basis can model the large-scale systems developed by Ford.

Also in the automotive industry, General Motors engaged in research related to functional recall of prior components for reuse in their advanced design teams in the 2000s (Nagel et al. 2008). One area of interest included using function as a way to link customer need statements to appropriate vehicle-related performance metrics that supported both Design for Six Sigma and requirements flowdown activities. The Functional Basis was presented to GM employees and utilized for these activities.

In a case of practical research application in an academic setting, a method for generating behavior models from functional models was applied to a Formula SAE car. This function-based behavioral modeling method (Hutcheson et al. 2007) contains the steps (1) functional modeling, (2) state identification, (3) behavioral model element identification, (4) model solution, and (5) model iteration; and allows a designer to simulate system performance based on a functional model and the historical connectivity between functions and behavior equations. A full-vehicle dynamic simulation model of a Formula SAE car was created, providing a test and evaluation platform for the team to inform vehicle tire selection (Hutcheson et al. 2008).

A project sponsored by the National Center for Defense Robotics extends functional modeling techniques to model product and process together (Nagel et al. 2006). The technique was used to model two vehicle decontamination processes: (1) the United States Army Nuclear, Biological, and Chemical (NBC) decontamination system and (2) the Kärcher TEP 90 decontamination procedure. The research assessed automation potential by calculating functional similarity between separate stations in each process, and showed that a single automated solution could likely accomplish the tasks of these multiple decontamination stations.

4.1 Guidelines and Platform Behind Transfer to Practice

The chief mode for moving this design research outcome into practice has been through training young engineers. The Design Repository, its related tools, and its data schema are used as a framework for teaching functional thinking in undergraduate engineering coursework. This approach has been used to teach the basics of functional modeling, and demonstrate its utility, using automated concept generation tools. These tools hide the historical data and matrix math from users while providing inspiration for multiple different concept variants.

For example, FunctionCAD (Nagel et al. 2009) is a functional modeling environment that can enforce Functional Basis terminology and integrate directly with the Design Repository tools described in prior sections. A major goal driving the development of FunctionCAD was to ease students into functional thinking.

Because of the extra effort associated with learning the function-based formalism, engineering students commonly opt to use natural language function terms instead of Functional Basis terms. The payoff for using a structured language is not immediately evident. FunctionCAD is a product of the design repository research that can experientially demonstrate this payoff without a lengthy learning process. For instance, a student using FunctionCAD might create a new functional model, export, and load the file into the Design Repository concept generator, and retrieve a morphological matrix for that functional model. The tool's interface clearly indicates the available function terms, and can enforce other rules such as conservation of mass and energy. This demonstrates one added benefit of using the Functional Basis while imposing minimal obstacles on the designer.

A key takeaway observed from deploying tools like FunctionCAD is that software usability can have a severe impact on learning and acceptance of conceptual design techniques. A poor implementation can actually be worse than nothing at all. In order to maximize the effectiveness of research dissemination, especially when students are a target audience, the implementation must be stable and easy to use. When using prototype software as a teaching tool, students were observed becoming frustrated with bugs, missing features, and other usability issues. As a result, some students discounted the underlying approach as troublesome and ineffective. This effect has been observed with prototype versions FunctionCAD and Design Repository concept generator tools.

More generally, the effort required to learn and adopt new research findings is a barrier to their acceptance into practice. Tools like FunctionCAD are designed to minimize that effort while demonstrating the utility of the research findings. When usability issues decrease ease-of-use, such tools can become no more effective than teaching the methods directly.

It follows that usability and polish should be highly ranked requirements when such tools are anticipated to have a significant effect on training activities. Similarly, researchers should try to consider usability heuristics when producing research artifacts for outreach purposes.

A related contributor to the success of the Functional Basis as a teaching tool is its ease of adoption. Its function vocabulary balances natural language, physics-based, and teleological views of function. This balance affords descriptive power, simplicity, and flexibility. Similar attributes can be seen in other commonly accepted design tools, including TRIZ and Failure Modes and Effects Analysis (FMEA). These tools are simple and flexible enough for anyone to learn, and powerful enough to solve practical problems. It follows that design researchers should aim to condense research outcomes into simple and flexible packages. In short, our experiences using Design Repository tools in the classroom indicate that usability and adaptability should be top priorities when formulating a design research outcome as a training tool.

5 Research Outcome: Function-Failure Relationship

The second research outcome discussed in this chapter concerns the relationship between functions and failure. Failure, put simply, occurs when a system becomes unable to perform its intended function. The failure state manifests as unintended behavior. This conceptual linking between functions and failures has led to a number of tangible research products with the potential to influence practice. The research described in this section falls into one of two categories: component level function-failure approaches and system level function-failure approaches.

5.1 Component Level Failures

At an individual component level, failures are often the result of loading exceeding material limits. The material limits are ultimately a function of variation in the manufacturing process while the loading can be described by the component's performance equations. If this variation is specified up front, then that variation can be propagated back through the performance equations. This enables a designer to define the component form such that failure is avoided even in the presence of manufacturing variation. Taking this one step further, if components are linked to function then a designer can predict what components to use and what failure modes are possible well before any components are fabricated.

Motivated by the success of the prior taxonomy research, and the need to perform failure analysis as effectively as possible, a research effort in this area produced a general electromechanical failure mode taxonomy. The helicopter-specific failure taxonomy of Collins et al. (1976), which formed the groundwork for a matrix-based failure lookup tool, also provides the basis for the electromechanical failure mode taxonomy. The end result is a taxonomy of updated mechanical failure modes (Tumer et al. 2003) and new electrical failure modes (Uder et al. 2004) (Table 4). This abstract failure mode categorization enables earlier consideration of failure modes in the design process by enabling an FCM-style relationship between function and failure.

The Function-Failure Design Method (FFDM) uses this standard failure mode taxonomy, along with historical failure data, to algorithmically predict failure modes from a design's functions (Stone et al. 2004). A binary function component matrix relates functions to components, and a second matrix relates components to quantity of observed failures for each failure mode. Multiplying the two matrices gives the failure mode frequency for each function. The Function Failure Matrix can be generated for a single product, or for an entire database of functions, components, and failure modes. A designer can use this matrix of function-failure correlations to revise the functional model, inform component selection, and rank concept generator results.

Table 4 Failure mode taxonomy excerpt (Tumer et al. 2003)

Primary Identifier	Failure Mode	Definition
Corrosion	…	…
Creep	…	…
Ductile deformation (ductile material)	Brinelling	A static force-induced permanent surface discontinuity of significant size occurring between two curved surfaces in contact as a result of local yielding of one or both mating members.
	Force-induced elastic deformation	Occurs when the imposed operational loads or temperatures in a machine member result in elastic (recoverable) deformation such that the machine can no longer satisfactorily perform its intended function.
	Yielding	Occurs when the imposed operational loads or motions in a ductile machine member result in plastic (unrecoverable) deformation such that the machine can no longer satisfactorily perform its intended function.
Fatigue (fluctuating loads or deformation)	High cycle fatigue	The sudden separation of a machine part into two or more pieces occurring when loads or deformations are of such magnitude that more than 10,000 cycles are required to produce failure.
	Impact fatigue	Failure of a machine member by the nucleation and propagation of a fatigue crack that occurs as a result of repetitive impact loading.
…	…	…

The Function-Failure Rate Design Method (FFRDM) extends the FFDM knowledge base by adding approximately 36,700 failures from Failure Mode/Mechanism Distributions 1997 (FMD-97) and Nonelectric Parts Reliability Data 1995 (NPRD-95). These additions improve the validity of the failure mode knowledge base, and using failure rate data from these documents instead of relative raw frequency improves the validity of FFDM's likelihood predictions.

In a separate parallel effort, the Risk in Early Design Method (RED) (Grantham Lough et al. 2007) extends FFDM to translate function and failure information into categorized risk elements. RED uses a set of risk-attitude heuristics to select from different types of likelihood and consequence equations. RED communicates risks according to their likelihood and severity in the form of a risk fever chart (Fig. 6), commonly used to display risk elements in various companies, including NASA and Boeing. In this chart, all system risks are plotted according to their likelihood and consequence, providing the designer with a visual snapshot of the overall system risk.

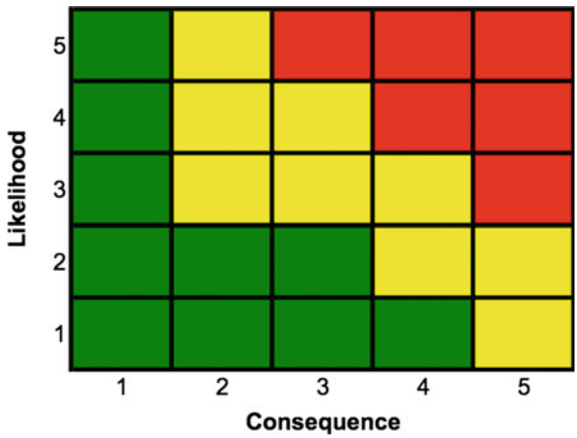

Fig. 6 Risk fever chart

5.2 System Level Failures

A systems-view product of the function-failure relationship in early design is the Function-Failure Identification and Propagation (FFIP) framework (Sierla et al. 2012). FFIP was introduced as a design-stage method for reasoning about failures based on the mapping between components, functions, and nominal and off-nominal behavior. The goal of the FFIP method is to identify failure propagation paths through the functional model by mapping component failure states to function 'health'. This approach uses simulation to determine fault propagation and fault effect, thus providing the designer with the possibility of analyzing component and interaction failures and reasoning about their effects on the rest of the system. The two main advantages of the FFIP method are: (1) a functional abstraction which allows it to be used in complex systems employing both software and physical components; and, (2) a simulation-based approach allowing analysis of multiple and cascading faults.

An FFIP analysis begins with a functional representation of a system and utilizes the mapping of functions to components in a component structural representation. A system simulation is built following the structural representation. The nominal and faulty behavior of generic components is stored as state machines in a component library. Each state represents a behavioral mode of the component where the qualitative intervals (high, low, etc.) of the input flow attributes are converted to output flow attributes. For example, in the nominal mode of a fuel line, the input flow level of fuel is the same as the output. However, in the blockage fault mode, the output flow level is reduced to zero. Finally, the approach introduces a Function-Failure Logic (FFL) reasoner which relates the input and output attributes of the component simulation to the expected change for the function mapped to those components. The result of an FFIP analysis is an evaluation of the health status of each function in the system. There are four potential health states for a function, as defined below. These states are based on the concept that a function is the expression of the designer's intent describing the actions that affect the flows of energy, material, and signal in the system.

1. Healthy: The function affects the flow as intended
2. Degraded: The function affects the flow differently than intended
3. Lost: The function does not affect the flow
4. No Flow: There is no flow for the function to act on (usually due to an upstream failure)

5.3 Impacts of Function-Failure Research

The failure analysis tools commonly used in industry (e.g. Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA)) rely on expert knowledge to identify failure modes. For example, Team X at NASA's Jet Propulsion Laboratory (JPL) is an expert team used to create conceptual designs of space missions. The design activity itself takes place in a setting that promotes constant communication, and a risk expert on the team solicits potential risks from subsystem chairs. This reliance on experts to identify failures can serve as a design process bottleneck.

Eliminating this expert knowledge bottleneck was a major motivator driving function-failure research. The function-failure abstraction provides the means for a novice engineer to reuse expert knowledge for failure prediction. For instance, the failure modes, likelihood values, and severity values generated by RED can prepopulate an FMEA table. This approach provides a secondary baseline to compliment a traditionally generated FMEA (based on tribal knowledge of similar projects), and can be created without expert involvement. Additionally, connecting failures back to functions reduces FMEA's reliance on physical component selections. This disentangling of form and function enables designers to begin FMEA earlier in the design process, reducing schedule pressures on failure identification.

In one attempt to apply the function-failure relationship in practice, the failure mode taxonomy was used to label failures described in JPL's Problem/Failure Reporting (P/FR) database (Roberts et al. 2003). In general, the authors found that the database contained insufficient detail about the spacecraft systems and their failures to create a confident failure mode mapping. When additional information was available from individual reports and expert interactions, high-confidence failure mappings were created for 69 out of 86 (80 %) of failure modes. A key takeaway from this work is that in order to make use of function-failure relationship design tools in practice, practitioners would need to capture additional information about failure events. In this case, the tools do not fit smoothly into existing practices, posing an obvious but important barrier to their adoption.

As indicated in the earlier section on the Functional Basis, the automotive industry (in these authors' case that was General Motors) has shown interest in the usage of function-to-failure correlations that grew out of the FFDM work. The primary interest (in the mid 2000s) was for cataloging historical failure information to support FMEAs for new vehicle systems. The function-failure correlations made possible by the specification of functional and failure taxonomies were considered a framework by which in-house knowledge could be formulated and retained despite employee turn over.

In the realm of defense, the US Air Force investigated functional modeling as a platform for supporting counterterrorism operations (Nagel et al. 2009). The researchers demonstrated how to identify the most vulnerable functions in the model through injecting failures, tracing each failure's propagation, and measuring function sensitivity. This failure propagation through a functional model closely parallels the FFIP methodology. As an example, a model of Improvised Explosive Device (IED) incidents was created using Functional Basis terminology. Faults were injected to demonstrate which functions in an example IED creation and use scenario are the most vulnerable to disruption. Due to the sensitive nature of this domain, the full extent of the research impact is unknown.

FFIP has been adopted in multiple projects in a variety of domains. At NASA projects, FFIP was morphed into Functional Fault Analysis to break down a system architecture (Kurtoglu et al. 2008) and analyze how faults propagate through aerospace systems. In this case, FFIP demonstrates the value of function-failure linking in relatively practical terms, lending to the adoption and adaptation of its basic underlying principles. FFIP has also been applied to the design of nuclear power plants, led by a group at Aalto University in Finland, who have been consulting with the Radiation and Nuclear Safety Authority (STUK) of Finland (Sierla et al. 2012) as to the applicability of the approach in future designs.

Finally, as a consequence of the complexity of modern vehicles, the Defense Advanced Research Projects Agency (DARPA) has invested in novel methods for design and verification of complex systems through their Adaptive Vehicle Make (AVM) program. FFIP was included as part of a model-based design effort led by Palo Alto Research Center under DARPA funding to establish "correct-by-construction" design prior to prototyping (Uckun et al. 2011). Sustained interest in model-based design points toward the abstract function-failure relationship as having a fundamental impact on future design activities. A company that has formed through this project, CyDesign has commercialized portions of this approach.

Both FFIP and FFDM are part of a graduate course at Oregon State University that teaches various methods of failure and risk analysis. Students who have graduated from Oregon State University with this training have every intention to introduce these methods as the next generation failure and risk analysis tools into the reliability engineering practices with their current employers, which include NuScale, Xerox, Daimler, and Raytheon.

6 Conclusions

The Functional Basis, its utilization as a building block of the Design Repository, and the function-to-failure mappings have made impacts in education and in the practice of industry. In the education arena, we are likely still in the early stages of seeing the results as the concept of functional decomposition as a key activity in design process continues to take root in the US engineering education landscape. Early data (it is largely anecdotal at this point) leads the authors to conclude that the abstraction that is possible through the Functional Basis pays dividends in better designed products (Oman et al. 2012) and more critical thinking by students in the engineering design courses. While the outcome is generally a better result, the qualitative data indicates that grappling with abstraction is at times a mentally stressful activity—particularly during the first few encounters with the approach. With repetition, the abstraction-making potential of using the Functional Basis during the conceptual design process becomes more natural and easier to implement for student engineers.

Considering the impact of the work on industry practice, the use of function has gained ground over the past decade. While industry is typically tight-lipped as to what makes up the "secret sauce" of their success, the authors speculate that based on our interactions there has been measurable acceptance of function-based methods within the design teams of US industry. As noted in our conclusions regarding educational practice, the abstraction-making potential of the Functional Basis and the function-failure approaches take some intentional practice to master. It therefore likely takes a supervisory champion to push these activities into the standard operating procedures at a given company. In general, we have seen at a minimum interest and preliminary use at automotive, aerospace, and product innovation companies as well as national labs and Department of Defense agencies.

7 Summary

These research contributions have made their way into practice in different ways and at different rates, though the full extent of their impacts is difficult to measure. Education and training activities provide direct bottom-up influence, though tracing the impacts caused by newly trained engineers is challenging. The effects of such training may not manifest for years, and cultural inertia within established organizations can present barriers to acceptance of new design techniques.

In contrast, direct collaboration with industry provides top-down influence. This arena affords more immediate impact, but requires buy-in from key people in the organization. In this respect, small startups represent a compromise between receptiveness to new ideas and capacity to impact practice. In all likelihood, the continued combination of top-down and bottom-up techniques is necessary to produce noticeable change in practice.

In both of these arenas, our experiences indicate that the research outcomes must possess demonstrable utility by providing direct solutions to practical problems in an easy-to-use manner. Simplicity and flexibility of the core research contribution are critical to facilitate the transition into practice, such that interested stakeholders can adopt and adapt the research outcomes with low effort.

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A Framework for the Dissemination of Design Research Focused on Innovation

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Abstract This contribution presents an original framework for transferring the results of design research into practice, specifically addressing the need of creating a circle of players from various companies interested in being part of both the mass dissemination process of already tested methodologies and in pilot experiences and preliminary dissemination activities with the latest design research developments. Moreover, the paper focuses the attention on the existing metrics for evaluating the impact and the viability of adoption of design methodologies in practical contexts, showing their lacks in covering aspects mostly related to the dissemination of design research concepts. An original metric is described and applied to six case studies of industrial interest that have been carried out, with the objective of consolidating the acquisition of skills through the practical application of more theoretical elements, by employees of industries that have already received a basic training. The main results are discussed also with a broader perspective, so as to highlight the potential benefits deriving from the adoption of a shared metrics to measure this kind of knowledge transmission from design research to practical applications.

1 From Scientific Research to Mass Dissemination: A Pattern to Be Empowered

The path connecting scientific research to the mass dissemination of the research outcomes usually consists of different steps where several players contribute to the transition from research to practice.

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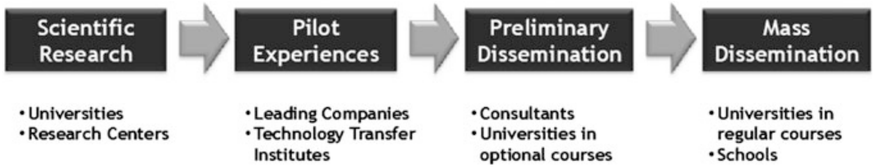

Fig. 1 A typical path for transferring engineering research toward mass dissemination. Red boxes represent common stages of diffusion; bullets summarize the main players involved in each stage

Figure 1, for instance, describes a typical path by which the results of research in the design domain get consolidated and progressively spread to a bigger audience.

Universities play a relevant role in several stages of this diffusion process: together with research centers they generate new knowledge, produce new theoretical developments and, moreover, they contribute in the dissemination process by educating future generations of practitioners and scholars. Besides, companies with a strong innovating behavior that usually are leaders in the reference market, are the most likely subjects interested in carrying out pilot experiences on the basis of the latest research outcomes. Technology transfer institutes usually play an auxiliary role along these processes, also by connecting academia and industries. After the success of pilot experiences, consultants and vendors contribute to the preliminary dissemination and, in some case, they independently improve specific techniques for focused applications in industry. As said, universities start introducing optional classes in their courses that, with a longer perspective, would become part of regular academic courses as well as topics in schools.

This path is now consolidated and there exist several examples of this transition for design tools. For instance, all the different generations of CAD systems (from 2D/3D CAD through CAM and CAE to PLM and Multiphysics applications) diffuse according to this process, with the concurrent support of vendors pushing for their spreading in later stages. However, the situation is different for what concerns the diffusion of conceptual design methods. Indeed, courses on CAD tools are nowadays present in all the industrial curricula of universities. On the contrary, classes on design methods, even those more renowned as Six Sigma or FMEA/FMECA, are not usually offered as mandatory academic courses apart from few exceptions. In this context, design methods, meant as specific procedures, techniques, tools, etc. aimed at improving effectiveness and efficiency of design processes, suffer from the lack of subjects pushing their dissemination in the long term: after the preliminary dissemination stage, this absence may trigger a drop in the interest of a wider audience. From this perspective, it appears as more and more important to trigger new motivations in potential adopters and define adequate subjects capable of fostering the diffusion of design methods.

To this purpose, this paper presents a framework to foster the diffusion of design research into practice, so as to improve the above-mentioned transition and sustain the dissemination with a longer perspective. Moreover, the authors define a tailored metric to measure the impact and the viability of this transition.

The next section introduces the metric and the methods of measurement of main interests for the purpose of the paper. Sections 3 and 4, respectively, present the original framework for sustaining the diffusion of design research toward its practical application in the long term and the metric to measure one of the steps of this transition. Section 5 shows how the metric has been applied and what kind of information it allows to map after the application of design methods by practitioners that have received dedicated vocational courses in companies. Then, the authors discuss the main evidences emerged after the application of the metric, as well as its strengths and weaknesses. Specific concluding remarks focus on the potential benefits triggered by the adoption of a shared metric for assessing the transition of design research into practice.

2 Design Outcomes and Design Process: Metrics for Their Evaluation

As mentioned in Sect. 1, since this paper focuses the attention on the impact and the viability of the practical application of design methods that influence both the design outcomes and the related processes, the authors briefly review the most acknowledged approaches and metrics for evaluating them. Still trying to produce a list of reference criteria as exhaustive as possible, the authors decided to put more emphasis on the practical implications of measures, rather than focusing on the different perspectives that are still debated in academic literature.

2.1 Object of the Measurement

The measure of a designing activity usually gets carried out with the purpose of evaluating the creativity expressed during the idea generation stage. Several contributions (e.g. Sarkar and Chakrabarti 2011) already review the different approaches available in literature. Despite the various viewpoints, there is a strong and shared orientation among scholars in considering some of the requirements for patentability as the most relevant features characterizing the creativity of newly generated ideas. Usefulness usually describes the suitability of the generated idea to practically solve a problem, or more generally a situation with discontentment. Novelty, in turn, indicates the conceptual distance of the idea from what existed before. The non-obviousness and the surprise, as well, are concepts related to the unexpectedness of the idea, respectively, concerning the one who generates it and those observing it.

On the other hand, some constructs have been proposed also for measuring the characteristics of the design process. Shah et al. (2003), for instance, proposed the introduction of two constructs, so as to produce meaningful insights about the creativity of the design process: variety and quantity. Both of them take into account all the ideas generated while designing. Variety considers the range of diversity resulting between solution concepts and quantity simply counts the productivity of the process in terms of the overall number of generated ideas.

The measurement of the quantity of ideas underlies the assumption that the probability of finding a good idea in a set of generated ideas is higher the bigger is the set (Osborn 1963). Nevertheless, this approach completely overlooks the assessment of the efficiency of the design process that can be measured in terms of resources devoted to the generation and the development of solutions (people, time, …) (Becattini et al. 2012).

At last, it is also worth mentioning that, in the logic of transferring the knowledge from theory to practice, there are relevant metrics tailored for specific purposes. Since this topic goes beyond the purposes of this paper, it is sufficient mentioning that correctness and completeness represent two among the most diffused criteria to evaluate the correct application of theoretical teachings to students of different subjects and of different ages.

2.2 *Method of the Measurement*

Different methods are used to assess the constructs presented in Sect. 2.1 and literature shows a particular attention on the quantification of these measures with numerical indicators. Nevertheless, some methods of measurement go beyond the design outcomes and the related process and aim at measuring also the creativity of individuals, with appropriate criteria. The Torrance Test for Creative Thinking (e.g. in Almeida et al. 2008) is a clear example of method for measuring the creativity of individuals after the administration of a test. It supports the definition of individual's creativity according to process-related constructs, almost completely overlapped with the ones proposed in Sect. 2.1 (e.g. flexibility matches with variety, fluency with quantity, etc.).

A more empirical method for assessing the thinking process of individuals and groups involved in design activities concerns the examination of their behaviors. This approach goes under the name of protocol analysis; a review of different protocol analysis approaches is available in Jiang and Hen (2009). Scholars have developed several methods and tools for improving this kind of analysis as, for instance: coding schemes (e.g. Gero and Kannengiesser 2004), criteria for segmenting the protocols (e.g. Suwa et al. 1998), as well as specific applications (Gero et al. 2011). For instance, linkography (Goldschmidt and Tatsa 2005) is a technique to represent the mutual relationships between ideas during a design process. This technique supports both the analysis of the protocols and enables a more straightforward application of specific metrics, as for the ones measuring the divergence/convergence of the thinking process or its entropy, as for Kan et al. (2007).

As for the learning process, there are different approaches to evaluate the different outcomes of students of various ages and experiences. Nevertheless, the different measures can be distinguished in objective or subjective, according to the kind of administered tests as, for instance, the objective tests developed within the OECD Programme for International Students Assessment—PISA (OECD, 2002).

From a very different perspective, professional certifications represent the other side of the approaches for evaluating the learning outcomes of trainees of vocational courses. However, the authors believe that this kind of method is not adequate for the evaluation of the impact of design research, since it is mostly suited for the evaluation of already consolidated theories, whose application has been already tested in several practical applications.

2.3 Metrics to Evaluate the Diffusion of Design Methodologies

With reference to the overall logic of the paper, it is also necessary mentioning the need for evaluating the diffusion of design methods and their perceived impact. To this purpose, a relevant example is the worldwide survey that the European TRIZ Association (ETRIA) carried out in 2009 (Cavallucci 2009) about the perception and the uses of TRIZ, Russian acronym for Theory of Inventive Problem Solving (Altshuller 1984). In that context, several aspects were observed, such as:

- the width of the knowledge in use with respect to the theoretical entire Body of Knowledge of TRIZ and the most commonly used concepts and tools;
- the size and the composition of research structures where TRIZ is a research topic;
- the penetration of the TRIZ concepts in the educational domain;
- the size and the technical field of industries using TRIZ within their development cycles;
- the benefits that companies expect as a consequence of the adoption of TRIZ.

3 A Model to Transfer Design Research into Practice: Academia and Center of Competence on Systematic Innovation

The following section presents the approach the authors have experienced during the last 8 years for transferring design research into practice (see Fig. 2).

The big circle at the center of Fig. 2 represents the core of the model since it collects the main players both developing design research and promoting the dissemination and the adoption of design methodologies in common industrial practices. The Yin–Yang (Tao) symbolic parallelism serves to clarify that within this model design research and the dissemination at industrial level are mutually tangled

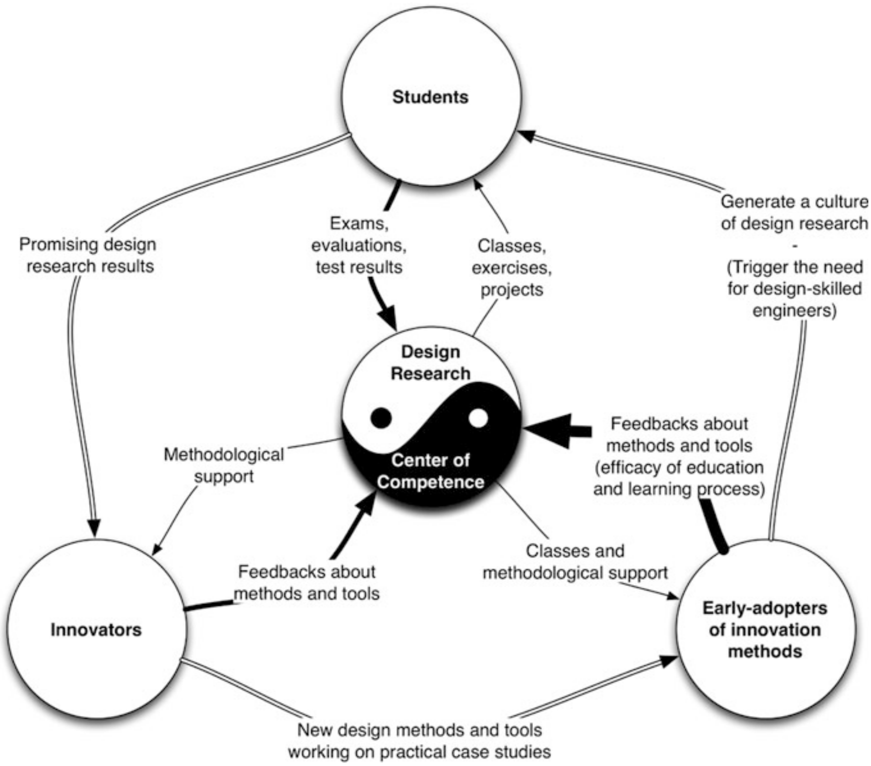

Fig. 2 A graphical description of the approach that links design research, dissemination, and industrial practice. *Thin arrows*: educational approaches; *thick arrows*: evaluation processes; *double arrows*: impacts on the content of the dissemination/education process

by the newly injected concepts from theory and the practical feedbacks coming from practice with design methodologies. The next subsections present the two parts of the Tao symbol.

3.1 Design Research and Its Diffusion in Academia

Both Politecnico di Milano and Università degli Studi di Firenze are carrying out researches on design focusing their attention on specific subjects, such as:

- the definition of new methods and tools for inventive design (e.g. systematic analysis of complex and difficult problems, identification of appropriate stimuli and sources of inspiration, methods and heuristics for problem solving, definition of new models of cognitive processes); and

- knowledge management (e.g. knowledge transfer for idea development, identification of elements for decision-making in technological forecasting and business process reengineering activities, Information Retrieval and Extraction; Intellectual and Industrial Property).

Moreover, both the universities offer classes on design methods that are optional for a wide range of students from different courses and compulsory for those focusing their curricula on machine design. These classes present topics ranging from the general aspects of the product development process to specific problem-solving theories and methodologies; from the management of intellectual property to the identification of relevant knowledge elements supporting the strategic planning of companies.

The dissemination of these concepts aims at educating the next generation of engineers and designers with some of the most advanced and widely experienced outcomes from design research. This transfer of knowledge occurs with different blends of theoretical lessons and practice with exercises and projects (both with and without the support of professors and teaching assistants). Moreover, the evaluation of the whole acquired competences gets carried out both with written and/or oral exams and with the discussion about a project the students developed during the course. This process produces feedbacks to both students and professors: the former better understand what needs to be further improved among their competences; the latter obtain a general picture of the effectiveness of the education process and the structure of the class.

Volunteering students are often involved in optional testing sessions whenever some of the latest design research outcomes require a preliminary validation with a significant amount of testers, so as to draw early but statistically supported evidences. These kinds of tests are usually more operative and strongly structured, so as to clearly define what should be measured during the specific application of, e.g. new tools and methods for design. In other words, these tests are mostly focused on the specific evaluation of characteristics of the research outcomes in order to fix criticalities and remove bottlenecks, rather than focusing on the specific characteristics described in Sect. 2.1.

As a result of this preliminary validation process, the widely tested successful experiences start to be proposed to industries for their pioneering application in industrial practice, as described in Sect. 3.2.

3.2 Center of Competence on Systematic Innovation: Closing the Virtuous Cycle Between Design Research and Practice

The Center of Competence on Systematic Innovation mainly operates in Italy and gathers professors, academic researchers, and experts with the purpose of deepening and diffusing topics concerning problems solving and systematic innovation methodologies to a wide audience: from industries to authorities and individuals (http://www.innovazionesistematica.it). The following players compose the consortium:

- Fondazione Politecnico di Milano;
- Politecnico di Milano—Department of Mechanics;
- University of Bergamo—Department of Industrial Engineering;
- University of Florence—Department of Industrial Engineering;
- Ceris-Institute for Economic Research on Firms and Growth, CNR;
- PIN Scrl.

They are differently involved in both research activities (universities and research centers) and technology transfer practices (Fondazione Politecnico and PIN).

The Center offers two main tracks to companies interested in systematic innovation activities. The first concerns the delivery of courses on innovation supporting methods (such as TRIZ) to individuals or companies (Early adopters in Fig. 2). The training is tailored to suit the profile of the participants (operational roles vs. executives). The second usually involves companies (Innovators in Fig. 2), which have already attended courses offered by the Center or having a more consolidated experience with systematic innovation methodologies. They constitute a sort of set of "retained" partners, available to test the latest research developments, both as new tools for performing established tasks (e.g. modeling complex situations and defining priorities for problem solving), or embedding new tasks in the design process (e.g. integrating technology forecasting as a means to foster radical innovation with higher probability of success).

These two dissemination activities (with early adopters and with innovators) are presented consistently with the anticlockwise order of Fig. 2.

Innovation-oriented companies represent, therefore, the more interested subjects in testing the design research outcomes in practical applications and they can be practically involved with a small or null amount of vocational resources, because of their previous experiences of training or practice. The common aspect pooling the dissemination of diverse research outcomes stands in the educational approach that, beyond a potentially required initial training, leverages the support of methodological experts for the application of methods and tools on real industrial case studies. This kind of approach enables capturing feedbacks about strengths and weaknesses of research developments, with both an "in-progress" and an "a posteriori" perspective. This twofold perspective allows measuring both the characteristics of design methodologies under testing and those mostly related to the industrial practice, such as:

- the accessibility and the possibility to share technical and strategic information;
- dynamics within companies and decisional chains;
- the tendency of individuals and groups to adhere to already developed ideas.

As said, the offer of the Center for early adopters of design methods addresses both the needs of individuals and companies interested in systematic innovation.

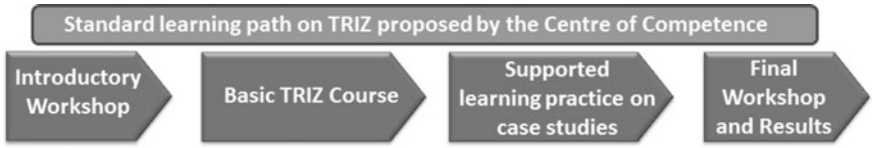

Fig. 3 The standard structure of the dissemination path of TRIZ, as proposed by the center of competence on systematic innovation

These courses are well structured and the topics focus on consolidated theories and research outcomes already tested with success in industrial practice. An example of structured dissemination path is represented in Fig. 3, which refers to TRIZ training.

An introductory workshop presents the philosophy underlying a systematic approach toward technological innovation and describes the structure of the whole training process to all the interested people, especially involving decision makers at different organizational levels that could have higher stakes in participating the training. According to the number of participants, the Center organizes an optimal amount of basic courses, so as to facilitate effective lessons and an adequate active involvement of all the attendees. The course provides operational skills on some specific topics such as structured brainstorming, inventive problem solving, technology scouting through patent mining, etc. After the conclusion of the course, small panels of motivated trainees (2–3 people each) are formed to make them focus on practical case studies of industrial interest. This activity is carried out also with the support of methodological experts that regularly monitors the autonomous application of the taught methods for tutoring and supporting them, with methodological suggestions and contextualized examples. All the solution concepts generated during these practical sessions get collected and ranked and a summarizing report is prepared. During a concluding workshop, the activities of the different panels working on practical problems are presented focusing the attention on both the design process and its outcomes.

A similar logic is followed also within pilot experiences with the so called Innovators, that are both involved in sessions aimed at transferring the use of the new methods and tools and follow-up sessions with practical application of the lessons learned to everyday activities.

Despite the standard approaches presented in Sect. 2 allow mapping many elements of designing and generating ideas, they should be integrated with more customized indexes, so as to properly evaluate the impact and the viability of these dissemination activities. This evaluation represents one of the paramount necessities to retrieve useful feedbacks for improving the newly developed design methodologies and increasing their acceptance and adoption in industrial contexts.

The following Sect. 4 describes the main objective of a metrics addressing this demand and its overall logic.

4 Criteria for Evaluating the Adoption of Design Methods and Tools in Industrial Practice

The assessment of the impact and the viability of newly developed design methods in practical context (the thicker black arrow in Fig. 2) requires both the evaluation of the activities carried out during the design process and its outcomes. Nevertheless, since designing is a knowledge-intensive process (Tomiyama 1994), there are other important elements that go beyond the standard evaluation of design outcomes as generated solution concepts.

To this purpose, the authors propose to evaluate the following elements, as described in the first column of Fig. 4.

Then, the impact evaluation cannot be measured simply through the goodness of newly developed solution concepts, but this measure needs to be compared with already developed solutions, as emerged from the state-of-the-art analysis. Moreover, the novel generated knowledge during the solving process of a design problem represents one of the other elements to be considered, even if its benefits are not directly and immediately measurable through design outcomes.

In turn, beyond what is depicted in Fig. 4, it is also critical to generally measure the usefulness and the viability of the practical application of design methods for the company as a whole. The overall objective is to evaluate or infer the global value of the newly developed concepts for the company and the resources consumed for generating them (e.g. people, knowledge, time).

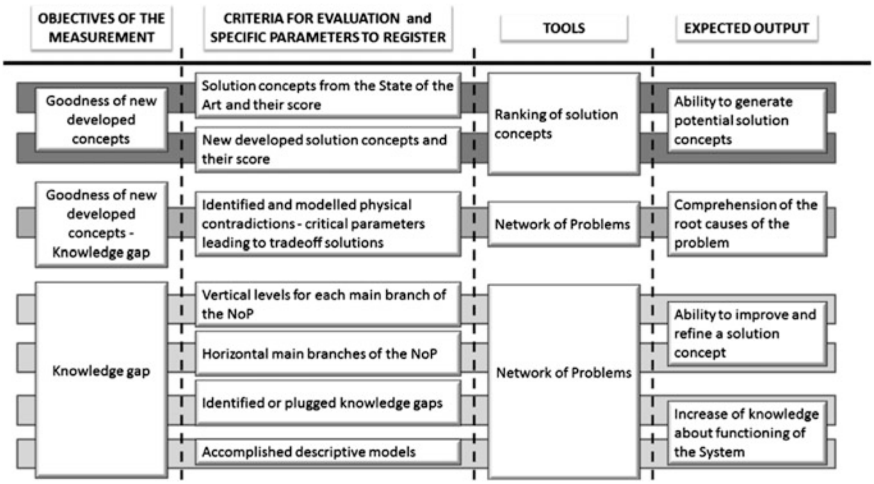

Fig. 4 Synoptic scheme of the proposed metric, with evaluation criteria, tools to be applied and expected impacts on design practices (NoP : Network of Problems)

4.1 OTSM-TRIZ Network of Problems: A Representation of Knowledge About Problems and Solutions

The Network of Problem (NoP) is one of the OTSM-TRIZ instruments (Khomenko et al. 2007) that aims at coping with the analysis of complex problems during a problem-solving process. It is presented in this context because it allows both problems and partial solutions (nodes) to be connected according to their relationships (links) in the same model with the form of a network, thus mapping critical elements to be taken into account for the impact estimation of design methods in practice. Different scholars are progressively improving this technique and one of its latest developments extends its suitability also for mapping design processes (Becattini et al. 2013), using the constructs presented in Fig. 5.

This general framework can be further enriched by nodes of a third type, collecting doubts and highlighting open questions about both problems and partial solutions to be answered before further proceeding along a certain direction of development.

The NoP is characterized by a good versatility, since it is possible to build it during the examination of the case study, as well as with an ex-post approach through the use of audio and video recordings of the design session, consistently with the approach for the analysis of design protocols.

Moreover, once this knowledge map about problems and partial solutions has been built, it just requires progressive updates so as to reuse it for developing poorly

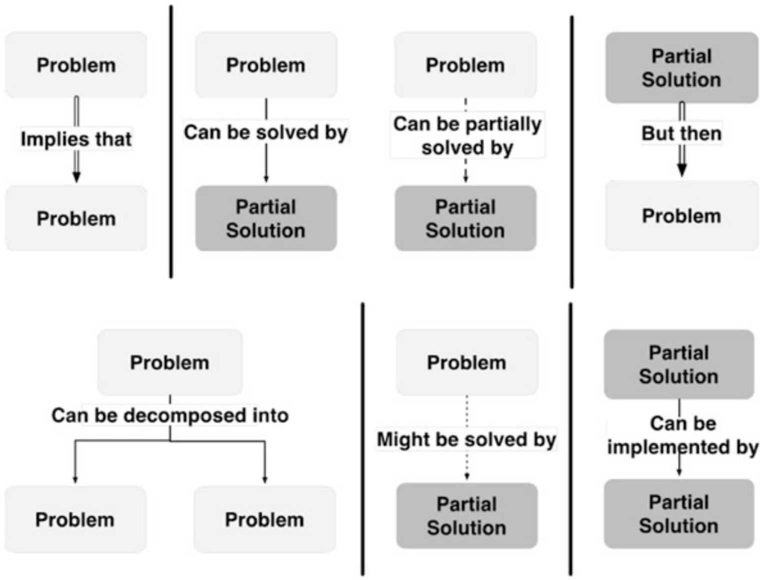

Fig. 5 The main elements and connections to be employed in the network of problems

explored branches of the NoP or for choosing solutions that become more convenient because of changes in the context.

4.2 Description of the Evaluation Metrics Based on the NoP

According to Fig. 4, the proposed evaluation metric consists of seven main criteria on which the impact should be measured both in terms of goodness of solutions and generated knowledge gap.

The number of solutions is counted for both those already known from the state-of-the-art analysis and the newly developed ones, with the purpose of comparing the two sets. This variable tries to extend the common metrics of quantity and fluency.

The score of solution concepts, for both kinds of solutions, gets calculated with the criteria of Weighted Sum Methods (e.g. in Pohekar and Ramachandran 2004). Different technical criteria are defined and weighted for the suitability of solution concepts, which are finally evaluated according to the judgment of decision makers. As for the number of solution criterion, the purpose is to evaluate the impact by comparing the solutions from the state-of-the-art analysis with the newly generated ones. From a practical perspective, this approach helps the designers to properly choose with a more objective approach the solutions to be developed with higher priority.

The identification of critical design parameters (i.e. with conflicting requirements) usually leads to trade-off solutions represents a critical parameter to be evaluated and a relevant criterion for defining the capability of design methods in supporting designers during the identification of the core elements of design problems, whose solution may trigger to brilliant, effective, and efficient ideas.

The number of vertical levels for each main branch of the NoP gives an idea of the convergence toward specific solution concepts through the identification of partial solutions and the new problems they trigger (blue connections in Fig. 6). The higher the number of vertical levels on a branch, the more convergent is the design process toward that final solution concept.

The number of horizontal main branches of the NoP is a criterion that supports the evaluation of the degree of exploration of the different implications and causes of an overall design problem (red rounded box in Fig. 6). Bigger is the number of horizontal branches of the NoP and more intense would have been the analysis. On the other hand, it also supports the estimation of the occurrence of detailing processes for solution concepts (Partial Solutions to Partial Solutions links) and the divergence of idea generation processes (Problems to Partial Solutions links).

The number of identified or plugged knowledge gaps represents, as well, one of the core criterion for the evaluation of the impact that the practical application of design methodologies have in improving the degree of understanding of technical problems. The identification of these knowledge gaps (pink boxes in Fig. 6), once

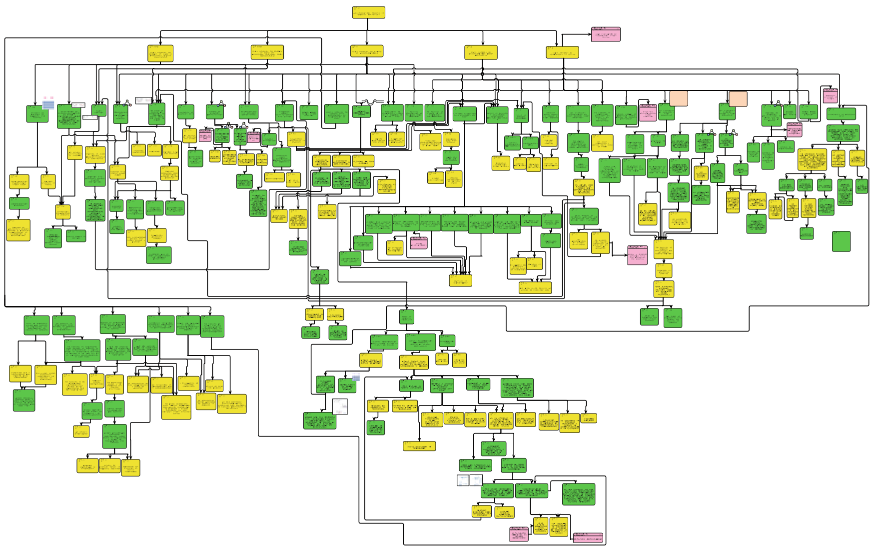

Fig. 6 An example of network of problems. The content of *boxes* is intentionally not readable due to confidentiality issues. *Yellow* and *green boxes*, respectively, correspond to problems and partial solutions (see Fig. 5). *Pink boxes* highlight the need to plug specific knowledge gaps emerged during the analysis of the design problem. The *red horizontal rounded box* spanning five subproblems shows the main branches into which the analysis has been subdivided. The *blue* connections show the path (10 vertical steps) into which the designers have deepened the analysis from one of the main subproblems

plugged, can trigger both the definition of critical design parameters, as well as novel ideas.

The number of accomplished descriptive models supports the evaluation of the frequency of adoption of taught concepts with methods and tools for problem analysis (e.g. one of the subproblems highlighted in the NoP has been examined by means of a functional or by a root cause analysis model). The higher the number of accomplished descriptive models is, the more effective is the dissemination process about instruments for the analysis aimed at improving the understanding of the way a certain system works.

4.3 Evaluation Criterion for Measuring the Overall Usefulness of the Practical Activity

For what concerns the evaluation of the usefulness of the application of design methodologies on industrial case studies, the authors suggest interviewing the involved subjects, so as to capture the opinion of trained people about the expected and the observed outcomes of a structured design activity for systematic innovation and its potential impact on their work.

Besides, it is necessary to avoid diplomatic answers that might hide criticalities, thus reducing the meaning of the feedback for the research activities. In this perspective, and also as a means to encourage the industrial partners for the testing and the adoption of the recommended methods and tools, the Center of Competence for Systematic Innovation proposes a peculiar formula in its training and coaching contracts. In fact, at the end of the coaching session, after the experimental application of the proposed methods and tools on some real case study, companies have to express their assessment on the quality of the design outcomes. A positive assessment implies (by contract) the payment of an extra fee, as a recognition of the success of the activity. A negative assessment allows the company to avoid any further payment beyond the training time, but the Center of Competence gains the possibility to autonomously file a patent application on the emerged solutions and/or to sell the same concepts to other companies. In turn, if the design outcomes are meaningless, the companies can easily reject the payment of the bonus and refuse any exclusive property on them, thus demonstrating a lack of practical benefit beyond any diplomatic comment on the proposed methods and tools. Besides, if they agree to recognize the bonus fee, they confirm the practical validity of the design activity.

5 Application of the Metric: Experiences in Reference Companies

This section presents the application of the metric described above to a number of case studies carried out within coaching sessions similar to the third stage depicted in Fig. 3. The design sessions involved panels of technical experts working under the supervision of methodological facilitators on the solution of tough design problems.

For confidentiality issues it is not possible to directly cite the industries with which the six case studies have been carried out and on which the metric is applied. Nevertheless, their general descriptions are briefly summarized in the following bullet list with the purpose of showing their diversity. The results of the application of the metric are summarized in Table 1.

Case study #1.
: The deposition of dust on sensitive surfaces;

Case study #2.
: The contamination of goods by nonadequately clean sanitization device;

Case study #3.
: The unconformity of geometrical tolerances in a manufacturing process for the assembly of two materials;

Table 1 Summary of the results obtained through the application of the metrics

	Case study #1	Case study #2	Case study #3	Case study #4	Case study #5	Case study #6
# of concepts from the SoA	5	5	4	8	1	7
Score (avg.) for the SoA concepts	259.8	–	–	33.5	8.67	7.78
# of newly developed concepts	11	50	6	14	31	–
Score (avg.) for the newly developed concepts	285.9	–	–	36.4	7.16	–
# of critical design parameters	2	2	1	2	5	6
# of vertical levels per branch of the NoP	3; 1; 7; 3; 3.	4; 3; 10; 3; 7.	4; 4; 3	8; 1; 1; 2; 1; 0.	–	1; 3; 1; 1; 1; 3; 1.
# of main horizontal branches of the NoP	5	5	3	5	–	7
# of identified or plugged knowledge gaps	12	10	13	4	10	12
# of descriptive models	Yes	No	Yes	No	18	2

Case study #4.
The presence of residual mechanical stresses triggered by sudden cooling after welding;
Case study #5.
Manufacturing a planar surface with tight tolerances by removing material;
Case study #6.
The precision of the process of positioning electronic devices.

Given the great variability of the different case studies, it is expected to obtain heterogeneous results in the different columns. However, before commenting the results of this application, it is necessary to start with a general remark. Table 1 shows that along some case studies (e.g. case studies #2 and #3) the designers did not define appropriate criteria for the evaluation of solution concepts and therefore they completely skipped the assignment of weighted scores. Moreover, blank cells for case studies #5 and #6, respectively, inform about the lack of knowledge modeling with the NoP and the complete absence of generated solution concepts. Both these cases have been purposefully chosen so as to point out different but critical aspects. For what concerns Case study #5 it is sufficient to build the NoP with an ex-post approach, if audio or video recordings are available. As for Case study #6, the complete absence of newly generated concepts represents a warning of something wrong in the training program or of a poor availability of resources or interest to properly carry out an appropriate practical application.

The comparison of solution concepts from the state-of-the-art analysis and the ones generated through the support of design methods shows that the adoption of design methods improves the ideation productivity, since in three cases out of six the number of generated ideas is more than the double of the ones already known before the beginning of the activity.

For what concerns the scores of the different solution concepts, the case studies #1 and #3 show better levels for the newly developed solution concepts. On the contrary, the results for the case study #5 present an opposite trend. Moreover, it is also important noticing that the values of this score strongly differs among the different applications, because the involved designers have a complete freedom in choosing the reference scale of evaluation (the scores may vary in the range 0÷1 as well as 1÷10, and so forth).

Considering the development of new knowledge among the results of this tutored design activities, it is worth noticing that all the analyses, at different extents, supported the identification of critical design variables that prevents the development of new and more radical solution concepts and that usually get a trade-off value for finding the best compromise between requirements (a physical contradiction, in the TRIZ jargon).

The examination of the NoP, beyond the aid for counting the different emerged solution concepts, also allows the analysts to obtain relevant elements concerning the divergence and the convergence of the design process, with particular attention to the exploration of solution concepts, their refinement, and the systematic perspective on problem analysis. Moreover, the numbers concerning the development of vertical levels in the NoP also suggest the different degree of involvement of the subjects participating the activities. Panels of experts working on the case studies #1 and #2 show a more intensive participation and application of the dialectical logic behind the identification of partial solutions and subsequently generated problems.

As well, the number of knowledge gaps that are identified or plugged along the analyses also witnesses the knowledge enrichment processes occurring with the practical application of design methods. A final remark concerns the criteria for measuring the adoption of prescriptive models. For some case studies (#1÷4) this evaluation followed just a qualitative approach; on the contrary, for the others it was possible to count the number of times the different models have been used.

6 Toward a Standard Metric for Design Research-to-Practice Transitions: Concluding Remarks

This paper stems from the analysis of the criticalities emerged in the process of disseminating design research outcomes and presents, to this purpose, an original approach for supporting the diffusion of design research methodologies. The authors also propose a metric suitable to capture some elements describing the impact and the viability of the transition to a new generation of design methods than the existing evaluation criteria, as reviewed in Sect. 2, are not mapping.

Figure 2 depicts the overall structure that joins academia, research centers, and institutes for technology transfer in a unique subject, called Center of Competence for Systematic Innovation. Throughout the activities of this Center, several pioneering research outcomes are tested with more innovation-oriented companies. On the contrary, the most consolidated ones get progressively absorbed into the curricula of less basic education course and get diffused to early adopters of design methodologies.

The authors originally developed a metric that specifically addresses the need of measuring the transfer of knowledge to practitioners by focusing the attention on the evaluation of the improvements (in other words, the positive impact) they obtain in both generating valuable ideas and producing new knowledge for the company they work for. The metric is based on criteria for which it is possible to retrieve data from a Network of Problems, a kind of knowledge map that can be produced both during the analysis, as well as with an ex-post perspective, in case recordings of the design activities are available.

In other terms, in order to foster the transfer of design research into practice the authors consider of paramount importance the following:

- Rely on a structure that links together academia and industries, such as a center of competence, with mutual exchanges on research objectives, best practices on design methods, and punctual assessment of the related impact;
- Assess the goodness of the outcomes of design research through intensive tests before their dissemination to a bigger audience. A reliable assessment should consider the effectiveness of the proposed methods and tools by validating them with statistical significance (e.g. by involving students in academia as testers, if needed) and on the field with companies to evaluate their industrial impact;
- Measure the outcomes of the transfer by means of appropriate metrics that also allow the identification of issues and troubles of the applied methods and tools, as well as the need of new ones addressing emerging situations.

For what concerns the further developments of the proposed approach, the authors expect to generate an active debate about the definition of an appropriate structure for subjects transferring design research into practice. Moreover, metrics for quantitatively evaluating the transfer, the impact and the viability of design outcomes and to share the results among scholars involved in design research are critical for obtaining meaningful feedbacks from practitioners. The adoption of a common metric represents a good chance to better exchange the results from the outcomes of design practice among scholars in a unique form, so as to enlarge the number of tests and related feedbacks about the application of design methodologies and better identify the directions for easing its adoption.

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Impact of Design Research on Practice: The IISc Experience

Amaresh Chakrabarti

Abstract This chapter undertakes a look into the broad development of design practice, research and education in the Indian context, and uses some of the major developments at Indian Institute of Science (IISc) as exemplars to illustrate its impact on design practice, research, and education. The outcomes of design research can influence practice through multiple routes: by developing organizations of practice to use outcomes of design or its research; by developing products or systems for use by organizations of practice; by developing support and transferring them for use in practice; by developing students, via training in product or support development; or by developing teachers and researchers, via training in research, teaching and/or practice of product or support development, so that they can train students or carry out research in organizations or change practice via any of the other routes. The chapter illustrates each route with exemplars from work carried out at IISc.

1 Introduction

Research into Design—the sense in which the term 'Design Research' has been used in this work, is a relatively young discipline, with universities taking up research in this area as late as in the 1950s, formation of peer research societies since 1960s, initiation of teaching of systematic design and associated methods and tools about the same time onward, formation of research journals and conferences since 1980s, and centralized call for proposals for setting up centres for excellence in this area since the 1980s (e.g. EDRC in CMU in 1986, or Engineering Design Centre in Cambridge in 1991), even though some centres started forming on their own since the 1960s (e.g. Institute of Product Development at Technical University

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of Munich in Germany by Rodenacker in 1965, or establishment of Design Research Center at Carnegie Mellon University in 1974). Influential books in this area started appearing since the 1940s, e.g. Kesserling (1942), Matousek (1957), Glegg (1969), Simon (1969), Pahl and Beitz (1977), Hubka (1982), Schön (1983), and so on. The first, major methodology for design research—DRM—while published in its initial form in 1991 (Blessing et al. 1992), got published in its fully developed form only in 2009 (Blessing and Chakrabarti 2009). Despite this relatively recent start, how has the impact of design research been, directly and indirectly, on practice?

This chapter peers into the broad development of design practice, research and education in the Indian context, and uses some of the major developments at Indian Institute of Science (IISc) as exemplars to illustrate its impact on design practice, research and education.

2 Historical Background

India has a rich culture of craft and design for several millennia, as evidenced in its multitude of art and craft traditions in painting, pottery, toy making, clothing design to temple architecture, steel making, making of ships, and so on. Much of traditional training in India happened in close association with masters of the art or craft—broadly known as 'Guru's. This 'Gurukul' system of education was widespread around the country and was practiced in a decentralized form, in which students or 'Shishya's resided with the family of the Guru and learnt from a holistic, immersive interaction with the Guru. Teaching of the craft would often be passed on from generation to generation, every subsequent generation taking the craft further. This was in parallel with the few universities that provided general education to students, the most notable being the University at Takshila (near Kashmir, J&K) which existed during 4th Century BCE to 4th Century CE, and the University in Nalanda (near Patna, Bihar) that existed during 5th Century CE to 12th Century CE until it was destroyed by invasion from Central Asia.

During the middle ages, with much of the Gurukul system losing patronage from the kings, craft education became increasingly more family—or community-oriented. Many of the technical craft, however, continued to flourish, such as the use of Indian stainless steel (since 375 CE) that was used, among others, to make the so called 'Damascus sword' (Wikipedia). Another notable craft was the development of guns and rockets. Mysore rockets were the first iron-cased and metal-cylinder rockets that were developed by Tipu Sultan, ruler of the South Indian kingdom of Mysore, and his father Hyder Ali, in the 1780s (Wikipedia). He successfully used these iron-cased rockets against the larger forces of the British East India Company during the Anglo-Mysore Wars. The Mysore rockets of this period were much more advanced than what the British had seen. After Tipu's eventual defeat in the fourth Anglo-Mysore war and the capture of the Mysore iron rockets, these were influential in British rocket development, inspiring the

'Congreve rockets', which were subsequently put into use in the Napoleonic Wars (Wikipedia).

During colonization of India by the British, many of these traditions lost patronage of the ruling community, or were strongly discouraged. From one of the major economies in the world in the 1700s, India became one of the poorest nations in about 200 years; according to Cambridge historian Angus Madison, the GDP of India was about 22.6 % of that of the world in the 1700s, almost equal to Europe's share of 23.3 % at that time, to come down to as low as 3.8 % by 1952 (India became independent in 1947) (http://www.hindu.com/2005/07/10/stories/2005071002301000.htm).

Post-colonial, independent India, under the leadership of Jawaharlal Nehru and the National Congress, had opted for a mixed economy, even though, strongly influenced by the Soviet model, the market had been under heavy state control, and much of the production was via rigid license regimes. Nehru initiated a remarkable number of national educational and public sector organisations that nurtured development of young minds on one hand, and provided jobs in high technology industry to these people on the other. While the growth rate was poor due to lack of freedom to operate in the market, India produced a large pool of trained professionals in science and technology areas, and excelled in several strategic sectors where external support was heavily restricted, e.g., nuclear, space, and machine tools.

A curious mix of political and economic debacles in the 1990s provided the opportunity to a minority government, for a group of its young ministers, including the last Prime Minister Manmohan Singh (who was then the finance minister) to open doors for market economy in India. The rate of growth has since grown steadily, with substantial growth in both manufacturing and service sectors, putting India presently as one of the fastest growing economies (https://en.wikipedia.org/wiki/Economy_of_India).

The above growth is reflected in development of new products, as well as betterment of old products. The first indigenous passenger car Tata Indica was designed in 1998, and till 2008 sold over 910,000 units (http://en.wikipedia.org/wiki/Tata_Indica); its first indigenous SUV Mahindra and Mahindra Scorpio rolled out in 2002 (http://en.wikipedia.org/wiki/Mahindra_Scorpio); and its first indigenously designed aircraft LCA received its airworthiness clearance in 2011 (http://en.wikipedia.org/wiki/HAL_Tejas). These epitomize a level of maturity Indian companies have achieved in design, manufacturing and service sectors in the face of acute international competition for its prized market.

Formal (e.g., university) education in design and systematic product development has been relatively new. While the first design institution—National Institute of Design—was established as part of the Nehruvian initiative in the 1960s, little beyond teaching industrial and a number of craft-centred design educations were on offer, its practice of design catering primarily to government sectors. Industrial Design Centre (IDC) at Indian Institute of Technology (IIT) Mumbai was established in the 1970s, primarily to support industrial design education within a technology-centred institution. Real growth in design education started in the

1990s, with a large number of new institutions or centres for design education, both privately and federally funded, being initiated; notable among these are the Master in Design (MDes) programme at the Centre for Product Design and Manufacturing (CPDM) at Indian Institute of Science (IISc), Bachelor of Design (BDes) programme at IIT Guwahati, and similar Design departments or MDes programmes on design at IIT Madras, IIT Delhi, IIT Kanpur, School of Planning and Architecture (SPA) New Delhi, a number of National Institutes of technology (NIT), besides various private institutions such as Symbiosis or Srishti. In the 2000s, CPDM at IISc took the pioneering step of initiating the first Ph.D. programme in design, and most of the above institutions followed suit, as the need for trained Ph.D.s in this area continued to grow with the initiation or expansion of design education programmes. A national design policy became established in 2007, and a design council and a national committee on design came into being in 2009 to promote awareness and policy level promotion of design. The ambit of design has since been extended considerably with the establishment of the National Innovation Council, to "discuss, analyse and help implement strategies for inclusive innovation in India and prepare a Roadmap for Innovation 2010–2020" (http://www.innovationcouncil.gov.in/index.php?option=com_content&view=article&id=26&Itemid=5).

3 Design Research into Practice: Multiple Routes

The outcomes of design research can influence practice through multiple routes; some are shown in Fig. 1 (self-referencing arrows represent recursive impact of a route, e.g. development of knowledge, organisations, teachers etc. promoting development of further knowledge, organisations, teachers, etc.:

- By developing *organisations* of practice to use outcomes of design or its research. For instance, products developed as part of design research can form the basis for initiating new startups. While few such cases have happened as part of the Incubation initiative at IISc, this is not discussed further in detail here due to its relatively nascent stage at IISc. As an indicator, about 10 startups have been created by the past students of CPDM, which is roughly one start-up per 20 students (0.5 %). Without a benchmark it is hard to judge this number, but it is certainly the highest among all departments in IISc, which is arguably the topmost science and technology institution in India.
- By developing *products* or systems for use by organisations of practice: the development of products benefits from knowledge of outcomes of design research, such as methods and tools. One such organization is APDAP, discussed in Sect. 4.
- By developing *support* (i.e. methods, tools etc. for enhancing teaching, research or practice of design) and transferring them for use in practice. One such effort is The 'SAPPhIRE model' and the 'Idea-Inspire' tool, see Sect. 5.

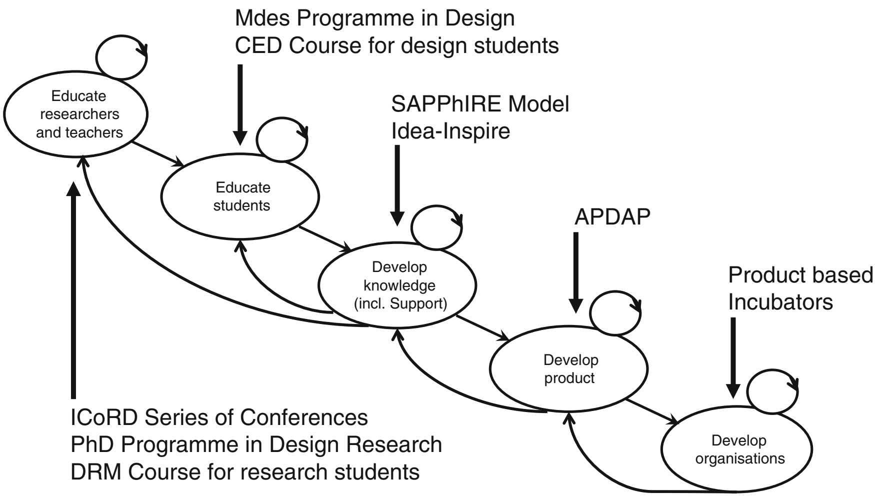

Fig. 1 Various routes to influencing practice

- By developing *students*, via training in product or support development. The students can be at various levels of education: schools, undergraduate level, post-graduate level, at work, etc. They can join practice, initiate new practice, or enhance existing practice of which they are part. Two such efforts are the MDes programme at IISc, and a course called Creative Engineering Design (CED) taught within this programme, see Sects. 6 and 7.
- By developing *teachers* and *researchers*, via training in research, teaching and/or practice of product or support development, so that they can train students or carry out research in organisations or change practice via any of the other routes. Three such efforts are the ICoRD conference series, Ph.D. programme in design at IISc, and a course on DRM, see Sects. 8, 9 and 10.

4 Design Research into Practice: APDAP

Advanced Product Design and Prototyping, acronymed APDAP, is a joint venture between IISc and TCS (Tata Consultancy Services)—the biggest ICT firm in India under the Tata conglomerate. APDAP was set up in 1996 at IISc, with the aim of providing cutting-edge technology and innovative solutions to the Industry, so as to enable them to compete in the global market. APDAP provides one-stop solutions from conceptualization to manufacturing. APDAP's capabilities, in general, include Industrial Design, Product Engineering, Prototyping, Tooling and Manufacturing, where TCS's knowledge and skills in marketing is married to IISc's knowledge and skills in science, technology and product development. (http://www.linkedin.com/groups/Advanced-Product-Design-prototyping-3318286/about).

Typically IISc professors work as consultants to product development projects, guiding development of products at the level of detail asked by the client: product sketches, renderings, 3D models, engineering drawings, prototypes, or even tooling. CPDM professors use methods and tools from various areas of design, and students as short-term interns who work with in-house engineers at APDAP to develop solutions for the real world. APDAP has carried out over 200 projects with over 50 companies from around the world, which include the likes of Tata Motors, General Motors, General Electric, Hindustan Unilever, ITC Limited, Proctor and Gamble, and so on in the private sector, and the likes of Indian Space Research Origanisation (ISRO), Aeronautical Development Agency (ADA), Defence Research and Development Organisation (DRDO), Defence Bioengineering and Electromedical Laboratory (DEBEL), etc. in the public sector.

5 Design Research into Practice: The SAPPhIRE Model

At the Innovation, Design Study and Sustainability Laboratory (IdeasLab) at CPDM, IISc, a small group of researchers developed the SAPPhIRE model of causality, in order to describe how engineered as well as biological systems work (Chakrabarti et al. 2005). The project was funded by the Space Technology Cell or STC, which was a special funding body created by the Indian Space Research Organisation (ISRO), in order to support 'blue sky' space-related research at IISc. The broad goal of the project was to support 'rocket scientists' at ISRO to be more creative and innovative; ISRO is among the six largest space organisations in the world, with indigenous satellites since 1975, launch vehicles since 1980, and its maiden and successful unmanned mission to the moon in 2008.

The project focused on the development of a tool that could be used to systematically obtain stimuli for solving technical problems. A special focus of the tool was to include both biological and existing technical systems as stimuli for ideation. While there have been many efforts to create biological catalogues, developing an ontology that applied well to both biological and technical systems has always been a challenge. The answer lied in finding the right structure for describing the explanation of how these systems worked, and developing analogical search procedures to identify relevant portions of these systems for a given technical problem. The main scientific contribution was the development of the SAPPhIRE model of causality (Fig. 2), which described how a system worked in terms of seven constructs (Ranjan et al. 2012) as follows: *Phenomenon* is an interaction between an entity and its surroundings. *State change* is a change in a property of an entity and its surroundings involved in an interaction. *Effect* is a principle of nature that governs an interaction. *Action* is an abstract description or high-level interpretation of an interaction. *Input* is a physical quantity, taking the form of material, energy, or information that comes from outside an entity's boundary and is essential for an

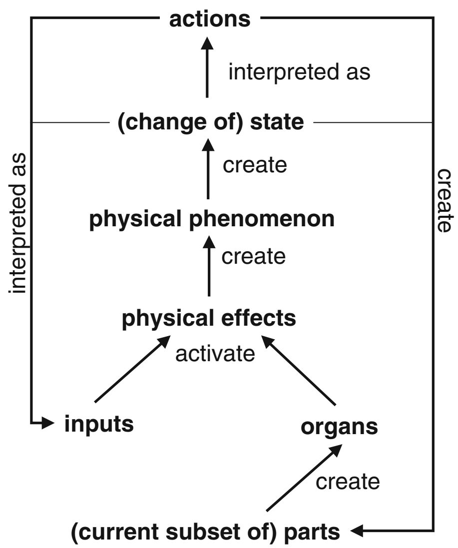

Fig. 2 SAPPhIRE model of causality (Image credit: Chakrabarti et al. 2005)

interaction. *Organ* is a set of properties and conditions of an entity and its surroundings that is also required for an interaction. *Part* is a set of physical components and interfaces that constitute an entity and its surroundings. *Entity* is defined as a subset of the universe under consideration, and is characterised by its boundary; *surroundings* are defined as all the other subsets of the universe; *interaction* is a communication between an entity and its surroundings, to reach equilibrium. Parts create organs; with appropriate inputs, organs activate effects, which create phenomena. Phenomena create changes of state in entity and surroundings, which create new parts or interfaces, destroy old parts or interfaces, or can be interpreted as further actions or inputs.

SAPPhIRE model has been used as the basic ontological framework to create a tool called Idea-Inspire, which has been patented by IISc. A follow-up project taken up with ISRO focused on demonstrating the efficacy of systematic approaches to design of space technologies. The project used design of a lunar vehicle mobility platform as the problem, as ISRO was keen to obtain a variety of concepts for input to the development of its lunar rover. The project led to development of an extended database for Idea-Inspire, and an associated framework for guiding the product development process. In interaction with the ISRO collaborators, a student team developed over 20 different concepts, detailed two of these shortlisted by ISRO, and developed the design and associated prototypes for these two designs for ISRO. The work demonstrated how a systematic methodology and associated use of Idea-Inspire provided a rich set of varied concepts for the problem (Srinivasan et al. 2011).

Idea-Inspire has subsequently been licensed to other companies, the most notable being IMI-Vision, UK—the innovation front end of the global conglomerate IMI-Cornelius. Interestingly, the SAPPhIRE model has been used as a backbone for developing a host of other pieces of knowledge (illustrating a case of the self-referencing arrow shown in Fig. 1): as a basis for an integrated model of designing (Srinivasan et al. 2010; Ranjan et al. 2014); as a basis for a new method for assessing design novelty (Sarkar and Chakrabarti 2011), as a framework for integrating various views of function (Chakrabarti et al. 2013), as the basic ontological framework for providing in-service information for engineering designers at Rolls Royce (Jagtap 2008), and providing product-in use information to engineers at Pratt and Whitney (McSorley et al. 2010).

6 MDes Programme at IISc

Initiated in 1996, the MDes programme at CPDM, IISc (http://cpdm.iisc.ernet.in/mdes.php) takes graduate engineers or architects as input, and aims at transforming them into holistic product designers who can join or initiate, and spur innovation in, design or manufacturing industry. The programme curriculum is aimed at developing skills, knowledge and aptitude in creative, knowledge based, hands-on problem finding and problem solving. The students are trained to approach product design from a holistic viewpoint integrating in a balanced and harmonious manner industrial design and engineering design perspectives to develop products that are well engineered, aesthetic and ergonomic with improved manufacturability. The courses offer the following:

- Process knowledge, e.g. CED course offers a systematic approach to product development.
- Domain knowledge, e.g. Ergonomics, Aesthetics, Fluid Mechanics, Materials Selection, etc.
- Skills in e.g. physical and virtual modeling e.g. computer aided design, prototyping, etc.
- Reflection: Research project based course called 'Design and Society' and a research training course called 'Methodology for Design Research' aid thinking about research into design.
- Hands on projects, e.g. the final project starts with user need to end with working prototypes.

Over the 16 years since its establishment, CPDM has graduated over 180 masters students. About 10 % of these students took up further studies (Ph.D. in various top institutions including Stanford, Cambridge, Oxford, IISc, IITs, etc.), about 5 % pursued own startups, and the rest joined industry (primarily aerospace, automobile, and industrial design companies). About 20 % of the final year projects have ended up as technology patents, a few of which are in the process of being taken up by industry.

7 CED Course

Creative Engineering Design, or CED course as it is commonly referred to, was initiated in the 1960s, by Professor M.R. Raghavan of Mechanical Engineering department at IISc, as part of its Masters of Engineering (ME) programme in Design of Mechanical Systems. It was then called 'Design of Engineering Systems', and followed the then popular books of T.T. Woodson, R. Matousek, and J.C. Jones. The author of this chapter had the privilege of attending this course in 1985 still taught by Professor Raghavan. In the 1990s, the mantle was passed on to Professor T.S. Mruthyunjaya, who renamed the course as it stands now, and brought new materials from the changing contexts e.g. Brezel and Hemmel to introduce sustainability as a central element of the course curriculum. In 2002, as Professor Mruthyunjaya was about to retire, the course was passed on to the author of this chapter, with further modifications being added in creativity, thinking skills, yoga, biomimetics, hands on competition and a strong emphasis on discussion and presentation—a decidedly constructivist approach to learning.

Successes of this course can be seen in four ways. The first is its incredible longevity, it has gone on for over half a century now, and has been accepted at various points of time as a core element of the curriculum in Masters courses in two departments. It is one of the oldest running design methodology courses in the world, and possibly the oldest in India. The second indicator of its success is that, the course has subsequently been offered, repeatedly, in four other schools in India in their MDes and MBA programmes, which at least shows that the course is seen as valuable by the teachers and students in these schools. The third aspect is the enthusiasm with which students go through the course each year and the consistently high student rating it gets (over 4.5 out of 5 in a scale of 1–5, where 5 is excellent, and 1 is poor), which shows that students value the course content and delivery. The fourth is the comments received from ex-students about how good the course was, and how they continue to use the various methods that were taught, referring in particular to evaluation, contradiction analysis, and FMEA; this shows that parts of the methodology knowledge are passed on, via ex-students, to practice.

8 ICoRD Conference Series

International Conference on Research into Design (ICoRD) is the first series of international conferences initiated (by the author) in India that focuses on design research. The idea behind its initiation was to provide an opportunity for researchers in India, most of whom find it hard to manage resources to attend a design research conference in Europe or North America, to continue to remain in touch with cutting edge research at the international level. This is a precursor to doing high quality research—to understand quality at the highest level and develop social networks that foster design research.

Since its first, and rather humble beginning in 2006 with just 30 papers, the biennial conference has now completed its 5th edition in 2015, with the number of papers gradually increasing to about 120. In its five editions, ICoRD managed to attract over 400 papers and twice as many researchers, about half of them being from the international community. It is possibly the first design research conference in Asia that has been endorsed by the Design Society and the Design Research Society.

One of the major strengths of ICoRD is its student-friendliness; over the years, it provided student scholarships to undergraduate and postgraduate students (who are not necessarily research students) to participate in this event with the hope that it would encourage some of them to take up design or design research as career. ICoRD'11 was also special in that it attracted global sponsors such as Boeing (USA), Volvo (Sweden), SMI (Germany), and others.

ICoRD'13 was the first time the conference moved from Bangalore to take place in IIT Madras in Chennai, with a structure similar to what is now regularly followed in conducting ICED conferences, where programme and conference chairs divide the responsibility of organizing the conference, a move, it is hoped, would encourage broader participation across the country and the world. ICoRD'17 is planned to be held at IIT Guwahati, the first time to be held in North-east India.

9 Research Programme in Design at IISc

Given that the first teaching programmes in design started in India around the 1960s, it is surprising that no formal Ph.D. programme in design was initiated for almost four subsequent decades. IISc at CPDM started the first formal Ph.D. programme in design in the country in 2003, with only three students joining in the first session. The programme currently has about 40 research students (over 30 Ph.D. students), having already graduated over 30 research students. The research programme (research based Masters as well as Ph.D.) spans across a variety of areas of design: design methodology, human factors, aesthetics, product safety, CAD, product informatics, and sustainability are some examples.

The primary purpose of initiating this research programme was to cater to the growing needs of the rapidly expanding teaching programmes in design around the country, and the fact that promotion for teachers at all federally funded institutions required that the teachers had a Ph.D. in a relevant area. Ph.D. in design was not possible until then in India, and Ph.D.s in design from abroad were rare to attract.

The immediate effect of the research programme seems to be that it is well on its way to fulfilling its mission: about 10 % of the graduates from the research programme joined further research, about 20 % joined post-doctoral research elsewhere, and an overwhelming 50 % joined industry (this is very encouraging as it shows that design researchers are seen as valuable to practice). The remaining 20 % has joined university teaching, with some credence to the fulfillment of the primary aim of the research programme.

10 DRM Ourse

Since 2002, a one semester, three-credit, Masters level course has been offered on 'Methodology for Design Research' for students at IISc, to train students in carrying out design research. The course is primarily based on the research framework DRM that was originated by the author together with Lucienne Blessing and Ken Wallace (Blessing and Chakrabarti 2009), and is one of core courses for research students at CPDM. This is probably the only formal course offered around the world in DRM, even though DRM is taught in several universities as part of broader courses on design research methods (e.g. at Blekinge University of technology, Sweden), and at the European Summer School of Design Research run by M.M. Andreasen, L.T.M. Blessing and C. Weber (http://www.designsociety.org/event/135/).

Over the decade-long existence of the course, it has trained over 30 students in various areas of design and management. As discussed in the book (Blessing and Chakrabarti 2009), there is some empirical evidence that MDes students who were trained in DRM did significantly better in a research course at CPDM (Design and Society) than those who were not; this was irrespective of their overall grades in the whole MDes programme. The course consistently received high student rating (over 4 out of 5). While it is hard to assess the real impact of the course on practice or education, at least a third of the students trained via the course have, or continue to have, used DRM as part of their subsequent research.

11 Lessons Learnt

What are the main lessons learnt from all these, regarding the two questions:

- What guidelines are learnt for successful transfer of design research into practice?
- What are the characteristics of an appropriate platform for academia-industry interaction?

The following guidelines were highlights from the SAPPhIRE model and Idea-Inspire projects:

- It is critical to have the right collaborator (the research champion!) as the industrial partner, one who, on one hand understands the problems in the industry and its time scale, and on the other hand the problems in the academia and its time scale. We were lucky to find Mr. BS Nataraju at ISRO who on one hand was an expert in space mechanisms, and understood at a broad level what space scientists needed, and was on the other hand highly knowledgeable about design methodology literature and its potential. Our subsequent collaborator Dr. R. Ranganath, with a Ph.D. from IISc on a problem dear to ISRO also knew and embraced both cultures well.

- It is useful to find a problem that is valuable for both the industry and academia to solve. While the first project was awarded partly for its curiosity value, the second had a clear need—ISRO needed the new rover concepts for its moon mission exploration. Similarly, the CEO of IMI-Vision, on his visit to IISc saw the goals of Idea-Inspire match his vision of stimulating thinking out of the box —and could envisage the potential of using Idea-Inspire as a tool for stimulating brainstorming and creative thinking.
- Frequent interactions between industry and academia were a key to success in both the projects. The interactions led to new ideas, quick evaluations, and modifications—in other words fast cycle for development that was in the right direction as seen by both the parties.
- For an offering to be successful in being transferred to practice, it should be evident that the solution on offer works. In other words, approach to validation should be clear and convincing, and results from validation should be clear and significant. In our case, the first project tested the tool for its ability to help generate a much larger pool of ideas (average 170 % more than those generated on their own by designers); the second project demonstrated that the framework and the tool developed could be used throughout the process (with outputs from each stage), could produce interesting and realistic results, at the end produced solutions that were significantly different from those existing before, and were demonstrated to have worked according to the specification from ISRO.

Following thoughts on platform seem to transpire:

- The evolving patterns of problems that are faced in industry are essential for academia to be aware of on an on-going basis.
- Similarly, awareness of new thoughts and solutions emerging in academia is useful for industry.
- A matchmaking of the two needs to happen somewhere on the middle, where scientific needs of the academia, which typically requires more time to solve, and practical needs of the industry, for which they need to find a solution in as short a timescale as possible, must meet.
- The platform should encourage exchange of a variety of problems that the two sides think are important to solve, and the timescale associated with them. It should also encourage 'tweeting' on the emerging trends in the solutions being explored in academia.
- Another issue is handling of intellectual properties and publishing results. This should be part of the agenda for discussion and resolution within such platforms.

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Industrial, and Innovation Design Engineering

P.R.N. Childs and M. Pennington

Abstract The Innovation Design Engineering (IDE) double masters programme, run jointly by the Royal College of Art and Imperial College London is now in its 34th year. Originally called Industrial Design Engineering, the aim of the programme was to provide an educational pathway for taking graduate engineers and produce a new type of industrial designer. The two-year full-time programme involves a series of themed but student-directed projects in the first year, prior to major group and solo projects in the second year. This chapter introduces the original purpose of the programme, documents some of the transitions as well as providing a description of the current format of the programme, with a particular focus on addressing the needs of industry and those of individual students and graduates, and the sometime tensions between these. The Innovation Design Engineering is characterised by a 'borrowed discourse' with no distinct disciplinary language owned by the community at the moment. This is manifest in the extensive engagement by the students in their collaborations across the Departments and Research Centres at Imperial and their willingness to explore diverse innovation spaces. Traditionally, graduates have gained subsequent employment in corporations and design consultancies. The last 5 years have seen a significant shift with the greater proportion of graduates setting up their own businesses and consultancies on completion of the programme.

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1 Introduction

The Innovation Design Engineering course (formerly Industrial Design Engineering) was created 34 years ago and is widely recognised as a highly influential degree programme worldwide. Based at the Royal College of Art (RCA) and Imperial College London, its aim has always been to recruit graduate scientists and engineers with latent creative talent and, by immersing them in a highly creative culture, to give them the opportunity and encouragement to develop their creative skills.

The international mix of graduates on the course is drawn from a range of disciplines including engineering, design, the sciences, and commerce. This mix reflects the multidisciplinary approach to the design process taught on the course, a blend of technical expertise, creative flair, human focus, and commercial reality. Learning is highly structured and includes a significant degree of group working, both within and outside the department, where the students learn the value of working with other disciplines.

The IDE degree team strives for, and promotes, best practice in collaborative postgraduate design teaching, research, and links with industry. It aspires to create an awareness of the excitement and rewards that creative engineering can bring to industry. Graduates are encouraged to recognise commercial and technical constraints but to develop a breadth of vision and push boundaries.

The course benefits from collaboration and support from a number of major industrial organisations with interests including consumer electronics, architecture and environmental design, materials development, and domestic appliance manufacture. These organisations benefit by being able to directly access a wealth of ideas and employable designers. The students benefit by being exposed to the realities of industry and to advanced technical and commercial practices.

The programme is informed on a daily basis as a result of the research activities of both Imperial College London and the Royal College of Art, with its long heritage in design research. The Design Engineering Group at Imperial College London was formed in 2008 and specialises in:

- Design knowledge repositories. Development of architectures to enable the capture and storage of large-scale richly traceable knowledge repositories. Approaches to integrate knowledge management tools such as Product Lifecycle Management (PLM) systems with tools to enable the routinely capture of design information.
- Design led demand for new manufacture technologies. Application of design thinking processes to new manufacturing and production technology capability to explore new concepts for development.
- Design rationale. Approaches to capture the design information produced in the conceptual and embodiment design stages of complex system development with a focus on explicit documentation of issues, alternative solutions and arguments as well as on integration of text, calculations, images, documents and videos.

Examples of tools used in the team are: Decision Rationale editor (DRed); Compendium and designVUE.

- Diagnosis. Approaches to prevent failure, understand the root causes of failure and capture the sources of manufacturing variation. Examples of tools used in the team are: Decision Rationale editor (DRed) and FMEA.
- Function analysis. In this area we have expertise in analysis and representation of functional interactions for complex systems with form-independent and form-dependent techniques such as Function Structure, Function Tree, Function Flow Diagram and Function Analysis Diagram.
- Knowledge elicitation. One-off and continuous approaches to elicit design knowledge from end users for the purpose of developing methods, tools and modelling frameworks. Examples of approaches used in the group are: surveys, interviews and observations as well as computer-supported knowledge modelling.
- Local manufacture. Use of one stop shop manufacturing centres focussed on a particular domain to enable local companies to share the cost of factory start-ups. Use of co-creativity tools for concept to realisation process.
- Microfactories. Development and implementation of a process to enable cottage industries in the form of microfactories to significantly expand their product and process capability, essentially offering production 'down your street' and added value design capability, with a sustainable life cycle emphasis.
- Requirement engineering. Approaches to: (1) elicit requirements from stakeholders; (2) analyse, structure and justify requirements; and (3) support the evolution of requirements from informal needs to a formal system specification.

The programme team comprises two course directors, a deputy head, two senior tutors, four tutors, and about 10 part-time tutors as well as a further 40 visiting tutors. In the academic year 2013/2014, there will be a total of 41 students in the first year of the two-year masters and a further 40 in the second year.

IDE is seen as a 'hub' discipline and graduates are well equipped to move off into industry and use their newly acquired creative skills to drive innovation in large businesses. Many of the alumni now hold key creative positions in consultancies and corporations around the world, and many return to the college to lecture and to tutor, to share their learning and skills with the students.

2 Inception

In the late 1970s, Professors Misha Black and Frank Height from the Royal College of Art recognised the need for specialisation in, what was then, a newly emerging discipline known vaguely as Industrial Design. They created a new vision that would bring designers directly together with engineers to work in creative partnership. On Monday 6th October 1980, after 6 years of planning, a unique course in design education began at the Royal College of Art (Pennington 2010).

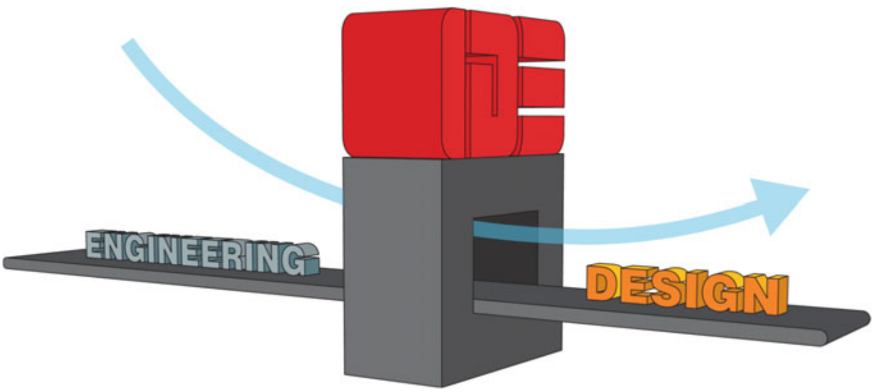

Fig. 1 Transitioning graduate engineers to design

This pioneering, postgraduate course in Industrial Design Engineering was conceived by Misha Black and Frank Height and brought to fruition by Professors' Hugh Ford and John Alexander from Imperial College. The course was jointly planned and run by Imperial College and the Royal College of Art and was a response to Prince Albert's ambition for the Great Exhibition of 1851. His vision was for a South Kensington Estate of colleges and museums and for them 'to be a place where institutions of science and art can work together for the benefit of manufacturing industry'.

The course was conceived with the sole aim of improving the design of British consumer and industrial products by teaching graduate engineers how to design (see Fig. 1). The RCA provided the design expertise and studio space and Imperial, the formal engineering lecture programme and workshop facilities for building functional prototypes. The students were to be funded by the 1851 Commission with profits of the Great Exhibition, along with RCA and Imperial bursaries.

The planning stopped—and the course started—when seven students assembled in the Level 3 Design Studio of the Royal College of Art on that October Monday morning, over thirty years ago. With them were Professor Frank Height, RCA's Course Director, Mike Starling, Len Wingfield, Imperial's Course Director Dr. Cyril Laming and Paul Ewing. During this first year, the Joint Academic Board appointed Paul Ewing as the Coordinating Director (Pennington 2010).

'Can you teach design to engineers?' This is the question that kick-started the IDE course in 1980. To the Royal College of Art's Sir Misha Black and Imperial College London's Hugh Ford, the question was not controversial; it was revolutionary (Pennington 2010). At a time when the educational system within the United Kingdom split students into streams of arts or sciences, those who had travelled the path to engineering were separated from design and other creative careers by an increasingly archaic barrier of educational heritage. In the new course, the two institutions took graduate engineers and introduced them into the world of industrial design.

3 Design, Engineering and Engineering Design

Many attempts have been made at defining design (see Childs 2013). The word can be used as a verb or noun, describing the process of design, and the outcome of design, respectively. Referring to design as a process, it can be considered to include all the activities of market assessment and user requirements, specification, concept generation and idea development, embodiment of details, risk mitigation, consideration of manufacture and production, and implementation. 'Referring to design as a noun, the term is commonly used to describe an artifact such as a vehicle, item of fashion or other product, with the associated features and merits. This may include description or commentary on aesthetic, ergonomic and technical features. In this book an inclusive approach to design is used with consideration of a range of functionalities ranging from technical, aesthetic, social, economic and latent. Design is considered to be the process of conceiving, developing and realising products, artifacts, processes, systems, services and experiences with the aim of fulfilling identified or perceived needs or desires typically working within defined or negotiated constraints' (Childs 2013).

Engineering involves significant overlap with design and indeed it is often difficult to make a clear distinction. A common distinction is the use of quantitative analysis in engineering to aid and inform the development, simulation, testing and refinement of a system or product. 'Engineering can thus be considered to be the application of scientific and mathematic principles in combination with professional and domain knowledge, in order to design, develop and deliver artefacts, products and systems to realise a societal, commercial or organisation requirement or opportunity' (Childs 2013). Mechanical engineering refers to the use of engineering processes to applications of a mechanical nature, typically involving moving components or energy processes.

The terms 'engineering design' and 'design engineering' are often used interchangeably. The inclusion of the word engineering in both suggests that they involve the application of scientific and mathematical knowledge and principles. It may be useful to think of 'engineering design' sitting alongside 'engineering science' as the strand of engineering that is concerned with application, designing, manufacture and building. 'Design engineering suggests a process in which engineering (scientific and mathematical) approaches are applied in the realization of activities that began with a design concept or proposal' (Childs 2013). However, such distinctions remain subtle and subject to context.

Industrial design practice has changed significantly over the years with global shifts in supply of goods and services and constant technological change. Speed is taken for granted professionally whilst quality and innovation are expected by consumers and users with simultaneous push and pull of products, services and experiences to and from users. Managing complexity, systems thinking and disruptive innovation are all current core attributes of successful design projects. Every new innovative material, practice and technology can be considered and exploited up by the ever hungry designer and transferred to their particular opportunity. But there is a distinct shift—it is not now all about ways and means—intelligent design thinking still takes time, careful observation and testing plus a liberal helping of serendipity. Projects are increasingly selfless, based on global, commercial and societal shifts with the designer as empathetic orchestrator. We all know the influence of Mr. Ives and Apple—the power to create demand, to employ vast numbers of people, to change peoples' lives in many different ways. But most products and services are beyond the comprehension and influence of individuals. A characteristic of many IDE alumni is that they do not tend to be designer names per se rather they are transdisciplinary team players (see Pennington 2010).

IDE does inhabit the triangle of design, engineering and transdisciplinary work but also strays outside of it by generating experimental work. We currently use a strand system with students able to elect to take a disruptive market innovation or experimental route. We have yet to see the strand system connecting together to run from experimental work through design for manufacturing (design for market is probably a better description) to design enterprise and commercialisation. This is surely a small next step? Many graduates may end up questioning 'what is design?' in the sense of IDE. The answer is probably that adaptable design thinking is the most valuable commodity which they possess—the ability to think laterally, to order, as well as vertically; the ability to leapfrog to solutions and propositions which can then be 'built backwards'. They could consider that perhaps Design is no longer a problem-solving activity, rather it is an opportunity identification activity (Pennington 2010).

4 Educational Model

There is no instruction book on how to do Innovation Design Engineering, the course is still very much about exposure to projects, whether this involves a product, artefact, system or philosophy. There are, however, key elements that are at the core of the course's ethos.

- Diversity. IDE has expanded both in its student numbers and in its types of applicants. From the start of the academic year 2013–2014, the course will host over 80 students, from over 20 different countries (including United States, South Africa, Mexico, Germany, France, Spain, Korea, China, Romania and India) with backgrounds from mechanical engineering, electrical engineering, through to product design, graphic design to fine art, economics, language and commerce. It is partly thanks to this mix of diverse backgrounds, experiences and cultures that innovative leaps can take place in group projects.
- Design and Engineering mix. IDE is about a lot more than good design, it is about combining design with engineering and technical mastery. The course takes advantage of the skills and cultures of a predominantly technical university (Imperial College London) and a college of art and design (Royal College of Art). The result is the rigour and precision of science and engineering in

combination with the inspirational and creative aspects of design. The relationship between the RCA and Imperial College has probably never been stronger; there is a sense of ambition and energetic involvement from both institutions. The graduates of the course are now not only awarded an M.A. from the RCA they are also awarded an M.Sc. from Imperial college—an act that really emphasises the commitments from both institutions.

- Making it real. Taking advantage of the workshops in the RCA, Imperial and beyond is not optional for the students of IDE; it is a necessity. The programme staff and associated departments are commercially outward facing, with staff and students liaising and engaging with industry. As such, there is, as there has always been, an emphasis on making it real. Whilst we encourage innovation in all directions, including future challenges, whatever the proposition, its proof of concept still needs to be produced and proven—prototyping the probable to make it the possible.

IDE's teaching philosophy has evolved considerably over the last 30 years, from the original remit of joining design and engineering through cross-disciplinary working to the later interdisciplinary model forming a 'T' shaped skills profile where we began recruiting from wider creative and technical disciplines. Group work produces graduates who can collaborate effectively between diverse disciplines and leverage the benefits of resulting relationships. In the last few years, we have moved into a transdisciplinary phase where students are competent across several disciplines simultaneously represented by an 'm' shaped profile of multiple discipline competence.

Many design courses rely on an implied narrative about how to design, a story composed of a series of modules which link up by building skills and knowledge in ever-increasing levels to be practiced on a final capstone project (Childs, Zhao and Grigg 2013). This can be highly suitable for an intake of candidates with similar backgrounds and educational levels. The 2013 IDE intake consists of 41 students from 17 different countries and 12 disciplines ranging from aerospace and engineering to economics and mechatronics. The educational challenge of teaching such a diverse cultural and disciplinary mix has necessitated the evolution of a new teaching strategy, a non-linear pedagogy. The IDE approach is to create a diverse mix of modules that vary from theoretical to practical and commercial to systemic. The aim is to create the maximum difference between modules to expand students' thinking, to encourage an individually tailored creative process. To help understand this structure a 3D module engine has been produced (see Fig. 2) to visualise the diversity of the first year programme modules (Hall and Childs 2009). The models run bottom to top with the grey sectors being modules, yellow plates are term dividers and other colours are workshops and special projects. The module profiles become more varied as the programme develops and the student experience becomes more challenging and diverse.

Engineering spans the sciences as well as the arts. It involves the development and embodiment of ideas for societal use. It relies on domains such as physics, chemistry, mathematics and the biosciences to ground its physical basis. As

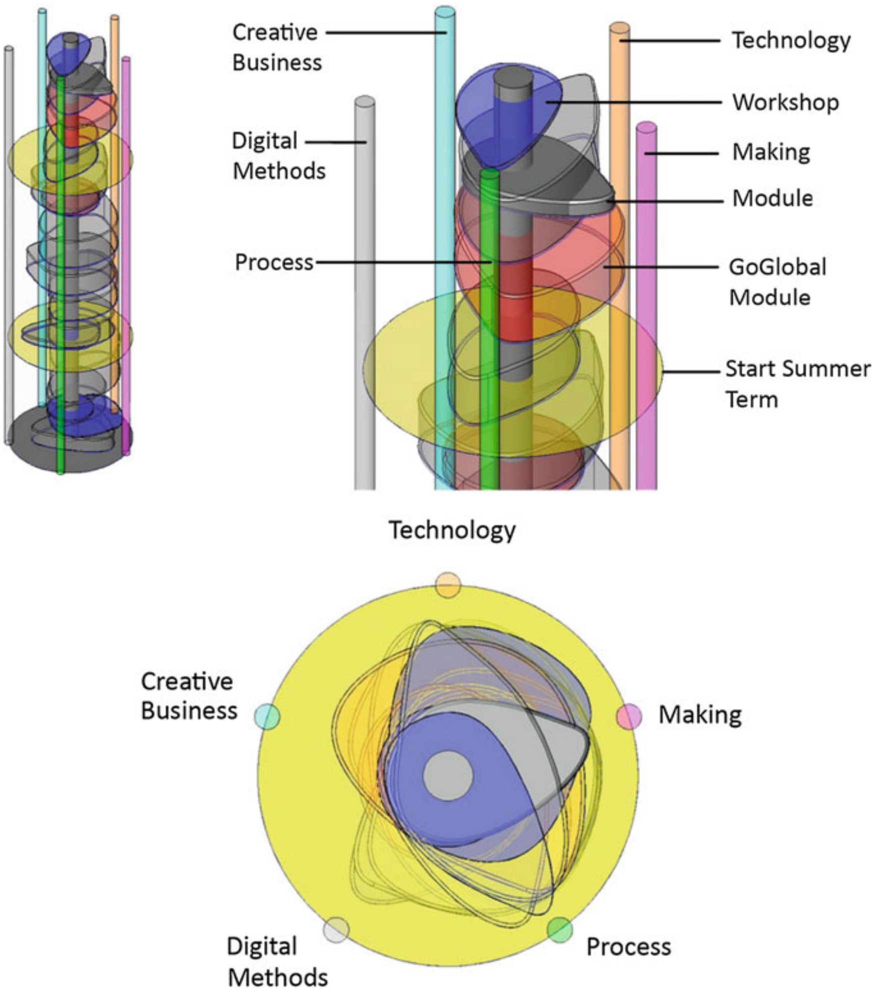

Fig. 2 First year programme—Innovation Design Engineering Module Engine [Hall and Childs (2009)]

engineering is about artefacts and systems for people, it also relies on the humanities and social sciences in order to develop context and understanding. It is therefore quite natural for a degree relating to engineering to involve collaboration between individuals, departments and institutions with diverse expertise. Combining the resources and cultures of the institutions of the Royal College of Art and Imperial College London enables depth and breadth to adventure in ideas, technology and science. The result is manifest in the award of double master qualifications, in science and art, to IDE graduates.

Day-to-day, the relationship involves a huge amount of talking, walking and enabling. Communication is key. We meet, have a joint presence at both institutions, and have organised the teaching, idea exploration and project work so that students and staff are active at both institutions. Although just a few hundred metres apart this means that any individual may walk to and fro several times a day. Given the importance of incidental meetings and collisions to creative acts, this movement serves an important function.

Creativity, the ability to imagine or invent an idea that is new, is essential to both engineering and design. Students arrive creative and they leave with this skill augmented by exploration of a wide number of ideas and increased skills in technology. Innovation, in contrast, can be viewed as the realisation of value from creativity or an idea, and is a key feature in the IDE curriculum. Both creativity and innovation benefit from involvement of diverse research groups and departments from across Imperial. The Design Engineering Group has a symbiotic relationship with the IDE masters programme with insights and trends in design and technology informing the research, and the research informing design projects and curriculum.

Design has a key responsibility in society. The products and artefacts enabled and embodied require resources for their production, use, reuse and possibly disposal. Their adoption can lead to trends and new directions for society. It is therefore a responsible approach to consider the possible implications at the design stage. It is not enough for low energy or a low carbon or negative footprint to be associated with an idea or artefact. Instead the design must be sustainable from both a societal and business context, with opportunity for realisation of appropriate income streams, to enable the idea to become a reality. These notions of embedded and embodied consideration of sustainable issues in combination with innovation and business contexts are key attributes of the course (Table 1).

Table 1 IDE year 1 structure, 2012, 2013

Module	Term	Descriptor
Guerrilla london	1	Contextual induction
Design enterprise	1	Enterprise models
Disruptive market innovation	1	Ideas to reality and innovation
Experimental design	1	Experimentation and exploration
Superform	1	Design process and Form exploration
I'll take 9	2	Meta-team working and Production
Gizmo	2	Gadgets and mechanisms
Innovation challenge	2	Innovation realisation
Goglobal	2	International collaboration
Critical historical studies	2	Critical thinking and theory
Solo major	3	Individual innovation project
Commercial projects	3	Client and commercial delivery

The curriculum is reviewed and updated year on year, often with changes being pulled in during the course of an academic cycle. The naming of some of the modules has served to enable this, as there is an expectation of adventure in experience, syllabus and learning outcome for modules such as Superform, Gizmo, I'll take nine, and the Innovation challenge. Having a substantial solo project in the first year has been a significant formative factor in preparing students for their second year group and solo projects.

An example of a recent commercial project is the collaboration with Airbus reported in Hall et al. (2013). This project explored the value of implementing design thinking insights in engineering practice and the relative merits of decisions based on optimisation versus win–win scenarios for aircraft cabin design. From an engineering design perspective optimisation tends to preclude certain strategies that deliver high quality results in consumer scenarios whereas win–win solutions may face challenges in complex technical environments. This was evident in this project where a team formed of IDE year 1 students and staff, as well as students from Vehicle Design and Textiles at the Royal College of Art, collaborated with Airbus to explore new design concepts. The project formed part of the commercial client activities of the programme aimed at introducing students to top global design scenarios with leading edge manufacturers. Previous projects have been conducted in partnership with the BBC, Elmar, Ford, Guzzini, Hutchison Whampoa, LG, Nokia, Philips, Pramac, RIM, Sony, Swarovski, Thales, Alenia, Unilever and Vodafone. The four-week intensive programme of work began with a client briefing from Airbus and continued with tutoring from IDE staff alongside Airbus through tutorials and project reviews culminating in a final critique of conceptual ideas for new cabin designs. A final project was selected and further refined in an eight-week phase 2 project combining design and engineering expertise from students and academics from the RCA and Imperial College.

Examples of the Airbus Concept Cabin rolled out in 2011 (Hall et al. 2013) show an approach where future passenger needs derived from extensive socio-demographic and economical trend analysis are translated into cabin touch points (see Figs. 3 and 4). Instead of maintaining traditional cabin classes those needs have been placed in an emotional value driven vitalizing zone whereas functional values have been placed in the smart technology zone. In between is an interaction zone providing possibilities for airlines to use the cabin as a flexible market place. All zones where aligned with long-term technology roadmaps to figure out possibilities and potential for realisation in order to use technology as a useful enabler. The concept was inspired by bionic principles, from neuronal network, a cabin membrane to a stiffening structure. The future customer and his needs have been in the very heart of the concept.

Fig. 3 Future cabin design, Hall et al. (2013). Image courtesy of Airbus

Fig. 4 Future cabin design, Hall et al. (2013). Image courtesy of Airbus

5 Destinations

The Industrial Design Engineering programme commenced with just a few students in the 1980s. The destinations of these students through the 1980s and early 1990s are illustrated in Table 2 and brief biographies for about 150 graduates are

Table 2 IDE graduate destinations during the 1980s and early 1990s

Type	1982	1983	1984	1985	1986	19877	1988	1989	1990	1991	Totals	%
Design consultant agency (founder)	1	3		1	2	1	1	2		2	13	14
Design consultant agency (employee)			1	1	1	1	1	1	2	1	9	10
Design consultant (Established individual)				1		2	1	1	1	1	7	8
Design consultant (Freelancing individual)											0	0
Corporation (Established)			3	1		3	2	2	3	5	19	21
Start-up entrepreneur				1	1						2	2
Educator	2		1	1	1	1		1	3	2	12	13
Charity or NGO or Government											0	0
The what						1	1	2			4	4
Lost to IDE unknown		1	1		5	4	5	4	1	3	24	27
Year totals	3	4	6	6	10	13	11	13	10	14	90	

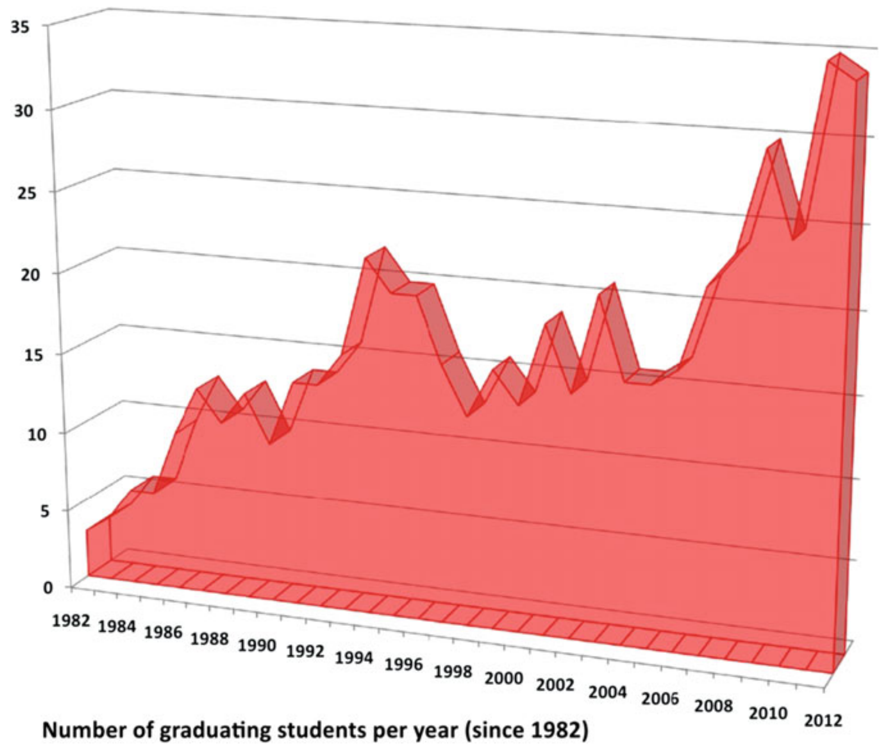

Fig. 5 IDE graduation numbers

described in Pennington 2010. The cohort has grown steadily and the cohort size is plotted in Fig. 5. Any statistical analysis of destinations for the small cohorts concerned is subject to significant uncertainty. Nevertheless the data for the cohorts, assessed by decade is provided in Fig. 6. This figure illustrates a shift away from corporate towards entrepreneurial and individual freelance activities.

Indicative of recent destinations of IDE graduates are the companies Omlet, Concrete Canvas and Bare.

- Omlet, founded by 4 IDE graduates in 2003 (Johannes Paul, Simon Nicholls, William Windham, James Tuthill). Their company grew out of the final graduation project of James Tuthill; in fact the inside story is that they had a highly developed strategy for assisting one another during the second year, focused on commercially exploiting Tuthill's idea of renting chickens to urbanites. The innovative business model has become perhaps less important as they have created iconic products which capture the imagination (e.g. see Fig. 7), not least

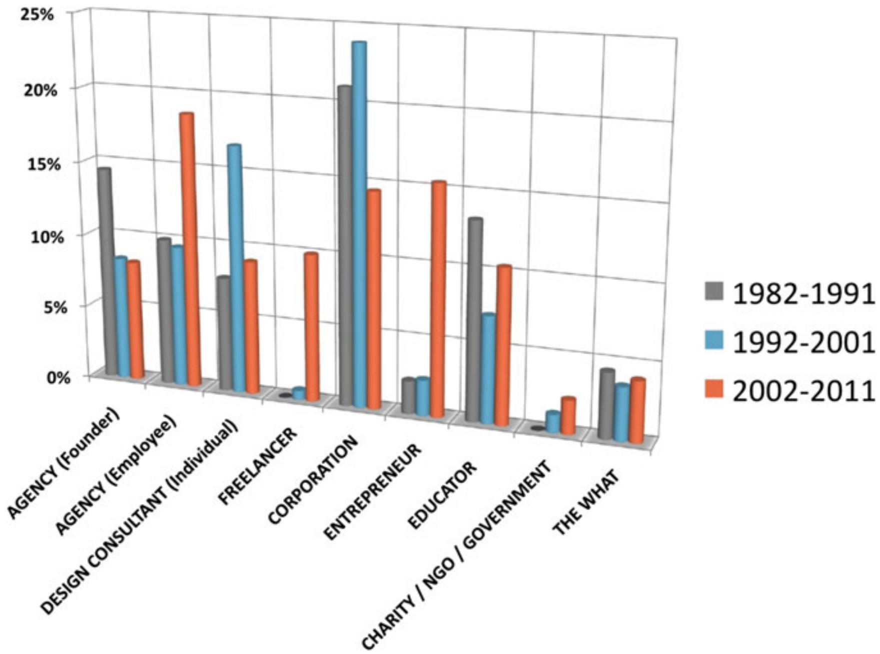

Fig. 6 IDE destination trends across three decades

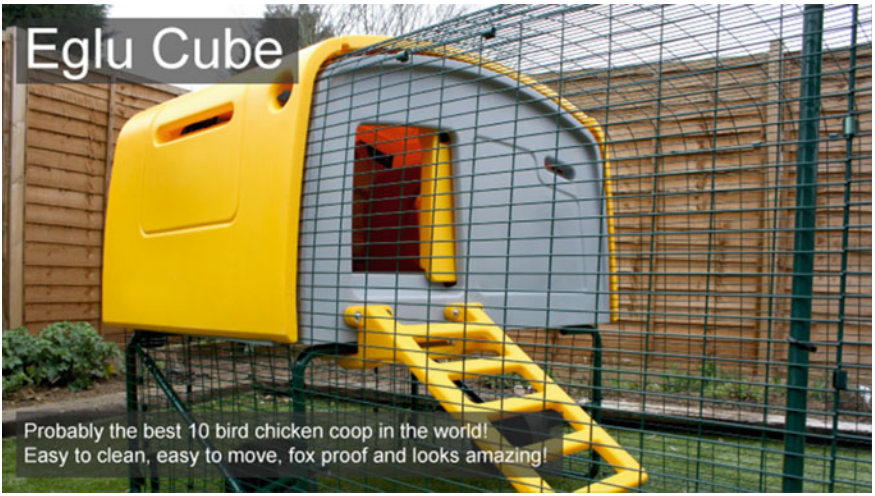

Fig. 7 Omlet http://www.omlet.co.uk/ Accessed 14th July 2013a

Fig. 8 Concrete Canvas http://concretecanvas.co.uk/ Accessed 14th July 2013b

the latest addition to the fold; the Beehaus. Omlet has a multimillion pound turnover. This demonstrates the power of the market, the power of the capability of design and innovation to capture the imagination of people and to influence their lives.

- The innovative shelter technology, Concrete Canvas (Will Crawford and Peter Brewin) was actually an IDE minor project; a notionally small idea developed as an addition to final projects. It has recently been developed with the US military and looks set to have a big impact on disaster relief (see Fig. 8).

Fig. 9 The BARE team at the Mini Maker Faire, Elephant and Castle, July 2013 http://www.bareconductive.com/blog Accessed 14th July 2013

- Some projects get absorbed into culture-like Bare Conductive Inks from 2009. Bare Conductive Paint is a multipurpose electrically conductive material perfect for all of your DIY projects! Bare Paint is water based, nontoxic and dries at room temperature. This captured the imagination of the writers of TV's CSI Miami who used it in one of their episodes. The inks have proven highly popular with the re-emergent maker community (see Fig. 9).

6 Conclusions

Sir James Dyson, who graduated from the RCA in 1970, has said that the UK's economic future needs a cultural change: 'To develop high esteem for science and engineering'. The Innovation Design Engineering programme has developed from a programme initially aiming at transforming engineers to a programme that embraces a wide range of disciplinary entrants, and guides them on a journey through experiences in design, technology, engineering, towards a destination of innovation enabled by their diverse skills and experience. The programme is characterised by an ever-changing curriculum, as would be expected for programme including the words innovation, design and engineering in the title. The continuous review and updating of the curriculum is seen as effective and crucial in ensuring the challenging nature of the programme. Quoting Sir James Dyson again: 'Innovation Design Engineering has produced and nurtured the most exceptional minds…'

Professor Neil Barron, Senior Tutor for the second year noted (11 July 2013) ‘Finding the innovation space is a key area students struggle with and we can help them with this’. This is enabled by a celebration of technology, engineering design, and science, embodied in the cultures of Imperial College London, a celebration of design and design discourse embodied in the cultures of the Royal College of Art. As the programme has developed so have the destinations of our graduates with an emerging trend towards the generation of companies on completion.

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Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA

Georges Fadel, Gregory Mocko and Joshua Summers

Abstract In this chapter, the authors summarize many years of design research at Clemson University and the subsequent impact on industrial practice, particularly in the evolution and transition of disparate ideas into cohesive concepts that were eventually transitioned to industry. In design research, a broad area of endeavor, design theories take the longest to develop and are the slowest to transition to industry. However, the development of methods, practices, and their applications to industrial problems are much quicker to transfer, since industry professionals see the immediate potential benefits or shortcomings of the methods and issues of interest to them. Finally, the training of students at all levels in design practice certainly affects industry as many assume positions in, and affect the practices of their companies.

1 Introduction

This effort involved three researchers of the CEDAR (Clemson Engineering Design Applications and Research) group at Clemson and their students who were engaged in research to design artifacts for industry, and to teach design. Because of our regular collaborations with each other, we became a single entity focusing on mechanical design research at Clemson. Consequently, we chose to write this chapter as a group. Though we do not always work together, we do have many projects in which we collaborate, and through which our individual directions complement each other. Through our regular weekly group meetings, in which our students shared their experiences, problems, and results, they both assisted each other and defined the group name and its code of ethics. While we also have many projects we conduct individually with students, each of us also serve on either the thesis or dissertation committee of all members of the group.

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This chapter is organized as follows: Each faculty member describes their research projects, listing one or two publications per topic, and their positive use to their industrial collaborators. The evolution of the descriptions shows how they coalesced to address several of the multiple facets of engineering design as they describe their collaborative efforts on these projects. Next, their impact on design practice through the education of students is highlighted, and finally they describe their use of the student designers as test subjects to learn about design, and to train their students in design research. The chapter finally concludes with the overall lessons from this effort.

2 Research Contributions

2.1 Fadel: CREDO (1992–2008) and CEDAR (2008–Present)

Dr. Fadel's contributions address theory, methods, and application in support of mechanical design. Presented in approximate chronological order, the section focuses on his research and that of his students which involved the improvement of design practices in mechanical engineering.

Dr. Fadel began his work in optimization during a spring semester at NASA Langley in which he collaborated with Drs. Jarek Sobieski and Jean-Francois Barthelemy. At that time, Dr. Sobieski was devising the basic methodology of multidisciplinary optimization (MDO), and an important part of which entailed the use of approximations to accelerate optimization and avoid long and costly analyses when possible. Dr. Fadel developed and published with Dr. Barthelemy a paper on the two point exponential approximation, (Fadel et al. 1990) and then later derived approaches based on that approximation to control the magnitude of change of design variables to ensure convergence during optimization. Scholars in structural optimization in academia and professionals at both industry and at NASA have used this approach to reduce computational cost.

Dr. Fadel's research team then began research to use optimization to elucidate solutions to complex design problems. The established goal was the development of a solution for packaging or layout optimization problems, considering complex non-convex shapes, and a multiplicity of criteria. One of the first problems they attempted to address was the layout of the under hood of a vehicle subject to ground clearance, the location of the center of gravity, and accessibility. Dr. Fadel and a team of collaborators applied for and received a grant from NASA to work on this multidisciplinary problem, a facet of which entailed tasking the students involved in this effort to collaborate with others from other disciplines. Several Ph.D. students worked on defining this problem and developing a method to encode the CAD data for use with an interference checker and an optimizer. This method was then used to locate the individual components within a non-convex allowable space subject to a multitude of constraints and criteria. To mitigate the expense of the interference calculation, in terms of computer time, the CDOM or the Configuration Design Optimization Method was adapted. Dr. Fadel and his team have since used this method to develop hybrid vehicle applications for the Tank Army Command (TACOM), particularly in addressing roll over prevention, survivability, ground clearance, dynamic response, and thermal considerations. The approach was also modified for the GM Corporation for computing the luggage packing capabilities of new vehicles. That code, which remains currently in use, is still outperforming other similar existing codes (Fadel and Fenyes 2010; Miao et al. 2008).

While addressing optimization and the associations with CAD in both the layout and packaging optimization, Dr. Fadel's group became interested in rapid prototyping, and began applying optimization to problems in additive manufacturing. First, the team developed a method to optimize the placement of objects on the build platform. The optimal direction of the build was next developed, followed by an optimization of the slice thickness to reduce stair-stepping. He and his group next developed a number of algorithms, one of which was a code to correct STL files (Morvan and Fadel 1996), and another for immersing users within their CAD representation in a virtual environment. Many of these codes and papers were published and some computer codes were sold to companies. The experience obtained in the development of these approaches enabled Dr. Fadel and his colleagues to establish a consortium of additional companies through which they provided training in the use of additive manufacturing and to transfer the results of that research as it became available.

Through this combination of the work on layout optimization and additive manufacturing, Dr. Fadel's students then began to explore the field of multi-material design and manufacturing. The approach used for the layout optimization was adapted to the layout of materials within a configuration to determine both the optimal shape and the optimal placement of materials. Since Dr. Fadel's students had assisted in developing the code to drive the LENS machine developed at Sandia and commercialized by Optomec, they used this opportunity to construct a flywheel of materials optimized to increase energy storage capability without a commensurate increase in size or weight (Huang and Fadel 2000; Morvan and Fadel 2002). The approach was also applied to the design of molds that are optimized to achieve rapid and uniform cooling by judiciously designing copper paths in the original mold material. This research has been of interest to industry since additive manufacturing is becoming more widely used. Moreover, as companies are eager to increase performance while reducing weight, they are therefore more inclined to consider novel approaches.

The development of ultrasonic consolidation (UC), another additive manufacturing process, was conducted in collaboration with the Solidica Company. The process, which consists in ultrasonically bonding thin foils of metal by ultrasonic vibrations, has the potential of bonding dissimilar materials and embedding fibers or sensors between the foils. With support from the National Science Foundation, Dr. Fadel and his team elucidated why the process failed at some characteristic lengths, and then determined that in excess of that length, there was no difficulty in consolidating additional material (Gibert et al. 2010, 2013). Solidica then used this research to resolve this difficulty in the continuing evolution of this process. The group is now trying to understand why the process works, an understanding which can be used to improve the additive manufacturing process. Though this UC process and the LENS process both allow multi-material manufacture, both have very different characteristics; UC is layer based and LENS is point based. Through their research, Dr. Fadel and his students determined the necessity of considering manufacturing concepts in the design phase to generate heterogeneous objects within the constraints of current manufacturing capabilities (Hu et al. 2006).

Through this research into multi-material constructs, Dr. Fadel and his students began collaboration with Dr. Summers, and the Michelin Corporation. They submitted a proposal to the National Institute of Standards and Technology (NIST) to investigate how to reduce rolling resistance when using a novel airless tire concept invented by Michelin, the TWEEL. Dr. Fadel's students developed a two-level approach in which they first identified the required material properties of the shear layer material of the TWEEL by performing analyses with models developed by his colleagues. They next used topology optimization approaches to design the geometry of a metamaterial object (an object with material properties that differ from the bulk material properties because of specific geometries). Again, issues of manufacturability had to be considered, the results of which, though understandable, were not initially envisioned by the design team (Czech et al. 2012). This industry/academia initiative was of direct benefit to the automotive industry and the TWEEL is now marketed by Michelin for certain classes of vehicles.

The work on optimization in support of the US Army TACOM continued with the investigation of approaches to optimize complex systems. Initially, Dr. Fadel and his colleague, Dr. Wiecek and their students applied the Analytical Target Cascading (ATC) approach, developed by Dr. Papalambros' group at the University of Michigan, to various vehicle design problems for the Army. Issues of convergence were studied, and a two-level approach based on ATC along with geometric considerations was then performed. In one application of interest to the Army and to one of its civilian suppliers, the cell configuration within a battery was optimized to reduce hot spots while its outer geometry and placement under the hood were simultaneously determined, considering the geometric and functional constraints (Dandurand et al. 2013). In the last few years, the NTC or Network Target Coordination has been under development by the Clemson team to optimize non-hierarchical and multidisciplinary systems. NTC is currently being applied to solve problems in army vehicle design.

While performing mostly optimization-based approaches and applying them to a multitude of problems, Dr. Fadel and his students also investigated design methods and theories. They initially researched Function-Based Design, and established a grammar to describe functions for a mechanical system (Kirschman and Fadel 1998), moving beyond earlier work on functions (Pahl et al. 2007; Rodenacker 1971). Though they favored the concept of Function for describing transformational processes and as an abstract concept to generate possible solutions during innovative design, they also deemed it necessary to create another paradigm to handle nontransformative aspects of the design. They adapted the concept of Affordances from perceptual psychology, (what a system affords the user, either for good or for ill) and developed a number of methods to support Affordance-Based Design (ABD) (Maier and Fadel 2008, 2009). They collaborated with Dr. Mocko and his students to determine the aspect of situatedness of the design and how to consider this aspect during the design. Using the perspective of interactions or affordances, Dr. Fadel and his students showed that a system consisting of a user, artifact, and designer behaves like a complex adaptive system and can be studied as a complex system. They applied this approach to various examples, the most current of which was the association with an optimizer to show that designers typically increase positive affordances, and decreases the negative counterparts as the design evolves into a variant design problem. This approach has gained significant momentum in the last few years, and is only starting to be used in industry as evidenced by the comments from the readers of an ABD textbook published by one of Dr. Fadel's students, Dr. Maier. Currently, the team is engaged in research to couple affordances to an optimizer to improve variant design during the conceptual stages, the results of which they have shown to various companies. Several other collaborative efforts with Drs. Mocko, Summers, and their students are described in the subsequent paragraphs.

The combination of these diverse aspects inherent in research design, and in subsequently managing the complexity of the various problems from such designs has been the central focus of Dr. Fadel's research. It has evolved over many years, in which the computational capabilities and the approaches have been configured to manage the increased complexity of the multiplicity of interactions in a design. Dr. Fadel believes that optimization, focus on interactions, and prototyping are critical to this continual evolution. The next step in that evolutionary process should involve applying complexity theory to these various problems so that design researchers can develop new theories, methods, and tools. These are certain to further improve industry and enhance the knowledge that mechanical engineering students learn at various levels of study.

2.2 Summers: AiD (2002–2008) and CEDAR (2008–Present)

There are three main research strategies that have emerged with regard to the types of research that Dr. Summers directs. The first is the development of new design enablers to support different engineering design activities. This area of research is typically supported through the development and testing of new tools, both manual and automated. The second is centered on developing fundamental understanding of the engineering design process, a research endeavor supported with empirical research strategies of case study analysis and protocol study research. The final research strategy is focused on application design and development. While the purpose of the first strategy entails providing justified and tested support for engineers, the purpose of the second entails elucidating the processes in which they engage. Finally, the third strategy is one of providing the members of the research lab with experiences in practicing engineering design from a first person perspective. In the past decade of graduate researcher training, Dr. Summers has created and completed several projects that have provided students with opportunities to grow as researchers, engineers, and professionals. Several of these projects are illustrated below to offer evidence of a major mechanism for design research transfer to industry via the trained students on industry sponsored projects.

One of the first projects that Dr. Summers established was the development of a “Lamelle Query Systems” for Michelin in 2005–2006. In this project, students used the design exemplar as a software prototyping tool to define geometric algorithms that could be used to match repeated line–arc–line patterns for tire tread inserts within bounding tolerances. This was the first industry sponsored project that employed the principles of the design exemplar as a CAD Query Language (Summers et al. 2006), recast into a dedicated system that was delivered to Michelin to support tire designers in reusing stamping tooling to construct the lamelles, or tire inserts, resulting in an annual estimate savings of several hundred thousand dollars (Srirangam et al. 2014).

The success of this industry sponsored design automation project led to two other industry sponsored projects. In the first, sponsored by Hartness International, Dr. Summers collaborated with Dr. Mocko to create a detailed method for capturing the design rules for configuration and manufacturing management (Chavali et al. 2008), a process that is in use at the company. In the second project, initiated in 2006 and sponsored by Wright Metal Products, a company that produces metal frames for shipping riding lawnmowers and jetskis to distributors, Dr. Summers developed methods to mitigate the knowledge loss of upcoming retirements of key frame designers. The Clemson team developed a tool that frame designers could quickly use, in real time, to configure frames and run basic load analysis to determine deflection while providing costing estimation for the materials and weld times (Kayyar et al. 2012).

Additionally, in 2006, Drs. Summers, Fadel, and Mocko initiated a project, described in the previous section, with BMW to explore the association of the mass with vehicle subsystem requirements. While a catalyst for Drs. Mocko and Fadel to explore requirements allocation and management for the US Army, the project also developed into additional design method development projects for Dr. Summers. One of the most significant of these was the development of a lazy parts identification method for BMW with Dr. Mocko (Caldwell et al. 2013) which is currently being integrated as a design process best practice within the BMW development teams. One of the lazy part indicators developed by Dr. Summers, known as duplicate geometry, served as the basis for the subsequent development of their feature recognition design enabler (Shanthakumar and Summers 2013). Building upon the success of these BMW design method development project, Drs. Mocko, Mears, Kurz, and Summers then undertook product–process modeling and support projects for BMW. In collaboration with colleagues, Dr. Summers also used the results from this project to develop computational tools for estimating assembly times from assembly models absent of installation instructions (Namouz and Summers 2014; Owensby and Summers 2014).

While the initial research direction that Dr. Summers undertook was a continuation of his dissertation research on design enablers and automation, he and his research group exploited additional opportunities to work with industry, specifically BMW in three discrete development projects. Begun in 2005 and funded through Clemson University, Dr. Summers worked on two of these projects in lightweight engineering redesign of car seats and of headlights. Here, executed collaboratively with Drs. Grujicic and Thompson, graduate and undergraduate students reverse engineered multiple competitors to establish benchmark best practices in an effort to reduce the weight of the two systems. Though a formalized reverse engineering tool was developed to support this activity (Snider et al. 2008), the primary objective involved identifying concepts that could be explored for mass reduction. Dr. Thompson worked on a follow-on project on seat design while Dr. Summers led the subsequent development project on LED headlight design (Morkos et al. 2009). In the LED headlight design project, Dr. Summers initiated a new undergraduate Creative Inquiry team that explored the creation of metal foams (Hess et al. 2011) which is now evolving into a collaborative graduate research thesis on metal foam manufacturing, jointly advised by Dr. Summers and Dr. Choi.

Other development projects that supported graduate students and provided motivation and demonstration platforms for graduate research include the development of an integrated trash and recycling truck for Environmental America, Incorporated (Smith et al. 2007), the development of a tire tread sample mud debarrage device for Michelin with Dr. Mears (Maier et al. 2012), the development of a cryogenic temperature non-pneumatic tire endurance “road wheel” for the Jet Propulsion Laboratory (Morkos et al. 2010), and the development of a tent ballast resistance testing system for the Industrial Fabrics Association International with Dr. Blouin. These projects provided graduate students with splendid opportunities to learn relevant design and development practices while in graduate school. Moreover, they have been used for the case study exploration of information exchange during the projects (Miller and Summers 2010) and as experimental elements in understanding how the presence of proposed controls influence students’ ability to estimate project success (Thimmaiah and Summers 2013).

Dr. Summers also undertook a different development opportunity in 2006, which came about from a brief three-week visit to NASA’s Jet Propulsion Laboratory. Funded by the Michelin corporation this expansive collaborative research entailed exploring possible material replacements for the polyurethane based non-pneumatic tire to support future manned missions to the moon and Mars. Dr. Summers also used this meso-structure design and analysis project to create a jointly sponsored capstone design initiative through which several undergraduate student teams designed, built, and tested the first generation of lunar Tweel concepts (Stowe et al. 2008). These successful concepts led to two NASA and NIST sponsored projects to develop non-pneumatic tires through meso-structures. In these collaborative projects, Drs. Joseph, Blouin, Cole, Fadel, Mears, Ziegert, Kurfess, and industrial partners, the team developed case studies (Stowe et al. 2010), new design methods (Berglind et al. 2010), and granted two patents. From this meso-structure development experience, Dr. Summers has advised subsequent student research efforts involving acoustic–vibration attenuation, energy absorption and crushing, and meso-structure design method development (Schultz et al. 2012).

In addition to this specific meso-structure research, a new endeavor from their projects involves the modeling of sand–tire interaction and the development of traction concepts, efforts supported by the US Army through an Automotive Research Center project with Drs. Joseph and Biggers. These efforts have been formalized in a 6-year Creative Inquiry project for undergraduate students. Modeling the sand–tire interaction computationally has provided numerous intellectual challenges to motivate graduate research (Reeves et al. 2010). The undergraduate teams have produced results that have been archived in various publications (Satterfield et al. 2013). More significantly, the undergraduate approach to physical testing of sand–tire interaction has resulted in design–build–testing opportunities for students, enabling Dr. Summers to recruit several graduate students with experience in the CEDAR lab.

Dr. Summers collaborates extensively with colleagues, uses the industry sponsored projects to initiate new research themes, exploits the sponsored projects as motivating and demonstrating cases for other graduate research, and continuously seeks opportunities for graduate and undergraduate student engineering skill development. This philosophy of highly coupled industry-driven, informed, and enhanced research has guided Dr. Summers in advising over four dozen graduate students over the decade of his experience at Clemson University (Summers 2013).

2.3 Mocko: EIML (2006–2008) and CEDAR (2008–Present)

The focus of Dr. Mocko's research encompasses two primary themes: (1) the development & formalization of knowledge to support mechanical engineering design and manufacturing and the application of tools to mechanical engineering design practice, and (2) the study of tools used in conceptual design to support the ideation process and generation of innovations. Several government and industry sponsored research projects, presented in chronological order, demonstrate the fundamental contributions to engineering design research and the application to industry practice.

Dr. Mocko began work in the area of automotive design and requirements and testing analysis with BMW AG. In this project, he collaborated with Dr. Fadel and Dr. Summers to develop methods and a computational tool to identify, manage, and mitigate changes in engineering requirements. In particular, a graduate student and postdoctoral researcher leveraged existing techniques from the Design Structure Matrix (DSM) and Design Mapping Matrix (DMM) to enable changes in engineering requirements, systems architecture, and validation and verification tests to be evaluated (Mocko Gregory et al. 2007). The research project resulted in an MS thesis under the supervision of Dr. Fadel and several papers presented at national and international academic conferences as well as at the BMW Research and Development Center (FIZ) in Munich, Germany. The contributions from this research were applied to several automotive systems to help identify key engineering requirements and tests during conceptual product development and generational redesign. In addition, the techniques developed were further explored by Dr. Mocko and his graduate students to address concepts of manufacturing flexibility and change management. An approach was developed to guide designers during system changes to understand the impacts of requirements on the manufacturing processes. This approach was subsequently applied to the evaluation and redesign of a vehicle headliner and design of innovative automotive seating structures for a first-tier automotive supplier.

Dr. Mocko and Dr. Fadel continued to collaborate through the integration of affordance-based design approaches and existing function-based design. In this research, sponsored by the U.S. National Science Foundation, the situated context of engineered products was explored as both [active] function and passive functions [affordances]. Situatedness is defined as how a product is used, the users of the product, and the interactions between the product and the user, other products, and the environment. Situatedness provides a larger scope and context that must be considered when designing a product over the traditional view of engineering function modeling. The goal of this research involved developing formal product design tools that integrate functional and nonfunctional approaches. Dr. Mocko's graduate students formalized a model and a method for capturing active product functions, product–product interactions, product–environment interactions, and product–user interactions. The different types of interactions as well as the activities performed by the user were modeled. A graphical modeling technique and template was developed to aid in the documentation, modeling, archival, and communication of situatedness for a product. Further, Dr. Mocko and his team validated and verified the approaches through several user and empirical studies. The model of situatedness was then applied to the development of automotive seating structures in which the functionality of the seating structure and the interaction of the seat with the vehicle occupant and vehicle is of primary importance. In addition, a focused research topic in the area of modeling and analysis of engineering requirements using advance text and language processing techniques was undertaken. A graduate student identified and developed formal models of engineering requirements using computational linguistics and natural language processing approaches and tools (Caldwell and Mocko 2012; Caldwell 2012; Caldwell et al. 2010; Caldwell et al. 2012; Ramachandran et al. 2011).

As mentioned previously, Drs. Mocko and Summers and two graduate students worked with an international packaging and machine design company to assess, develop, and integrate rule-based CAD design systems into their product design process. In this project, students worked closely with engineers, developers, and sales engineers to identify the business and design rules associated with their products, documented the rules in a formal manner, and implemented the rules in commercial CAD and rule-based systems. Using the results from this research (i) the industry sponsor captured and recorded their business rules, (ii) the rules and parametric CAD models were developed for use by the industry sponsor, and (iii) the rule-based approach, what was learned about rules helped to integrate the rule-based application into Solidworks. This project was a great example of close collaboration with industry on both a practical design problem and a research opportunity (Chavali et al. 2008).

Drs. Mocko, Fadel, Maier (a former student of Dr. Fadel), and a graduate student worked with the Automotive Research Center (ARC) at the University of Michigan and the ARMY TACOM to develop methods for mass reduction in military vehicles to increase safety, material costs, transportation, cost, and fuel consumption. An engineering requirements method was developed and exercised in the conceptual stages of design to identify requirements that impact significant amounts of mass. These engineering requirements are linked to mass through the creation of a standard requirement statement using preprocessing rules and syntax rules. These rules and guidelines are applicable for authoring new requirements and analyzing existing requirements documentation. The processed engineering requirements are linked to physical components and assemblies based on how the requirements affect the components. These relationships are captured in Design Structure Matrices (DSMs) and Domain Mapping Matrices (DMMs). These DMMs and DSMs are used to attain the amount of mass each requirement affects and the level of coupling of each requirement. The method is demonstrated on three subsystems of Family of Medium Tactical Vehicle (FMTV) truck (McLellan et al. 2009a, b; Maier et al. 2009).

Dr. Mocko collaborated with Drs. Ziegert and Summers with several engineers and product designers to develop (1) innovative and lightweight seating concepts, and (2) a method to support design space exploration and concept development. Several graduate students and researchers from Clemson University worked directly with design engineers to explore innovative manufacturing methods, new technology developments, analysis of seating requirements, and mechanism design with the goal of radical design and innovation. During the development of innovative seating concepts, Dr. Mocko and the students developed a conceptual design method to support distributed conceptual design space exploration. The process and information was developed in collaboration with industry partners and has resulted in an Options Exploration method currently in use at Johnson Controls Incorporated (George et al. 2013).

Drs. Mocko and Summers worked with researchers at BMW AG and BMW MC to develop methods to analyze existing vehicle designs and future concepts to reduce mass. As part of a 2-year project, several graduate students developed methods and computational tools to support the analysis of vehicle to reduce mass, and thereby improve performance, from the perspective of both design and manufacturing. The methods and tools developed were applied to a conceptual vehicle design workshop attended by several vehicle designers and manufacturing engineering, and a Clemson University student. In this workshop, and existing vehicle was reverse engineered, benchmarked against other vehicles, and the Lazy Parts Identification Method was applied to identify areas for mass reduction. The approach is currently being used by BMW associates and has led to several new research projects.

Dr. Mocko has been collaborating with Dr. Summers in the development of next-generation knowledge representations for manufacturing enterprises. In collaboration with Dr. Funk and Dr. Schulte at BMW AG, the Clemson team have identified and formalized the knowledge associated with assembly line process descriptions and relationships with other sources of engineering knowledge including CAD representations, logistics models, and work place models. These knowledge representations were developed to support a closer integration of existing databases and tasks that are performed in the extended supply and manufacturing network. In addition, Dr. Mocko has collaborated with Drs. Mayorga, Mears, Kurz, and Summers to support mixed assembly line balancing algorithms. Dr. Mocko's students have developed several tools, including web-based and local tools to support line balancing. During this three-year project, they developed a formalized language for the representation of assembly instructions. The project has directly enhanced the development of next-generation tools and approaches for modeling, managing, and analyzing assembly instructions in the automotive field with potential applications in consumer product and aerospace (Renu et al. 2013; Peterson et al. 2012).

The common themes across the sample of research and development projects are summarized as follows:

- Close collaboration with industry. This includes several site visits, teleconferences, meetings, and workshops during the projects to have a true impact on industry. Academic research can quickly veer off course. During the completion of these projects, the PIs and students have been intimately involved with industry—often through interns or extended work periods.
- The research themes continue from project to project with a particular focus on information and knowledge representation and methods to support conceptual design.
- Research must be both demonstrated and validated with real problems.
- There must be a value proposition for industry.

3 Design Education and Its Impact on Industry

Being an education institution, our biggest impact on industry is certainly our education of engineers who join the work force and bring some of our methods and tools to industry and transfer that knowledge to their companies. One fundamental component of the education of design happens at the undergraduate level. Though undergraduate education can be deemed as separate from the results of our design research, it does indeed affect and is affected by that research. At the graduate level, the research is directly incorporated into courses and the knowledge is therefore readily transmitted to students who pursue advanced degrees. We will first describe the undergraduate and then the graduate experience.

3.1 Undergraduate Design

At Clemson University, capstone students are expected to have completed their introductory and secondary technical engineering courses. This capstone course provides students an opportunity to apply the knowledge gained from their previous courses while adapting design techniques to execute technical tasks. Capstone is a three credit hour course given during a single semester in which each student is grouped into a team of three to four students. This encourages the student to work on his or her own social skills alongside their technical knowledge. The student teams are provided with an industry sponsored design project. Teams must apply their knowledge of the design process to complete the project successfully.

The capstone design program in the Department of Mechanical Engineering at Clemson University has been a critical part of the curriculum for over 40 years. Industry partners sponsor all projects and three to five teams of four to five students are assigned to each project. The expectation of each student is ten to fifteen hours of work per week so that for a team of five, the final deliverable is well over 600 man-hours throughout the semester.

The capstone course occurs during a normal Fall or Spring semester. During those 15 weeks, students are expected to work in their assigned teams to design, build, and test a solution to their design problem. A summary of available projects is distributed amongst the capstone students and each student must submit a resume form to ascertain each student's experience level in design and fields of interest. The form also requires students to select one negative and two positive choices for their preferences in terms of projects or teammates. These forms are then used to assign students to teams.

Each design problem is assigned to three teams of at least four students. The teams work independently to solve the same industry problem. Each student team is presented with the problem simultaneously by the sponsor on the Clemson campus and provided the same information regarding the project. Each team is also expected to design, prototype, and test their proposed solutions, and document their test results and solutions. Assigning multiple teams to the same problem permits the development of at least three distinct developed, prototyped, and tested solutions.

Industry sponsors provide the teams with a presentation of the problem to be solved. This presentation is succeeded by a plant tour and student verification and clarification of the proposed problem. Student teams provide the sponsor with an official progress report in their midterm presentation. They must then present the analysis of the problem during their midterm presentation. The sponsor is expected to be available to answer questions periodically throughout the semester. At the conclusion of the semester, teams present their final design and recommendations to the sponsor.

On campus, students have access to multiple forms of technical aides. The student machine shop is available during normal business hours where students can use machining tools such as mills, lathes, and other power and hand tools to prototype their designs. They also have access to a computational lab for the creation of computer models and analysis as well as a meeting and discussion room reserved solely for the capstone design teams. Students are encouraged to use this room to meet weekly to collaborate on their team-based designs.

Two faculty members and a graduate coach are assigned to each project as an advisory committee. Weekly design reviews are conducted to provide feedback to the student design teams. Teams prepare a 15-min presentation to summarize the work completed over the past week and to propose a schedule of tasks for the upcoming week. Approximately 8 weeks into the semester, teams are required to give a midterm presentation to the sponsor, including the understanding of the problem and their proposed solution ideas. During the second half of the semester, the teams must choose, build, and test a prototype solution. The results of the testing must be included in their final presentation and design report. Final deliverables include a prototype, fully detailed solution, and final design report complete with any necessary drawings and information for implementing the chosen solution.

The graduate coach, known as the gradvisor, is a graduate student specializing in design. The gradvisor must have taken graduate design methodology courses, and properly advise the students to ensure that they apply the design process properly, understand the design tools they were taught for applying this process, and support their decision-making with analysis, reasoning, and experiments. The gradvisors also provide feedback on oral and written communication. This gradvisors participation is rather unique, and several have used the opportunity to coach teams to also conduct research on the design process. They observe how students work, run experiments with them, and produce results that have been published. Naturally, IRB approval is sought, and the students must agree to be observed and used in the experiments. We have used much of this research to improve the process, which has also been invaluable to our graduates who have taken this knowledge and their respective employers upon graduation.

3.2 Graduate Education

We have designed an evolving list of courses offered to our students, starting with technical electives that senior undergraduate students and entering graduate students may select (4000/6000 courses) and ending with much more in-depth courses for Masters and Ph.D. students (8000 courses). These course descriptions are provided below. Note that occasionally, engineers working in industry enroll in these courses. Several were precursors to research and others were the results of design research. The Rapid prototyping and the Integration through Optimization courses are the results of sponsored research identifying new methods and tools and transitioning them to classroom for eventual use with future employers.

ME 4550/6550: Design for Manufacturing Concepts of product and process design for automated manufacturing are discussed. Topics include product design for automated manufacturing, inspection and assembly using automation, industrial robots, knowledge-based systems, and concepts of flexible product manufacture.

ME 4710/6710: Computer-Aided Engineering Analysis and Design Students learn geometric and solid modeling, finite elements, optimization, and rapid prototyping. Students design and develop a computer representation of an artifact, and then use FEA to analyze and optimize it before prototyping.

ME 4930/6930: Rapid Prototyping Students are introduced to the additive and subtractive manufacturing and associated technologies that affect the contemporary design for manufacture (DFM) practices. The course includes CAD issues for rapid prototyping (RP), reverse engineering (RE) for model reconstruction from existing physical parts through digitizing, and an understanding of the several layer-based and "rapid" manufacturing technologies. Theory and methodology are supplemented with examples and case studies.

ME 8700: Advanced Design Methodologies Topics include nurturing or creativity and decision-making processes for design. Students also undertake an in-depth study of the mechanical design process and tools, quality function deployment, concurrent design, systemic design, robust design, design for assembly, and axiomatic design.

ME 8710: Engineering Optimization Students learn optimization in the context of engineering design; nonlinear and linear, static and dynamic, constrained and unconstrained formulation, and solution of practical problems; structural optimization; multi-objective optimization; genetic algorithms; and simulated annealing.

ME 8720: Design Automation for Mechanical Engineers Students learn data structures, search algorithms, geometric algorithms, geometric modeling, and software engineering for mechanical engineers. Students design and implement mechanical CAD software packages. The use of software development tools, algorithm design, and their interfaces in mechanical engineering is emphasized.

ME 8730: Research Methods in Collaborative Design Topics include research methods for studying collaborative design, influencing factor of collaboration, computer issues in collaboration, and mechanical engineering as facilitated by collaboration. Technical writing and experimentation are emphasized.

ME 8740: Integration Through Optimization Students learn theory, methodology, and applications of decomposition, integration, and coordination for large-scale or complex optimization problems that are encountered in engineering design. Topics include conventional and nonconventional engineering optimization algorithms, analysis models and methods, multidisciplinary optimization, and multi-criteria optimization. Case studies are included.

ME 8930: Design Informatics Students learn database management development and implementation, software engineering, knowledge representation and reasoning, search and retrieval to support engineering design and manufacturing enterprises. Students are introduced to current issues associated with information management systems in engineering, technologies, and tools to address these issues, and systematic methods to design and develop solutions. Students design, develop specifications, and implement engineering information management software packages.

4 Conclusions

This chapter summarizes some of the research topics conducted by the faculty and students in the CEDAR group at Clemson University. The close collaboration with industry shows that the work they undertook has enhanced industrial manufacturing practice. Continued support by industry and government, and the transition of this fundamental research supported by the US National Science Foundation for use in both the industrial environment and the classroom indeed shows both the success and effectiveness of our model.

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Evaluating Tactual Experience with Products

Georgi V. Georgiev, Yukari Nagai and Toshiharu Taura

Abstract This chapter focuses on design research that analyzes users' tactual experience with product interfaces, especially, the analysis of users' impressions of such experiences. In practice, a systematic approach is required to evaluate users' interactions with product interfaces. Therefore, the research objective is to propose a systematic method and tools for evaluating users' tactual interaction with products on the basis of users' inexplicit impressions, so that the method should benefit the practice. The method was developed and applied in a case to evaluate users' tactual interactions with product interfaces in the context of the car industry, particularly in the research and development of interfaces of vehicles. The method was applied in a trial evaluation for vehicle interfaces of navigation systems, audio systems, and air conditioning systems. The role of this design research is to propose a systematic approach to evaluate product interfaces based on users' inexplicit impressions and deeper feelings; this approach can be applied in practice of product design. Based on the inconclusive results of this first application in practice, further developments of the method are needed.

Keywords Product interface · In-depth impressions · User experience · Tactual interaction

1 Introduction

One of the critical factors in the design practice is the product interface and how the user engages with it. Different research investigations have targeted the product interface. However, very few of these investigations have influenced the practice of

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designing product interfaces. One issue is that the interface is usually designed in ad hoc way and it is not systematized. A *systematic approach* to product interface design is needed. In particular, the approach should not focus only on a superficial analysis; rather, it should tackle users' *deep feelings*. We propose such an approach for analyzing users' impressions, which can be applied in the practice of product design.

A proactive approach to product interface design involves using interface analysis to determine why and how good interfaces should be designed. To analyze the product interface, the main question that must be addressed is the following: How is a good interface perceived by users?

To achieve a deeper understanding of users' experiences of product interfaces, the focus should be on the fundamental mechanism that forms users' feelings for and impressions of designed products. Moreover, a systematic method to detect these inexplicit impressions should be devised.

This chapter discusses design research on a systematic method to detect and analyze such impressions, and the corresponding tools, by focusing on the *tactual* way that users experience products—the most fundamental way in which users form feelings and impressions from products and their interfaces. To clarify the term *tactual*, we introduce a definition:

Definition 1 *Tactual* is understood as caused by touch. The term *tactual* represents the interactions in touch modality.

The above definition distinguishes *tactual* from *tactile* (the latter is understood as representing the sense of touch only). The interactive aspect of the *tactual* way of experiencing products is also discussed in previous research (Sonneveld and Schifferstein 2008).

On the basis of the experimental findings, when applying the aforementioned method and tools, the influences on design practice are discussed herein. The method was applied in a trial evaluation of *vehicle device interface* operations in the practice of product design.

2 The Focus on Product Interface

Regarding the product interface, we focused on user feelings and impressions. A systematic method was developed to better understand how users' impressions were formed while tactually experiencing a product and its materials (Georgiev et al. 2012a).

The foundation of the method utilized in this chapter is the viewpoint that users form not only explicit impressions upon interacting objects, however, also inexplicit impressions. Such viewpoint has been introduced previously (Fasiha et al. 2010; Zhou et al. 2009). The method discussed in this chapter focuses on identification and analysis of inexplicit impressions (Fig. 1). This is in contrast to the focus of existing methods of analysis, systematizations, and representations that have focused on explicit impressions. In this research, the method has been

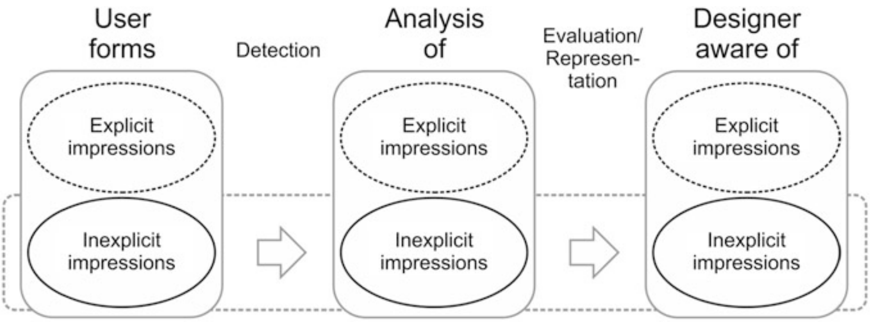


Fig. 1 Framework of users' impressions, their analysis, and designers' awareness of these impressions

discussed in the context of tactual user experience. However, it not restricted to this case only; it may have applications in other aspects related to touch, including operations and tactual-visual interactions with objects.

The *objective* is to propose a systematic method and tools for evaluating users' tactual interaction with products the basis of users' inexplicit impressions, so that the method should be beneficial for the practice. The method helps to gain insights into the fundamental mechanism that forms users' impressions of designed products (Georgiev et al. 2012a). That is to say, it reveals not only the explicit impressions, but inexplicit impressions as well. However, the inexplicit impressions will allow further systematization and representation of these experiences so that designers can be aware of these particular impressions; it will also aid them in analyzing their contribution to the total concept of the designed product.

The method utilizes the following features in particular:

- Detection of inexplicit impressions.
- Analysis of inexplicit impressions.
- The possibility of suggesting what impressions the product will form when used.

The details of research and its outcomes are discussed in the following sections, starting with bases of the method.

3 The Focus on User Experience and Tactility

In the further discussed study, we propose a method and tools for the assessment of tactual interaction, in order to understand how users form their impressions of this interaction. We focus on particular case of tactual interaction with product material. We consider this case in the base of the users' interactions with product interfaces. Not trying to develop a perceptual set, this new method is developed to assess the products' tactility.

Product experience has been referred to as the research area that develops an understanding of people's subjective experiences that result from interacting with products (Hekkert and Schifferstein 2008, p. 1). In this area, tactual user–product material interaction has been recognized as a highly important topic in the experience of man-made objects (Karana 2010; Sonneveld and Schifferstein 2008). Moreover, tactual user–product material interaction is critical for building users' emotions, thus, has fundamental role in emotional engineering (Fukuda 2011). Therefore, it is essential for designers to develop tools and methods that offer a conceptual framework for the tactual sensory experience. It has been suggested that the requisite approach can be based on cognitive and perceptual learning (Sonneveld and Schifferstein 2008, p. 62). However, product design practices do not yet offer such methods and tools.

A central concern of product design is the designers' understanding with regard to how user impressions are formed. Such understanding will lead to an effective assessment approach and to new method, which will contribute to product development by fitting products to expected, everyday, tactual experiences. In other words, user impressions and expectations—the human element—must be fully comprehended in order to facilitate the development of products. Tactual sensory experience creates difficulties that relate to the provision of such methods and tools. They are twofold. The first difficulty lies in the insufficient understanding the formation of the user sensory experience. The second is in providing an effective approach to assess this experience.

3.1 Experience of Objects

Tactual interaction is a foundation of human embodied experience of objects (Sonneveld and Schifferstein 2008). Karana (2010) investigates and identifies the complexity of user interaction with product materials. People interact with various products, ultimately accumulating experiences and building attachments or repulsions to these products. Previous studies have shown that user impressions of product materials in tactual interactions depend on the level of user familiarity with the product material (Nagai et al. 2010).

To increase comprehension, product designers must focus on user interaction and answer questions on how users form impressions of products. Previous studies have focused on perception and affect, paying little attention to the cognition of tactual interaction with product materials. Thus, understanding user cognition is essential for providing methods and tools for assessment of tactual interaction.

3.2 Tactual Experience

The state of the art in research in the field of tactual experience of product materials is concerned with systematic approaches to the sensorial properties of product materials (Karana 2010). It has been shown that meanings are attributed to product materials, depending on factors such as meaning type, material type, the product itself, its usage, and the user's background.

Furthermore, the significance of a deeper understanding of user interaction with product materials (particularly in a tactual mode) has been recognized from both user and designer viewpoints (Sonneveld and Schifferstein 2008). Sonneveld and Schifferstein argue that tactual interaction, as a primal form of experience, comprises a foundational component of knowledge itself. People need to touch to know and understand the man-made objects they are manipulating, and ultimately attribute meaning to the objects. The first attempts to penetrate deeper into the topic of tactual experience of product materials show that user impressions depend on how "natural" the product material is perceived to be, including how well users are accustomed to it (Nagai et al. 2010). Moreover, such impressions are related to user preferences.

4 Modeling Tactual Interaction

4.1 Model of Tactual Interaction

Previous research on tactual interaction with product materials provides clues such as materials that are experienced often (or in other words, which users are habituated to) differ in their impressions and evaluations in comparison with new and tactually unknown product materials (Nagai et al. 2010). Moreover, the constructed meaning depends on factors such as material properties, the product the material is embedded in, how we interact with it, and the context in which the interaction takes place (Karana 2010). In light of these factors, an individual's previous experiences, memories, associations, emotions, and cultural backgrounds influence the constructed meaning. These components are central in the construction of a meaning evoking pattern (Karana 2010). Past experiences, memories, associations, and emotions are thought to be critical for the formation of user impression (Nagai et al. 2010). Thus, in this research we investigate the formation of user impression in light of previous experiences, memories, associations, and emotions and apply a systematic method in order to investigate them.

Tactual interaction is fundamental to user interaction and experience; it is the foundation of feeling and emotion. Touch is a communication channel for affection. The key aspect of touch to perception is that as a physical experience it provides verified content to specified concepts (Karana 2010). However, a time-experience model of tactual interaction is needed to explain the formation of impressions as an experience providing content to specified concepts.

According to the above discussion, this study discusses a model of tactual interaction (Fig. 2). Through (in this case, primarily tactual) interaction with a product material, a concept of the material is created on the basis of a formation spiral. We discuss the following definition of concept of material:

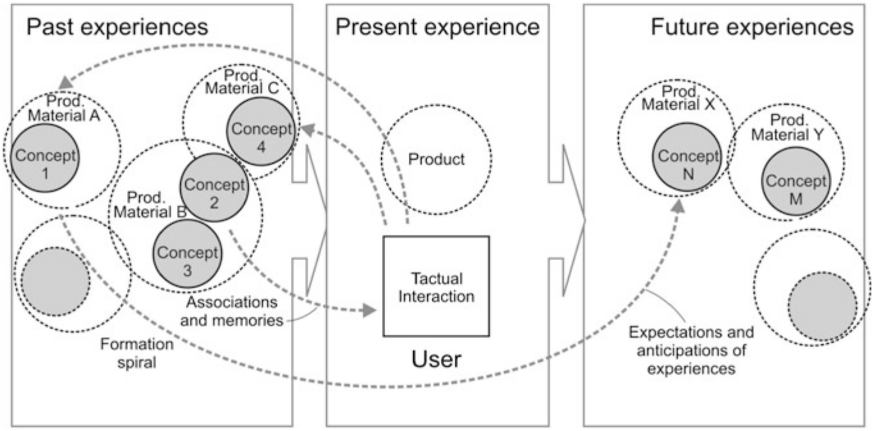


Fig. 2 Model of the tactual interaction

Definition 2 Concept of material is a specified set of concepts (which can be expressed as words) that are formed on the basis of a user's tactual experience with product material.

In the perspective of this definition, the current experience is influenced by past experiences of concepts that are based on association, memory, etc. Past concepts influence current experience, which again refers to past experiences and concepts. The final result is the construction of a current concept of the material that includes expectations of future experiences of product, their materials, and concepts about them. In this model, the generation of concepts of materials has been represented as a process of user cognition in which associations based on past experience play a major role. The spiral of past and current interactions creates an expectation (which can also be referred to as a "meaning") of future tactual experiences of products.

Creation of products with new or different material characteristics will require some amount of insight into how successful concept creation may be facilitated for that material. Proper facilitation would result in emotional satisfaction and a meaningful experience of the product.

4.2 Explicit and Inexplicit Impressions

In their interactions and experiences with products, humans cannot express all their impressions explicitly. In order to capture the nature of impressions that products evoke in users, Taura et al. (2011) used semantic networks to develop a method for constructing 'virtual impression networks' in connection with user preferences. They investigated the thought process in which both explicit and inexplicit cognition exists. Furthermore, they employed a method of constructive simulation in order to investigate the structure of impressions in creativity (Taura et al. 2012).

4.3 Structure of Inexplicit Impressions

'Inexplicitness' is a major characteristic of user impressions. Previous research indicates that user impressions are partially hidden within an inexplicit mind (Taura et al. 2012). Memory that is formed by associations is a strong factor for user impressions derived from interactions with products (Zhou et al. 2009). Associations are probably based on personal experiences in interactions with product materials (Karana 2010). However, in cases of tactual interactions, a common tendency of associations and preferences was observed (Nagai et al. 2010).

5 Method

5.1 Bases of the Method

In order to analyze how users form impressions of products and their materials, we focus on the issue of where the impressions come from. An answer to this is that words are connected through user experience.

Experience with words creates a structure, which is associative in nature and is derived from ever-changing experience (Deese 1965). It is assumed that dynamic associative structure is created in a type of memory that involves representations of the words themselves, as well as connections to other words, and that this structure plays a critical role in any task involving familiar words (Deese 1965).

We consider that, on the basis of this associative structure, the experiences can be described as having two layers—a layer of expressed user impressions and an inner associative layer—a viewpoint that has been discussed in previous research (Fasiha et al. 2010). Moreover, we consider the second layer as consisting of in-depth impressions, which initiate the expressed user impressions but remain primarily unconscious to the person who is actually expressing impressions on a particular experience. Thus, we define in-depth impressions as follows:

Definition 3 In-depth impressions comprise an inner associative layer of outwardly expressed user impressions of interaction with products.

Definition 4 Expressed user impressions are verbal impressions that are freely expressed upon interaction with products.

Figure 3 illustrates in-depth impressions as such an inner associative layer on the basis of which users establish numerous, rich (metaphorical) concepts (or expressed user impressions). This definition was developed on the basis of previous research (Zhou et al. 2009).

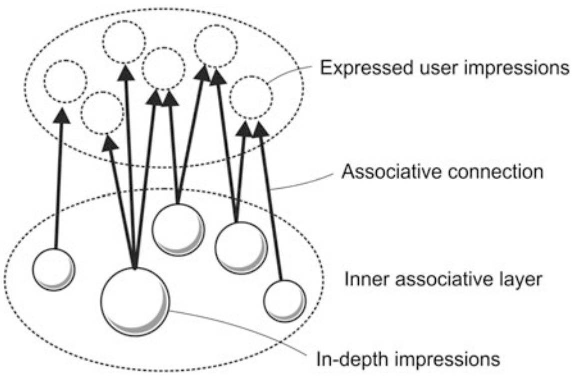


Fig. 3 In-depth impressions as an inner associative layer

5.2 *Methods Employed in the Assessment*

The following methods were employed to analyze tactual interactions from a cognitive perspective. Detection and analysis methods of in-depth impressions of users were developed. Accordingly, the techniques used in this method of assessment include (Fig. 4):

- Association analysis of expressed user impressions. On this stage, all expressed user impressions were examined for words which they are typically associated from. A list of all such common associative pairs (stimulus word–response word) was created.
- Concept network construction. The associative pairs are added to a network structure, which is associative in nature, with two types of nodes—expressed user impressions as associated nodes (receiving connections) and stimulus nodes (initiating connections).
- Graph visualization of the resultant concept network to detect the in-depth impressions as the nodes initiating the highest number of connections.
- Further analysis of the typology characteristics of the detected in-depth impressions (Fig. 5) to identify their common features.

The in-depth impressions identified and grouped by common features provide clues for the nature of user impressions and from what kind of experience these impressions are derived.

We consider that cognition-related impressions are those in-depth impressions that result from acquired concrete knowledge of products or man-made environment objects. In other words, the cognition-related in-depth impressions result from the knowledge or thinking about concrete products, for example, ‘steering wheel’ or ‘armchair.’ We assume that the cognition of such products determines the in-depth impressions associating the particular expressed user impression. It is noteworthy that all in-depth impressions are determined by associative connections.

Fig. 4 Method of assessment

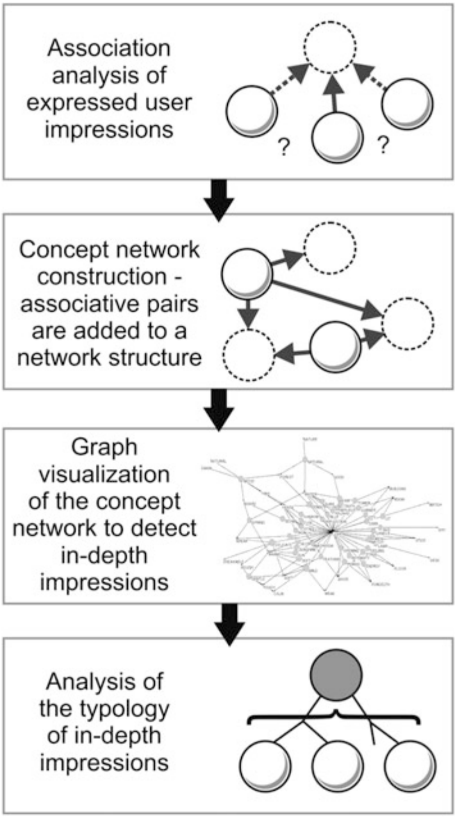
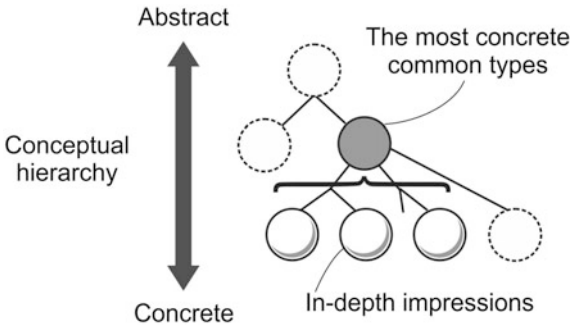


Fig. 5 Analysis of the typology characteristics of in-depth impressions



5.3 Steps of the Study

In-depth impressions were analyzed in an experiment. The methodology comprises the following steps:

Step 1 Evaluate tactual interaction of users via protocol analysis of: (A) Freely expressed user impressions of tactual interaction with product materials; and (B) Explanatory inquiry to extract users' own assessment of the reasons for their impressions. Expressed user impressions, explanations, and reasoning were collected in this step.

Step 2 In-depth impressions detection and analysis, as outlined in the proposed method of assessment.

Step 3 Analysis how impressions are developed through analysis of the explanatory inquiry, in order to identify the patterns of formation of impressions.

6 Study

6.1 Setting and Procedure

The specific details of the study are as follows: samples of seven materials from everyday products were used as stimuli. These materials were: aluminum, cork, glass, rubber, steel net, plastic, and wood. These materials have been selected from the products commonly used in daily life, that is, materials that are encountered every day. The participants interacted with the samples tactually and freely. We did not apply blind test owing to the difference in blind test and everyday tactual experience of various product materials. The study comprised eleven participants (five females and six males).

6.2 Analyses

In analysis 1, we used data from our previous study (Georgiev and Nagai 2011). The samples were presented in a random order and two questions were asked regarding the user's tactual interactions with each product material. Participants were instructed to touch the samples and to provide a detailed answer. The first question was as follows:

(A) What are your impressions and image (imagination) of this material?

We limited the instructions to basic ones in order to minimize the influence of the instructions on the interaction.

In order to extend analysis 1 and investigate the basis of the formation of user impressions, we considered analysis 2, which was focused on obtaining data for the expected tactual experiences of the participants.

Additionally, we obtained new data for analysis 2, which was based on questioning the reasons for the impressions of the participants.

After the participants provided a free and undisrupted verbalization of their tactual interaction with product material samples, the following second question was asked:

(B) What were the reasons for your impressions of these materials?

6.3 Tools

Based on the responses of the participants, the expressed user impressions from question A (nouns, verbs, adjectives, and adverbs) were classified according to the product material samples and analyzed.

For detection of the in-depth impressions, we used a common applicable associative analysis tool—associative concept dictionary (database). The 'University of South Florida free association, rhyme, and word fragment norms' database created by Nelson et al. (2004, 2012) contains very large number of English-language associative words (word-pair associations). This database was collected from more than 6,000 participants who produced nearly three quarters of a million responses to 5,019 stimulus words. The tool considers nouns, adjectives, and verbs in associative pairs and was constructed in a large-scale association experiment. This extensive coverage is suitable for searches of word-association pairs, thus it is used in the current analysis.

Furthermore, for creation of the conceptual networks and graph visualization we used Pajek graph drawing software (Batagelj and Mrvar 2003; Pajek 2.04 2011). From the constructed conceptual networks the in-depth impressions were detected on the basis of their weights (calculated as an out-degree centrality scores). A threshold of in-depth impressions was set to 50 % on the basis if the highest number of connections (maximum out-degree centrality scores).

In the next step for classifying in-depth impressions, the conceptual hierarchy of the concept dictionary database was used to identify type—using the hierarchy of concepts in the concept dictionary WordNet (Fellbaum 1998; WordNet 2.1 2006). The most concrete common types were examined (Fig. 5).

6.4 Results

Protocols of the answers on question (A) were analyzed, and in-depth impressions for each sample were identified with the previously described method.

Examination of all identified in-depth impressions revealed the most concrete common types of (a) Artifact, (b) Substance, Phenomenon, or Living thing (including natural thing and person) (c) Other including abstraction and not classified as appropriate to our case (Table 1).

The in-depth impressions from the category of (a) Artifact were, for example, ceiling, tower, lamp or porch; from (b) Substance, Phenomenon, or Living thing

Table 1 The obtained typology of in-depth impressions

Product material	Most concrete common types of in-depth impressions		
	(a) Artifact (%)	(b) Substance, phenomenon or living thing (%)	(c) Other including abstraction and not classified (%)
Aluminum	17	19	64
Cork	35	15	50
Glass	26	26	47
Rubber	27	25	48
Steel net	51	16	33
Plastic	6	19	75
Wood	25	23	53

Table 2 Participants' reasoning about impressions of product materials

Product material	Example reasons in answers of question (B) (from all participants)
Aluminum	"It is like metal plate used in machinery …;" "I touch and feel cold …;" "The material is not special, but I was scared to touch this material …"
Cork	"I certainly imagined picture board …;" "I think it can make people to imagine so many things …"
Glass	"It is used fully in daily life. And because the daily life, there are so many emotions in people's lives …;" "It was as the glass table I use in my room …"
Rubber	"… comfortable, but not something that usually touch in life …;" "… fairly smooth, slippery surface that is really something I like …"
Steel net	"I imagined touched the screen door when I open window …;" "It is like touching something personal …"
Plastic	"It was as often touched name plate … or plastic plate … but it is hard …;" "… it is a bit stiff as a whole …"
Wood	"It is warm and I imagined house …;" "It is like natural wood used in many man-made things …;" "… comfortable feel of something traditional …"

(including natural thing and person), they were, for example, feather, sunshine, sun, or wood; from (c) they were, for example, shade, truth, aura, or reflection.

Protocols of the answers on question (B) were analyzed, and example reasons about impressions of product materials were identified (Table 2).

7 Discussion

7.1 Approaching Product Interface Using In-Depth Impressions

The obtained proportions found in these classifications show that product materials like cork, glass, rubber, and steel net contributed to user cognitive interactions in the associative layer of artifacts, substances, phenomena, or living things (Table 1). The product materials like aluminum, plastic, and wood create user cognitive interactions in the associative layer of other types such as abstraction type. A possible interpretation of this finding is that materials like cork, rubber, and steel net are found in fewer products than materials like aluminum, plastic, and wood.

The study identified in-depth impressions that are most likely cognition-related (e.g., steel, plug, marble, tread, display, stage, sun, etc.)—mostly in-depth impressions from (a) Artifact and (b) Substance, Phenomenon, or Living thing (including natural thing and person) categories, as compared to other in-depth impressions that are most likely to be perception and affect-related (e.g., rigid, mild, crisp, clear, delicate, cozy, extreme, harsh, unstable, influential, powerful, etc.). Such conceptual characteristic shows that the cognition-related conceptual component of the inner associative layer of in-depth impressions is predominant in most cases.

The observed large proportion of artifact, substance, phenomena or living thing (considered as cognition-related) in-depth impressions demonstrates their fundamental characteristic in the interaction with products and their materials.

Impression formation patterns were drawn on the basis of the participants' explanations from question (B) (Table 2). These patterns, along with typology characteristics of in-depth impressions, validate the proposed model (Fig. 6).

In Fig. 6, some examples of past experiences are visualized on the basis of identified in-depth impressions and examples of expected future experiences are visualized on the basis of participants' reasoning about impressions of product materials. For example:

- Past experiences of 'wood' reveal in-depth impressions of 'power', 'sunshine', or 'bedroom', leading to expectation of future experiences of 'comfortable' or 'warm'.
- Past experiences of 'plastic' reveal in-depth impressions of 'harsh', 'dense', or 'bold', leading to expectation of future experiences of 'scary' or 'stiff'; etc.

The method of the identification of in-depth impressions partially accounts for metaphorical concepts, as metaphors can be included in the associative connections used to identify in-depth impressions, for example, 'cold' and 'person'. For at least partially judging future experiences (expectations and anticipation), we used explicit explanations from the responses of the participants. However, a more elaborated approach to analyze future experiences may be needed.

The past experiences with particular product material can be understood on the basis of in-depth impressions, such as 'feather', 'delicate', 'bedroom' or 'damage' or 'defrost'. These in-depth impressions reflect into expected future experiences such as 'comfortable' or 'scared'. The concepts of materials that are found in fewer products like cork, rubber and steel net are based on type of associations, represented by artifact-related in-depth impressions.

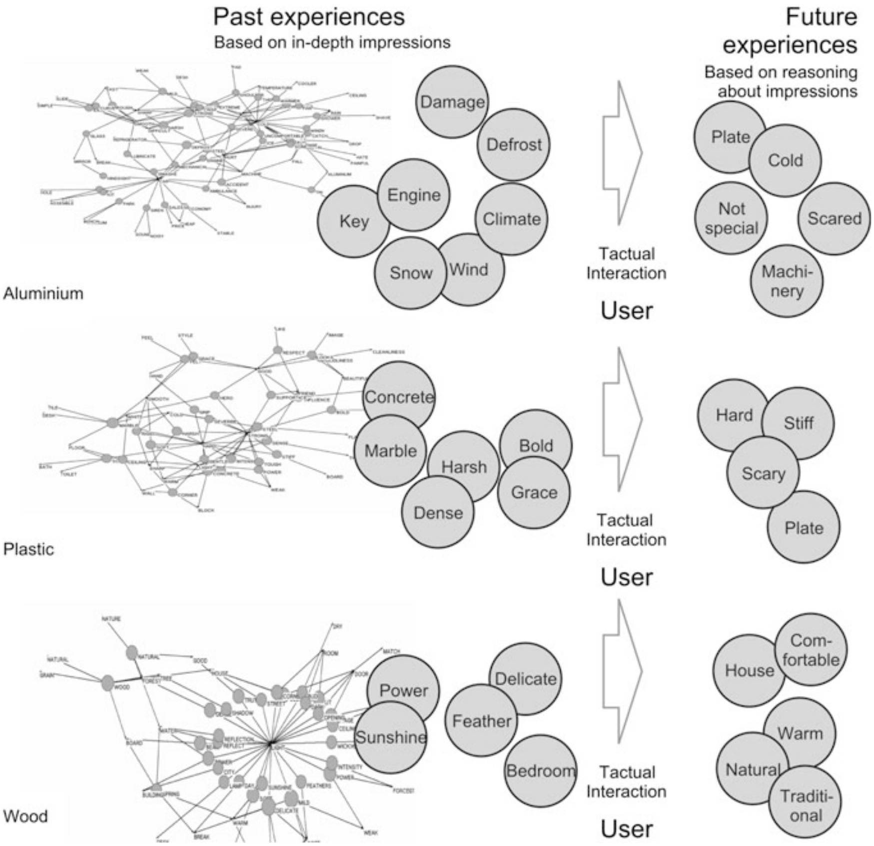


Fig. 6 Examples of impression formation patterns of three samples

The main findings can be summarized as follows. The cognitive component is a contributor for the creation of concept of material. User impressions of product materials are formed on the basis of associations with past tactual experiences, as well as cognitive interactions with materials of artifacts, which were referred to a number of times during the tactual interaction. Such concepts of materials can be sought in a formation spiral (Fig. 2). The newly formed concept of material creates expectations of future tactual experiences of product materials.

7.2 *Contribution and Implications*

According to these findings, using the proposed method and tools is a tangible way to model tactual experience; this also facilitates its implementation in computational tools that aid evaluation and selection. Consequently, the main contribution of this research is the proposal of a method and corresponding tools for the evaluation of a tactual experience; the method utilizes users' unrestricted verbalizations and detects inexplicit impressions, thereby, focusing closely on human cognition.

Furthermore, the awareness of the in-depth impressions by designers would improve the evaluation and selection in product design. This improvement would result specifically in cases when the functional requirements are not predominant for this selection.

Implications of the proposed method and corresponding tools are twofold. First, the method will improve evaluation and selection in product interface design, thereby helping designers and engineers. Second, the method an implicit significance: it provides direction for the systematization and modeling of tactual experience based on inexplicit impressions in computational tools to assist in evaluation and selection.

7.3 Limitations

The experiment conducted in this study is limited in size, particularly in terms of the number of participants and number of samples. Larger-scale investigation is required for the identification of product materials and impression formation patterns for further implementation in product design.

Furthermore, for the purposes of the experiment, the choice of product material samples is general rather than being dictated by particular product requirements (functional or otherwise).

Although the tools used in this study represent the best achievements in the field thus far, they have some limitations. The tools are appropriate for the study; however, for the specific use, the future development of more specialized tools will increase the appropriateness. The 'University of South Florida free association, rhyme, and word fragment norms' database has limitations derived from the limited generalizations across languages and cultures. Furthermore, the terms in the database were collected in the general (everyday) sense; therefore, they do not have specific implications. WordNet also suffers from the limitation of a lack of domain-specific language data. Finally, human language is very dynamic and it would take time for the latest language information to be reflected in the subsequent versions of these tools.

8 Summary of the Findings

The discussed method and tools provide a systematic approach to assess tactual interaction on the basis of user's deep feelings and impressions. Using this method and these tools, tactual interaction can be assessed only on the basis of user verbalizations, without the need of predefined experimental settings or restrictions. The proposed method analyzes the free verbalizations obtained on tactual interaction with product and identifies the inner associative layer of in-depth impressions. The tactual interaction with product is investigated on the basis of these in-depth impressions.

The study provided a tangible way to evaluate tactual interaction and facilitates its implementation in computational tools to aid evaluation and selection. Furthermore, awareness of the in-depth impressions by designers would improve the evaluation and selection in design of product interfaces. By understanding how user impressions of product materials are formed, designers could identify particular concepts and employ them in the evaluation and selection processes.

The method and tools as discussed are able to be applied for the cases of subtle differences between products' interfaces; this is largely because the method and tools utilize users' unrestricted verbalizations, and differences can be identified on the basis of different verbalizations.

9 Outcomes from the Design Research

9.1 Roles as Method for Design

The objective of this study was to propose a systematic method and tools for evaluating users' tactual interaction with products the basis of users' inexplicit impressions, so that the method should be beneficial for the practice. This is because in practice systematic approach to evaluate users' interactions with product interface is needed.

On the basis of the summary in the previous section, this study provides a deeper understanding of how users' impressions were formed from their tactual interactions with products. Moreover, the study also provides insights into the mechanism from which users' impressions of designed products are formed. The main features of the proposed method to evaluate tactual experience are as follows:

- The utilization of unrestricted free verbalizations
- The detection of inexplicit in-depth impressions
- The evaluation of tactual experience based on detected in-depth impressions

The evaluation uses easy-to-obtain, free verbalizations by the user; it also goes into the deep cognition though the in-depth impressions. Consequently, this represents a new assessment framework for evaluating the tactual experiences of product interfaces.

This research informs design practice—particularly, product interface design practice—in the following two ways:

- The analytical role in understanding of the user (by providing deeper understanding of tactual experience of product interfaces).
- The synthetic role in designing (by improving evaluation and selection approach with regard to intended experiences from interface). This helps increase designers' awareness of the inexplicit impressions and, therefore, aids the selections with respect to inexplicit impressions.

Through these two roles, the method may answer the need for a deeper understanding of users' tactual experiences.

9.2 Trial in Practice

Based on the study of product materials, the method was extended and applied in a trial evaluation of users' tactual interactions with vehicle device interface operations in the practice of product design (Georgiev et al. 2012b, c). In particular, collaborative research on building a sensitivity index for a vehicle control devices utilized this method (Georgiev et al. 2012b).

There are two main characteristics of the trial:

- The context of the car industry, particularly in the research and development of interfaces of vehicles
- An evaluation method for vehicle interfaces of navigation systems, audio systems, and air conditioning systems

This trial application aimed to assess human sensitivity during the operation of control devices in vehicles on the basis of underlying, in-depth impressions. The method explored the means by which the degree of sensitivity to device interfaces can be compared and evaluated. This can be beneficial for the design process phase where alternatives must be compared and evaluated; the method may help designers make relevant technical choices. Furthermore, particular extracted in-depth impressions can indicate and/or characterize the comfort people experience during the operation of user interfaces (Georgiev et al. 2012b).

The method discussed in the aforementioned research took several roles in the design practice:

- Development of a systematic approach to evaluate the product interface based on users' inexplicit impressions and deep feelings
- Exemplification of how the users' perceive product interface on the basis of these deep feelings

However, based on the first application in the case of control devices in vehicles, the results of the extensive experiment were inconclusive compared to the initial experiments. Based on these inconclusive results in this first application in practice, further methodological developments are needed.

9.3 Reflections on the Factors that Contributed to the Role

This section discusses lessons learnt and some of the most significant factors that contributed to the role discussed in Sect. 9.2. First, with respect to the research content, the method was applied to an underdeveloped area of research. Second, with respect to expected benefits, the expected output, the time required, and other resources were well defined at the beginning of the research. Third, with respect to the types of research and collaboration, the publishing of the results was defined in the initial stages of the research. Fourth, with respect to collaboration sustainability, support was obtained from different levels of the company management (Fig. 7).

There are three most important messages for the research influence on practice:

- The form of the research content must show clear developments in the specific area.
- The expected benefits must be clarified in terms of outcomes and required resources.
- Sustainability and support for the project are important.

However, more research is required for further methodological developments and to make the method applications more practice-relevant in design.

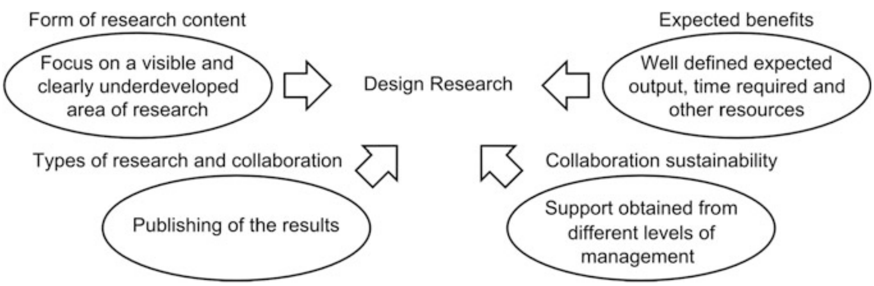


Fig. 7 The most significant factors that contributed to the impact

Acknowledgments Earlier version of the study discussed in this chapter was presented at and appears in the proceedings of the 9th Tools and Methods of Competitive Engineering TMCE 2012, May 7–11, 2012, Karlsruhe, Germany (Georgiev et al. 2012a); and was rewritten, extended and submitted for review to the International Journal of Computer Aided Engineering and Technology. Acknowledgments are also due to all IDRP13 workshop participants and the editors of this book for the fruitful and insightful discussions and comments that helped to improve this chapter.

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Multiple Forms of Applications and Impacts of a Design Theory: 10 Years of Industrial Applications of C-K Theory

Armand Hatchuel, Pascal Le Masson, Benoit Weil, Marine Agogué, Akin Kazakçi and Sophie Hooge

Abstract C-K theory has been developed by Armand Hatchuel and Benoit Weil and then by other researchers since 1990s. In this chapter, we show that its very abstract nature and its high degree of universality actually supported a large variety of industrial applications. We distinguish three types of applications: (1) C-K theory provides a new language, that supports new analysis and descriptive capacity and new teachable individual models of thoughts; (2) C-K theory provides a very general framework to better characterize the validity domain and the performance conditions of existing methods, leading to potential improvement of these methods; (3) C-K theory is the conceptual model at the root of new design methods that are today largely used in the industry.

1 Introduction

In the 1980s there has been great debates in Germany to know whether Systematic Design was applied and efficient in practice (Ehrlenspiel 1995; Heymann 2005). Many empirical studies were made to assess the use and efficiency of the methods. It appeared that, when working alone on a design problem, a designer did not fully follow the methods or was more efficient when he did not fully follow the steps. Still, at the same period, in the industry and the companies appeared norms for engineering (see VDI Richtlinie 2221 and 2222, see the French AFNOR norm NF EN ISO 9000:2000) that were directly inspired by the systematic design framework; the routines of project management (list of requirements, stage-gate, steps, V-cycle,…) as well as the software and tools associated to product development relied on systematic design; the theory also inspired the organization charts

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and procedures used to organize collective design work like the relationship between marketing department and engineering department, between integrators and suppliers of components in complex systems, between engineering department and research laboratories,… Hence, the language of a design theory was used as the language to organize collective action (functional description, conceptual models, embodiment,…).

More generally, the "applications" of a theory can take multiple forms. As indicated by the etymology, a theory (from the Greek theorein, contemplate, observe, look at) is a way to look at things. As such, in a very broad sense, it provides a rigorous language for action. This is not only true for design theory. For instance, when Steinmetz, by General Electric, used complex numbers to design electric circuits, he actually used a theory to "look at" electrical circuits with specific lenses. Decision theory provides us another example of multiple forms of applications. Of course it was "transformed" into methods (decision trees for risk management, real options,…). It was also used to create new organizational roles and procedures (manager as decision-maker, the role of experts in decision-making, …). As a general language of performance, it helped to discuss the rationality of past decisions or the validity of empirical methods (in statistics it provided firm ground for the theory of tests). Even more: as a very general, transdisciplinary paradigm, it had an impact in other disciplines; the theory diffused, for example, in management, economics, or neuroscience, where it helped, for instance, to analyze decision-making situations or to diagnose "bias" in decision making. These new results led in turn to other, polymorphic applications.

In a nutshell, evaluating the industrial applications and impact of a design theory might consist in evaluating four dimensions:

1. Improvement of analytical and descriptive capacities.
2. Improvement and positioning of existing methods and processes. The theory helps to characterize (and occasionally increase) the validity domain of (empirical) methods and processes.
3. Development of new tools and processes. These tools and processes will, for instance, address situations that are out of the validity domain of the available methods.
4. Impact on other disciplines and on design professions. We trace here the diffusion of the theory in other academic disciplines and how the theory is taught to professionals who could, in turn, develop individually or collectively develop new methods and techniques in the future.

In the following, we will use this framework to analyze industrial applications and impacts of C-K theory in the last 10 years.

In a first part we remind of the origins of C-K theory, showing that the development of the theory was stimulated by the lack of methods to address so-called innovative design. We finish this part by underlining some critical aspects of the theory. In the following parts we address the four dimensions.

To this end, we build on the work done by (Agogué and Kazakçi 2013). We gathered all the publications in blind peer-reviewed journals, as well as books, thesis, book chapters, conference papers with peer reviews on abstracts and/or full papers and we analyzed the material regarding the four dimensions mentioned above. In this paper, we do not want to describe all this material but we shall favor some cases where we were directly involved and for which we are more competent. We completed our data collection with interviews and feedbacks from students and practitioners who applied C-K methodologies and tools.

2 Origins and Specific Features of C-K Design Theory

2.1 From Product Improvement to New Identities of Objects

In the 1990s, several works contributed to characterize deep changes in the design of new products and services by engineering departments. Knowledge management studies (see for instance: Blackler 1995; Hatchuel and Weil 1995) underlined the crisis of expert knowledge; innovation management underlined the shift toward "radical", "breakthrough," or "disruptive" innovation and some in-depth studies of engineering design department showed that this shift would require a deep change in the models of thought (Weil 1999). Far from being a managerial fashion, the call for "innovation" was actually a symptom of a strong change in the nature of innovation: contemporary innovation does not only require constant performance improvement of a fixed dominant design, but also the repeated invention of new object *identities*, requiring a capacity to break design rules at every level—new values, new business models, new functions, new technologies, new architectures, new design ecosystems.

Still available methods in engineering design departments and, more generally, in R&D organizations, had been historically thought to support so-called new product development processes. Methods like functional analysis and QFD, processes like NPD projects, stage-gate and V-cycles, organization like project / competences matrices were adapted to listen to the customer, to select the right requirements at the right level and to optimally use technical skills and competences to meet the specifications, relying on a network of suppliers and R&D laboratories. Methods were available for rule-based design. But, beside this rule-based design mission, new design missions appeared that consist in exploring an innovation field, without clear customer requirement, consist in creating new knowledge instead of just using the available one, consist in breaking existing design rules precisely to explore out-of-the-box, and consist in creating new ecosystems instead of relying on the existing one. For this "innovative design," the usual methods, processes, and organizations were at their limits.

This analysis stimulated the development of a design theory that would be a model of thought on desirable still partially unknown, undecidable objects.

2.2 C-K Theory—The Dual Expansion

In 1996, when teaching design theories to MINES ParisTech students, Armand Hatchuel proposed a first formulation of C-K theory. In the following years, the formulation was strengthened, leading to multiple publications in French. In 2002, Hatchuel and Weil (2002) presented their first French conference paper exposing the main principles of C-K theory: this theory is based on the distinction between two expandable spaces: a space of concepts, the C-space (concepts are defined as undecidable propositions), and a space of knowledge K. The process of design is thus defined as the co-evolution of C and K through four types of independent operators (C-C, C-K, K-C, K-K). Since the seminal English-written paper from 2003 (Hatchuel and Weil 2003), the features of C-K theory have been recognized as being unique for describing creative reasoning and process in engineering design, as stated by Sharif Ullah et al. (2011). Specifically, these scholars highlight the fact that one of the most noticeable features of C-K theory is its foundation on the notion of a creative concept—a concept being an undecidable proposition with respect to the existing knowledge at the time it emerges.

In the following years, it appeared that the impact of C-K theory was not limited to the engineering design community. For instance since 2003, the RATP, the public transport operator for the city of Paris operating the subway, has deployed C-K driven tools (Hatchuel et al. 2009): they indeed use regularly the KCP approach, a method for collective creative design, on subjects such as "Bus Rapid Transit," "21st century Metro," "Local bus services," "Walking," or "Night bus stations". Another symptom of the impact in the industrial field: in 2010, the French company Thales, which designs systems and services for the aerospace, published a book on its design process and advocated C-K theory as a way to organize innovative design activities (Defour et al. 2010). In management and organization, so many works were done that in 2012, a paper was presented in the French International Management Conference on the impact of C-K theory in management science over the last 10 years (Benguigui 2012).

To present these impacts in more depth we will address four different dimensions: (1) Improvement of analytical and descriptive capacities; (2) Improvement and positioning of existing methods and processes; (3) Development of new tools and processes, and (4) Impact on other disciplines and on design professions.

3 C-K Theory, a New Language to Describe and Analyse Innovative Design Activities

C-K provides researchers and practitioners with a framework to describe, analyze, and evaluate innovative design processes. In his conference paper retracing the influence of C-K on management research, Benguigui (2012) stated that C-K theory is an excellent theoretical framework to explain the process of early phases of innovation, to interpret the misunderstandings (or quiproquos) in management context, to develop managerial tools, and to relate the history of inventions. We would not detail here all the analyses made with C-K theory, the reader can refer for instance to (Silberzahn and Midler 2008; Eris 2005; Zeiler and Savanovic 2009; Pialot et al. 2011; Sharif Ullah et al. 2011; Elmquist and Segrestin 2009; Elmquist and Le Masson 2009; Gillier et al. 2010; Lenfle 2012).

As an illustration we focus on the evaluation of innovative projects and projects portfolios.

3.1 Innovative Projects Evaluation

C-K theory provides a relevant analytical framework to evaluate innovative projects, since it helps to analyze rigorously the multiple outputs of innovative design projects: with the C-K framework it is self-evident that the outputs are not limited to a final artifact (e.g., a product), but also the knowledge produced during the design process and all the other concepts that did not yet give birth to new product but might be reuse in the future (Fig. 1).

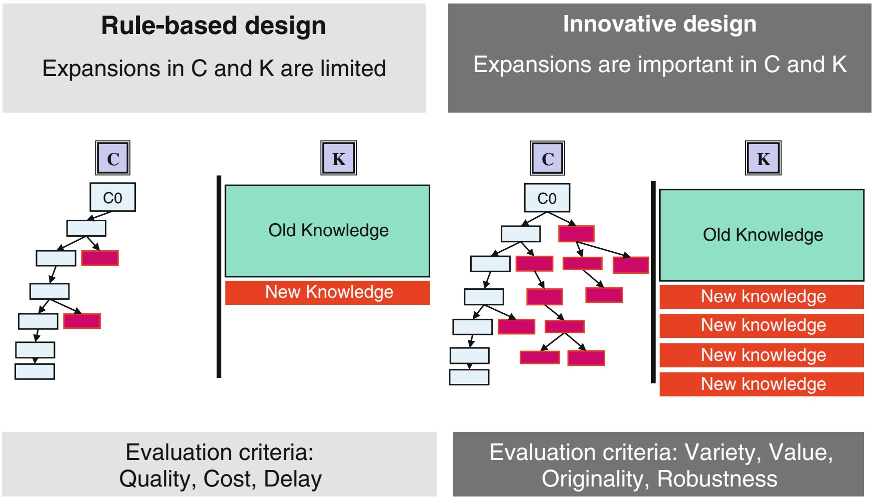


Fig. 1 Innovative project evaluation: contrasting product development and innovative design

This kind of evaluation spread in many firms (Elmquist and Le Masson 2009; Hooge 2010; Hooge and Hatchuel 2008). More sophisticated evaluation criteria were proposed: for instance the V2OR scale (variety, value, Robustness, originality) uses creativity measures and rule-based design criteria to analyze innovative design outputs in C and K (Gardey de Soos 2007; Le Masson and Gardey de Soos 2007; Le Masson et al. 2010):

- The outputs of an innovative project in C can be evaluated in term of Originality and Variety, which are close to Guilford criteria: Fluency, Variety, Originality, with the great advantage that C-K theory enables to measures originality as an expansive partition (avoiding the difficulty of Guilford measure where the measure of originality requires a large sample since it is measured as a low frequency proposal in a set of proposals).
- The outputs in K can be evaluated in term of Value and Robustness, the first one indicating knowledge that helps to regenerate the possible set of values for stakeholders (new potential functional requirements) whereas the second one relates to knowledge on the new means of action (new possible design parameters) that are now available to the designer (Fig. 2).

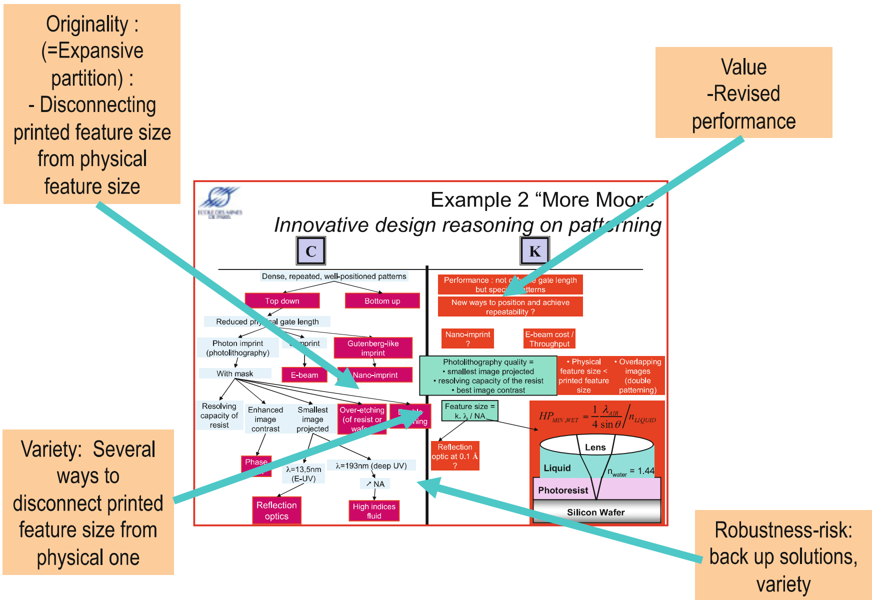


Fig. 2 Evaluation criteria for innovative design explorations: V2OR (Variety, Value, Originality, Robustness)

3.2 Evaluating a Portfolio and Its Positioning

Based on C-K theory, new analytical instruments were developed, like C-K referential (Ben Abbes 2007; Agogué et al. 2012; Agogué 2012). Given an innovation field, such a referential maps all the alternatives that can be imagined by a group of C-K experts using a set of expert knowledge—as large as possible. It has be shown that such a referential is significantly broader that classical roadmaps and included unexplored but identified paths as well as paths in the unknown (Agogué et al. 2012).

This tool was used in multiple cases such as “2 wheelers safety,” “biomass energy,” or “autonomy of elderly people” (see Fig. 3). It helped to diagnose *orphan innovation* situations: positioning the projects actually funded in an ecosystem on the referential reveals large unexplored areas in the innovation field. Even more: it is possible to show that one of the common features of all the unexplored areas is that they require at least one expansive partition (a partition in C that uses an unusual property from K), whereas the explored areas tend to correspond to restrictive partitions (a partition in C that uses usual properties from K) (Agogué et al. 2012).

This kind of technique was also used to analyze the “roadmaps” elaborated by working groups of the International Technology Roadmap for Semiconductors (see

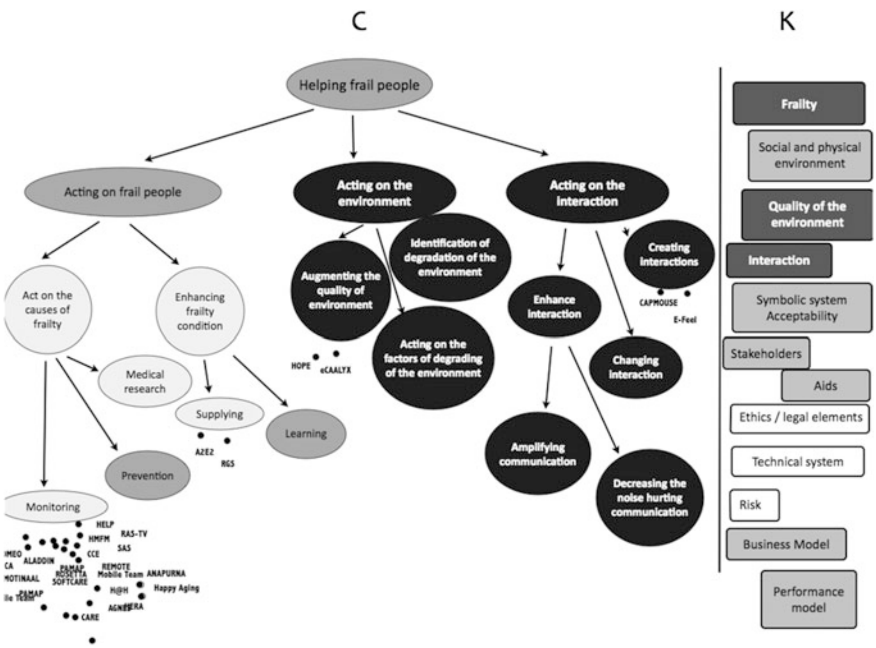
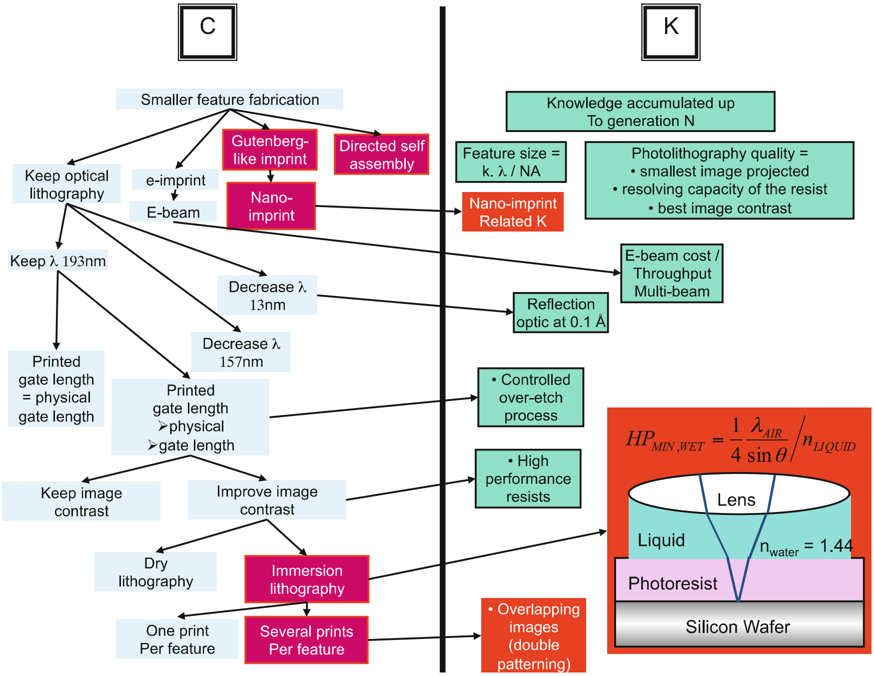


Fig. 3 C-K referential in the case of “autonomy of elderly people”



$$HP_{MIN,WET} = \frac{1}{4}\frac{\lambda_{AIR}}{\sin\theta} \Big/ n_{LIQUID}$$

Fig. 4 C-K referential of the ITRS roadmap for photolythography

Fig. 4). In this case, the diagnosis showed that the working group roadmaps were able to cover very large areas of the C-K referentials, hence avoiding orphan innovation (Cogez et al. 2011, 2013).

3.3 *Tuning Breakthrough*

Another refinement of C-K graphs led to structure the C-graph depending on the "heredity" degree of the attributes: the higher the attribute in the C-tree, the most hereditary it is, i.e., the oldest and the most difficult to break (see Fig. 5).

This criteria supports an order in the C-K graph. This kind of ordering is illustrated by (Brogard and Joanny 2010), who realized a C-K graph associated to the concept "engines for green aircraft in 2025" (see Fig. 6). Their work encompassed improvement of jet engines as well as gliders or other complex systems that would require to change not only the engine but also the aircraft, the air transportation companies, and airport organization, i.e., the whole ecosystem. The first solution is low in the graph, many attributes are kept unchanged, from the highest hereditary to the lowest one; the second one is very high in the graph, keeping very few attributes from the existing solutions.

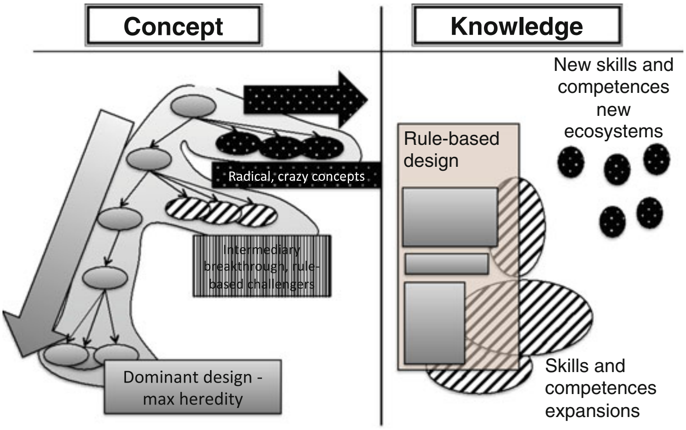


Fig. 5 Tuning the breakthrough with C-K graphs

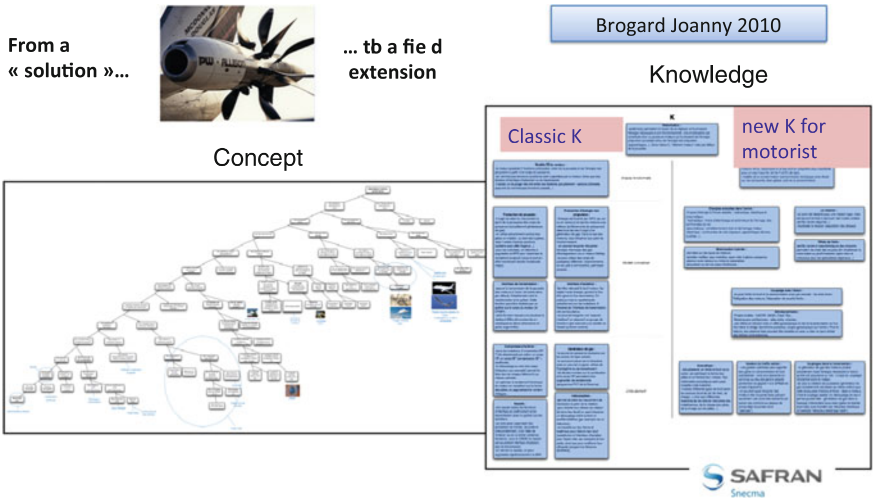


Fig. 6 C-K graph associated to the concept "engine for green aircraft"

This kind of graph helps to analyze the level of breakthrough that an innovative project implies, compared to its neighbor in such a C-graph. For instance, the work of Brogard and Joanny (2010) helped to show the level of originality of the concept of "open rotor" (see Fig. 7). Beyond this analytical power, such graphs also leads to tune the level of breakthrough in a portfolio of projects.

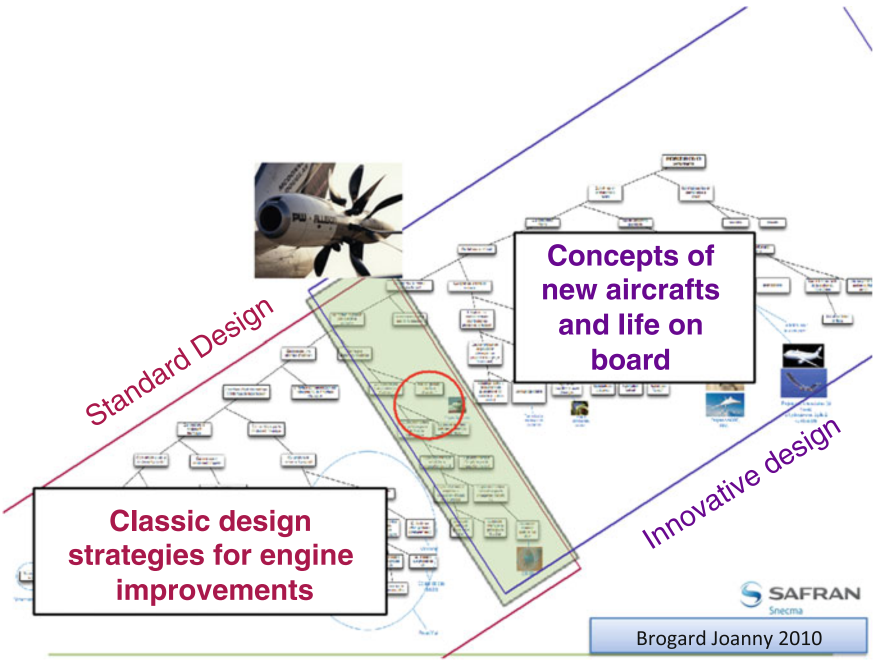


Fig. 7 C-K graph to position the "open rotor" in the innovation field of "engines for green flights"

4 C-K Theory, a Framework to Position and Develop Existing Design Methods and Processes

As a general design theory, C-K theory helped to analyze exiting design methods. Casting any method into the C-K theory leads to uncover and clarify some implicit aspects: hypothesis on the available knowledge, on the user capacities, on the kind of concept that can be expected from the method… Even more: it can lead to propose improvements to these methods.

Let's mention some examples:

- C-K was used to analyze Advanced Systemic Inventive Thinking (ASIT, a special method derived from TRIZ); it helped to underline the critical issue of the "closed world assumption," it showed that ASIT was a specific way to be creative "while staying in the box" and it led to propose improvements to ASIT (Reich et al. 2010).
- C-K was used to compare Parameter Analysis to other forms of Conceptual Design (Kroll 2013). It then led to show that Parameter Analyse relied on a specific way to evaluate concepts, and that, as such, it was actually an extension of the well-known Branch and Bound algorithm to Design cases (Kroll et al. 2013).

- In an historical perspective, C-K helped to compare some of the theories that led to the systematic design framework. It led to reveal the critical features of systematic design, namely: a structured language of the unknown (and not only the "known" as tend to do scientists in a modeling perspective) and a constant effort to improve the generativity of the theories (Le Masson and Weil 2013).
- In (Shai et al. 2009, 2013), the use of the Infused Design methodology in the creative scientific discovery process is modelled with C-K theory, leading to a deeper understanding of both Infused Design and C-K theory.
- In (Lenfle 2012), Lenfle uses C-K theory to analyze and evaluate the methods used in breakthrough projects. He revealed that, contrary to conventional wisdom, these methods were strongly different from project management techniques like PERT and stage-gate processes; and he was able to clarify some specific features of these very original methods for breakthrough innovation projects.
- Studying the most recent CAD tools for industrial designers, Pierre-Antoine Arrighi identified critical features with the help of C-K theory (Arrighi et al. 2013). For instance, he uncovered a logic of "acquired creativity:" whereas it is often considered that there is a trade off between robustness and creativity, some CAD tools managed to simultaneously increase the originality and the robustness of a design (Arrighi et al. 2012).

5 C-K Theory, a Conceptual Model to Develop Methods and Processes for Innovative Design Situations

Beyond this analytical perspective, C-K theory was also used as a "conceptual model" to design methods and processes for managing innovative design processes. Here again it is not possible to account exhaustively for all the methods that were developed. We will just mention some examples in three families: the methods to manage innovative design processes; the methods to organize innovative design in companies; and the methods to support innovative design in ecosystems (beyond the single firm).

5.1 Methods for Innovative Design Processes: KCP, C-K Invent, C-K Expert, C-K for the Design of Generic Technologies,…

KCP is a method derived from C-K theory to support innovative design processes that need to involve many participants like experts, users, researchers, engineers, designers, customers…. C-K theory helped to analyze the limits of traditional methods of collective creativity (Hatchuel et al. 2009): methods of group creativity (like more or less sophisticated brainstorming) tend to lead to a consensus with very few breakthrough; by contrast, task force create breakthrough but due to their limited size they often lack expert inputs. The theory was used to overcome these risks, while creating a linear process for innovative design. KCP is a “linear approximation” of a C-K process:

- The K phase is introduced to create a common knowledge base, which will support venture into the unknown. More than a state of the art it has also to be a state of the non-art, i.e., a work on the limits of available knowledge, on anomalies, and “holes” in knowledge.
- During C-phase, participants generate concepts in a guided way; relying on C-K graphs, the leading team will support divergence in the exploration to avoid fixations.
- During P-phase, participants will structure an agenda of action. Aware of the interdependencies between all the paths they will set of portfolio of action that should cover all the imagined alternatives (with a fixed budget).

As shown by in-depth research studies made on KCP (Arnoux 2013; Elmquist and Segrestin 2009), one of the most surprising features of this method is that rigor, rationality, and control do not limit participant’s creativity whereas they drastically increase its scope and value in a structured way. Moreover, the collaborative work favors the innovation process. These claims as well as the creative power of KCP workshops have been confirmed through field experiments conducted in several projects (Metros of the future with RATP, new types of cockpits with Thalés, new home networking with Sagem and several others with Vallourec, Volvo, etc.). More than 30 KCP were run with 10 companies.

C-K theory was also used to develop a method to design patents, C-K invent (Felk 2011; Felk et al. 2011) or a method to involve experts in “rule-breaking” processes, C-K expert.

More recently, C-K theory was used to manage risk in “double unknown” situations: when market and technologies are unknown, techno-push and market-pull strategies are impossible. It is often said that such situations are doomed to (costly) trial and error or, a bit more optimistic, “try and learn.” Still advances in design theory, and in particular the logic of K-reordering in C-K theory, helps to figure out strategies to design generic technologies that break the fatality of low market and technology probability (Kokshagina et al. 2013a). Interestingly enough, this method shows that the risk management in a design perspective does not consist in uncertainty reduction but in structuring the unknown and designing independences (Le Masson et al. 2013).

5.2 Innovative Design Organizations: RID, Rc, Dc,…

In an organizational perspective, C-K theory helps to clarify that innovative design is a specific model of action, different from New Product Development and

Research: whereas Research can be characterized a controlled process of knowledge creation and Development as a process that maximizes knowledge reuse and minimize knowledge creation in design, C-K theory helps to cover a large span of design processes that include Research and Development but might also go beyond R&D, including activities that consist in breaking design rules intentionally, aiming at generating original objects. C-K theory helps to understand critical aspects of innovative design action; it enlightens what has to be managed (explore largely and rigorously the C-space, relates creativity to knowledge and knowledge creation,…) and hence helps to define the mission, role, time horizon for action, resources or performance of an "innovation director" or an innovation department. The theory helped to distinguish innovative design from R and D and to organize the new "R-I-D," i.e., the shift from R&D organization to R-I-D organizations, where I stands for innovative design (Hatchuel et al. 2006; Le Masson et al. 2010).

The growth of innovative design activities has also led to the emergence of new forms of research. Based on C-K theory, it was possible to characterize (analyze and support) a new form of advanced research: this so-called "conceptive research" consists in mapping rigorously a concept C0, as exhaustively as possible. They are many similarities with "research:" we characterized research as a controlled process of knowledge production (where the value of research is more on control than on the use of knowledge); conceptive research is as controllable as research, but, contrary to modeling and optimizing, conceptive research is made on C and not on K, i.e., it is done on unknown objects instead of known ones (Felk 2011; Le Masson et al. 2012b, c). C-K theory helped to clarify the performance, the organization and the resources relevant for conceptive research.

Scholars also identified a new form of development, conceptive development Dc. Dc appears in situations where both markets and technologies are unknown. In this situation of double unknown, the usual development processes are not feasible (no clear target, no available proven technologies…); still C-K theory helped to identify a specific strategy consisting in developing a generic technology that target a set of potential markets; paradoxically, this activity in double unknown can be organized to become almost as predictable and controlled that a usual NPD process (Kokshagina et al. 2013a, b).

5.3 Colleges and Architects of the Unknown

C-K theory helped to analyze and improve new forms of inter-firm collaborations at ecosystem level. On the one hand, it led to uncover the logic of "unlocking rules:" scholars have long analyzed how rules might lead to "path dependency" and provoke "lock in;" with C-K theory it was possible to show that some rules might be unlocking and can help organize forms of path creation. These rules were associated to specific organizational forms, so-called "colleges for the unknown," i.e., ecosystem level collaborations where experts don't share knowledge but discuss on the agenda of open questions, i.e., the unknown in the field (Le Masson et al. 2012d).

On the other hand, C-K helped identify specific intermediary actors of open innovations, which were called architects of the unknown. Contrary to brokers who support the exchange of knowledge in pre-existing networks of seekers and solvers, the architects of the unknown organize collective action when there are no clear interests and no pre-identified seekers and solvers (Agogué et al. 2013b). C-K theory was also used to support new forms of organizations by these architects, enhancing their capacity to "visualize the invisible," to creatively solve conflicts, to design new identities and new ad hoc expert networks (Agogué et al. 2013a); it was also used to clarify their way to efficiently deal with expectations, avoiding technological bubbles by managing so-called "generative expectations" (Le Masson et al. 2012a).

6 C-K Theory, a Transdisciplinary Impact, on Academic Disciplines and Design Professions

Being models of thoughts, design theories have a great potential of transdisciplinary impact. This means that the formalism can diffuse into other discipline and be reused in many different fields. Moreover it can also diffuse to many professional groups, like engineers but also industrial designers or business managers who, in turn will use it to develop ad hoc methods and processes. Hence, the importance to analyze the impact of the theory in professionals education and in academic disciplines.

6.1 Teaching De-fixation to Professionals

C-K theory formalisms are taught today in different countries (France, Sweden, US, UK, Israel, Tunisia) in various contexts: engineering schools, management schools, business schools, design curricula, entrepreneurship schools, and universities… Over the last 5 years, the team from Ecole des Mines de Paris has supervised closely 41 master students doing internships using C-K theory in French institutions and firms (big firms, medium size firms, and start-ups). They worked in sectors such as transports, energy, food, NTIC, health, nanotechnologies, and urbanism.

The impact of this kind of education was studied by researchers (Hatchuel et al. 2008; Dym et al. 2005; Hatchuel et al. 2011) and recent experiments based on a cognitive perspective showed that this kind of teaching significantly increase the capacity of students to resist to fixation (Agogué and Cassotti 2012).

Observations through empirical investigations (interviews with consultants specialized on C-K methodologies, industrial partners, students) show that today, the diffusion and adoption of C-K theory through teaching and companionship leads to the emergence of practices outside of the scope of the Design Theory and

Methods for Innovation team at Mines ParisTech. Those practices are indeed adapted very finely to the technological, social, and organizational contexts of their applications.

6.2 Impact on Disciplines, Beyond Engineering Design

The implications of C-K theory have disseminated in many academic fields (see Fig. 8), such as creativity research (Le Masson et al. 2011; Hatchuel et al. 2011), data mining, and knowledge management (Ondrus and Pigneur 2009; Poelmans et al. 2009; Goria 2010), history of engineering design (Le Masson and Weil 2010a, b), psychology and cognition (Hatchuel et al. 2011; Agogué et al. 2014), ecology (Berthet et al. 2012a; Berthet et al. 2012b), philosophy (Schmid and Hatchuel 2014) and economics (Colasse and Nahkla 2011).

In the domain of cognition, Hatchuel et al. (2011) have shown how C-K theory can help overcome fixation effect, i.e., being fixed on a small number of solutions, binding creativity. They stated that the outcomes of C-K theory based design curriculum can be measured, being a possible catalyst while teaching creative thinking to students with the ability of creative thinking. Building on the notion of fixation effect, (Agogué et al. 2014) claimed that there are two types of examples that C-K theory helps to characterize: (1) restrictive examples that do not change the definition or the attributes of the object, and (2) expansive examples that modify its identity by adding unexpected attributes. Using an experimental protocol, they showed in the field of cognitive psychology that the solutions proposed by the group exposed to restrictive example are less original than those given by groups exposed to expansive examples.

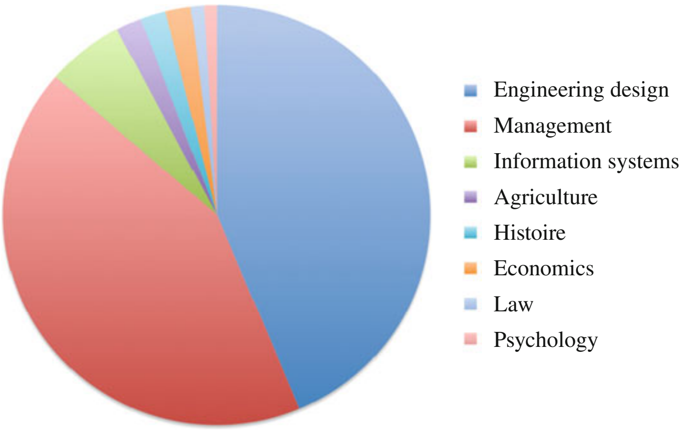


Fig. 8 Repartition of the publications on C-K theory in diverse academic fields (end of 2012)

In ecology, a stream of research focuses on identifying and exploring effective solutions for integrating development of agriculture and conservation of biodiversity at a landscape scale. Berthet et al. (2012a) presented a case study on an intensively farmed French cereal plain, where the reintroduction of grasslands has been proposed to protect the Little Bustard, a threatened European bird species. They analyzed the design reasoning that fostered this idea in order to highlight the innovative paths that were opened. They used C-K theory to do so, and revealed the links between the production of scientific knowledge and the generation of various solutions. It allowed them to state that specifying the ecological functions of grasslands facilitates their management.

There is today an impact of C-K theory in a branch of philosophy, called contemporary epistemology. Traditional epistemology discusses the truth or proof of truth of sciences. Contemporary epistemology is interested more in how science can create new techniques and control processes through ethics and democratic principles. Interestingly, researchers in this field have found in C-K theory an operational framework to describe processes and principles for generic epistemologies (Schmid and Hatchuel 2014).

7 Conclusion

In this chapter, we have distinguished three types of applications of the C-K design theory: (1) C-K theory provides a new language, that supports new analysis and descriptive capacity and new teachable individual models of thoughts; (2) C-K theory provides a very general framework to better characterize the validity domain and the performance conditions of existing methods, leading to potential improvement of these methods; (3) C-K theory is the conceptual model at the root of new design methods that are today largely used in the industry. We also highlight the impact of C-K theory on other disciplines and on design professions.

All these cases reveal a shift in our contemporary societies between a "decision paradigm" dominant during the second half of the twentieth century and that we can call a post-decision paradigm, "a design paradigm."

We have shown that we have to broaden the usual term of "applications" if we want to be able to evaluate the impact of a design theory. The matter is not only to "apply" such theories, but also to use them as means to increase our ability to reinvent and regenerate industries and to deal with the so numerous challenges our contemporary societies are facing. How design theories could help us to explore and move the new frontiers of the unknown?

This first attempt to analyze applications and impacts of C-K design theory leads us to formulate the hypothesis that the evolutions of recent design theories are very closely linked to the transformations of our contemporary society and the knowledge they use and produce. Design sciences would appear as a means to rebuild new forms of epistemologies relevant for contemporary knowledge.

Further research is needed to explore the relationship between design theories and the transformations of "episteme" in our societies.

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People with a Paradigm: The Center for Design Research's Contributions to Practice

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Abstract Stanford University's Center for Design Research has been in operation for 30 years. Its primary impact on practice comes through its people. In this chapter, we summarize the CDR's research approach and themes, and then look at the mechanisms through which the people of CDR affect the landscape of industry and education and impact the practice of design.

1 Introduction

The Center for Design Research is a research center at Stanford University, in Stanford, California. The Center for Design Research was founded in 1984 by Larry Leifer with funding companies including Apple Computer, BMW, Hewlett-Packard, Sun Microsystems, and Toshiba Corporation. Since its founding, the Center for Design Research has acted as a nexus for PhD students and researchers in a number of affiliated research laboratories, headed by Professors Larry Leifer, Mark Cutkosky, Sheri Sheppard, and Allison Okamura.

The CDR is located in Building 560 at 424 Panama Mall, at the center of the "Design Quad." The Center for Design Research is home not only to design research work but also related research in robotics, rehabilitative technologies, engineering design education, STEM education, and business innovation, among other topics. It is affiliated with the Stanford Joint Program in Design, which offers an undergraduate and terminal graduate Master's degree in Design, and with the Hasso Plattner Institute of Design, also known as the Stanford d.school, which offers interdisciplinary courses on real-world design challenges to graduate students at Stanford.

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Within this broader research agenda and larger design ecosystem, the Center for Design Research is still, at its core, focused on academic research in design theory and methodology, as well as design technology, innovation, and education. In addition to facilitating interdisciplinary research in these topics, the CDR also provides educational outreach, partners with industrial affiliates on research and brings together an international body of leading researchers and scholars in design theory and innovation. In this chapter, we will focus on the impact of these aspects of CDR's research on design practice.

1.1 Research Themes

From its founding, the Center for Design Research has had a forward orientation, using a lot of early computer aided design, artificial intelligence, and robotics tools to both augment the capabilities of designers to generate, capture, and document design knowledge and to study design activity. Early projects focused heavily on novel computer-aided design and computer-aided engineering systems, computer-supported systems for visual drawing systems. More recently, research has focused on communication with/through technology in design settings, applications of design in health and rehabilitative robotics, and business case studies looking at the impact of design. Many of these projects are interdisciplinary, incorporating software design, hardware design, artificial intelligence systems, ethnographic observation, and controlled experimentation.

The long running research themes at CDR have been:

(1) design team performance
(2) design team cognition
(3) communications between designers and interactions with their design environments
(4) knowledge capture and reuse

Much of the research has centered on a graduate sequence in team-based design innovation that we use as a "simulation environment" for design. In addition, there has been an ongoing body of research relating to the application of design research to a variety of fields, such as robotics and medicine, and an emerging interest in broader surveys of design performance at a business or corporate level.

1.2 Point of View

Although the research emerging from the Center for Design Research reflects a variety of views, there are some common characteristics of CDR research:

(1) Empirical. One of the core goals of research at CDR is to find out what is it that designers do when designers do design. One of the premises to this research approach is that the seeds to better design are present in the current practice of design.

One asset that has enabled the CDR to perform a lot of empirical research on design activity is the Design Observatory, which is a laboratory equipped to support teams engaging on conceptual and technical design and engineering tasks (Carrizossa et al. 2002: Tang and Leifer 1988: Leifer and Mabogunje 1998). The environment of the Design Observatory is outfitted with cameras and microphones that make it possible to make detailed observations of what is transpiring in design interactions at a very fine grain level (e.g. Brereton et al 1996), and the set up is flexible enough to accommodate anything from designers brainstorming with post-it notes to people taking apart a transmission to reverse engineer how it functions.

Another asset which has permitted longitudinal research on design is the CDR's long-standing relationship with project-based design courses as a "simulation environment" wherein to observe, analyze, and test design activity. Of particular significance is Leifer and Cutkosky's graduate course in team-based engineering design innovation (Mabogunje et al. 1995). The course features graduate students working in teams of 3–5 people over the course of 9 months on projects sponsored by industrial, corporate, and governmental partners; these projects are all open-ended enough that the students need to do needs assessment and problem framing, but still require a solid and working deliverable at the conclusion of the course. In recent years, these projects have been carried out not only with corporate sponsors but with global collaborators at partner universities; this setup reflects the increasingly global nature of design practice, and allows students to learn how to rise to the challenges and seize the opportunities presented by a distributed design workforce.

This expertise in using "learning environment as lab" has allowed CDR researchers to observe phenomena that otherwise might be off-limits to researchers, to establish better-controlled comparisons, and to introduce novel technologies and interventions in a way that would be difficult in more naturalistic design settings. For instance, this been crucial to research understanding the effect of learning styles (Carrizosa and Sheppard 2000) or emotional dynamics (Sonalkar et al. 2011) on team work to understand the roles that wikis and blogs play in the design process (Chen et al. 2005), and to understand how engineering design best practices need to be adapted when applied to lesser industrialized economies (Donaldson 2002).

(2) Technical. Research at the Center for Design Research both focuses on designers working on technical problems, and features researchers who readily employ technical solutions in their research tools, metrics, and interventions. Over the years, these technical tools included large servers to host digital information repositories, early broadband networks that enabled us to predict the nature of distributed design work, online group design wikis (Leifer et al. 2002), video

prototyped shared whiteboard (Tang and Minneman 1991b) and drawing systems, electronic designer logs (Lakin et al. 1989), embedded workspace capture and analysis tools (Ju et al. 2004), and telepresence robots (Sirkin and Ju, 2012).

(3) Social. The Center for Design Research focuses on design as a social process between teams of people. This focus acknowledges a fact, which is that design is increasingly the provenance of large numbers of people working together rather than something that people perform by themselves, as well as a belief, that the social, emotional, and human aspects of design teams profoundly affect the outcomes of the design (Minneman 1991).

This attention to the social aspects of design is evidenced in the research looking at how design teams communicate with one other in the courses of performing design tasks, in systems that help to communicate bodily position, proximity, and gesture in remote interaction in research that looks at the types of questions people ask during the research process (Eris and Leifer 2003), in the analysis of how emotional reactions between team member predict performance outcomes.

1.3 Key Findings

Here is a sampling of major outcomes from design research undertaken at the Center for Design Research that has been of particular interest to global partners and industrial affiliates:

(1) Over a third of design activity of collaborators working together in a shared drawing space is mediated by gestures. These gestures and actions are crucial to retroactively understanding the meaning of the resulting drawn or written artifacts (Tang and Minneman 1991a).
(2) Designers traffic in ambiguity to maintain design options throughout the course of the design process. They hold it dear, and communicate it artfully (Minneman 1991).
(3) The number of unique noun-phrases used by a design team in their communications throughout the course of design projects predicts breakthroughs in innovation (Mabogunje and Leifer 1997).
(4) Designers move from one type of design information to another on average every 13 s; most frequently they spend about 6 s with any one kind of information (Baya and Leifer 1994).
(5) The implicit gestures and timings that people use in their communications can be applied to the design of machines to make them seem more intelligent, personable, and less obnoxious (Ju and Leifer 2008).
(6) Affective interaction dynamics between collaborative design teams even in short group discussions can be analyzed to predict design team performance (Jung and Mabogunje 2008).

(7) By notating design interactions, we are able to identify eight patterns of interaction that characterize moment-to-moment concept generation, such as transitions between ideas and facts, the occurrence of improvisation behavior, question asking, and blocking behavior (Sonalkar et al. 2013).
(8) Designing surgical products to maximize benefits for financial beneficiaries and end users (hospitals, physicians) can have a greater impact on product adoption than designing to meet end-customer (patient) needs (Aquino Shluzas 2012).

2 Impact Through People

While the research projects and findings at the Center for Design Research are certainly important outputs of our research community, we feel strongly that the most crucial "products" of the design research are the students and researchers who make up the community and its culture, and then go on to spread the "CDR paradigm" to other institutions, companies, and communities.

Consider the example of Vinod Baya, who got his PhD from CDR in 1996. Baya worked, as many students in the 1990 s did, on the project of Generative Design Knowledge Capture (Baya and Leifer 1994). Much of the work was sponsored by NASA, and centered on capturing the design rationale that went into parts that were generated by CAD and CAE systems. It was motivated in part by the reflection that the Apollo rockets could not be built today because so much knowledge about those systems had been lost. One of the systems that emerged from this project, DEDAL, for example, was an intelligent tool that uses a representation of the device model for indexing and retrieving multimedia information about the device being designed (Baudin et al. 1992). It incorporates a methodology for incremental, real-time modeling, and indexing of design information as it is generated during the design process so that it can be available for retrieval and reuse. This work was helped by Vinod Baya, who then went on to work at NASA as the chief architect of many knowledge management, collaboration, and search and retrieval systems. He then went on to apply his broad expertise in analyzing the socio-technical aspects of information technology systems to advise on a broad array of technology areas at PricewaterhouseCoopers, where he is now a Director for the Center for Technology and Innovation. While Baya's research and system design contributions were strong, Baya himself, with his ability to analyze the implications of socio-technical systems that manage information, has made the most impact on design.

In this section, we trace some of lineage of CDR alumni to indicate how these people with a paradigm go on to impact the world at large.

2.1 Impact on Design Industry

One of the key ways that the Center for Design Research's design research has impacted design practice is through the development of drawing and collaboration technologies to support design collaboration that are now part of offices and studios everywhere. While some of this work was directly the product of CDR research, it is more commonly the case that researchers from the CDR who worked on collaboration and knowledge systems research then continued to local industry to create these influential products.

Early on, several CDR researchers were sponsored by and did research at Xerox PARC. These included John Tang (PhD '89), and Scott Minneman (PhD '91). Tang and Minneman focused on computer-supported systems to support design activity; they performed empirical studies on design teams working in co-located workspaces and distributed team work settings to better understand the design requirements for systems that recorded and mediated design activity that was time or location shifted. A lot of the early work at PARC on systems such as VideoWhiteboard (Tang and Minneman 1991b) and VideoDraw (Tang and Minneman 1991a) was based on CDR research; the goal of recording the design process to capture knowledge generation for future reflection and reuse, the employment of cutting edge video and computation technology, the influence of empirical social data, and the empirical testing of how such systems were used in practice established the hallmarks of CDR research. These projects are widely considered to be classic works in Computer-Supported Cooperative Work, and are generally regarded to be the forbearers to the commercial interactive whiteboard systems that are used in meeting rooms and classrooms.

CDR's research into team-based knowledge capture and sharing repositories also influenced activities at Xerox PARC. Tao Liang's (PhD '00) dissertation looking at inter-team knowledge sharing in product development made him an excellent fit to be collaborative sharing into Xerox's DocuShare product. Early CDR research looking at web-based tools to support design teams on the SHARE project (Kumar et al, 1995) was expanded upon to enable greater uploading and editing. CDR collaborated with Liang at PARC on then-novel web-based editing tools for DocuShare, and on special configurations of DocuShare for education. The lessons learned in CDR-based roll-outs of DocuShare-based knowledge capture and reuse tools helped Xerox to understand larger issues of tool adoption and use (Liang et al. 1999). This is a solid contribution to the world of design practice. However, Liang then went on to become Principal Software Development Engineer at Skype, and architected and developed the Skype Web RTC platform. Many of the features of Skype—the support for many platforms, the ability to switch between camera and desktop views, the support for multi-point interactions—were features that were under active development and research in the Interactive Spaces project during the time that Liang was sponsoring other research at CDR; again, we are not claiming a direct causal relationship between the research and the subsequent product, but it easy to see how the paradigms at work at CDR are present in the most popular remote communication software in the world.

CDR's continuing research on technologies on interactive whiteboards also went on to commercial practice a decade later with Andrew Milne (PhD '05) and his start-up Tidebreak. Whereas the earlier CDR systems were built around ecosystems where the whiteboard was central to collocated interaction, the subsequent research looked at situations where participants might be remotely distributed, where interactants might have brought their own computers or personal digital assistants with a variety of operating systems to a meeting and where people would want to seamlessly move data objects from one platform to another. Tidebreak commercialized a lot of the research innovations developed in the Interactive Spaces project to support team-based learning in informal learning spaces, and in interactive technology classrooms.

Graduates of the Center for Design Research go on to companies small and large, but usually continue the theme of looking at collaboration and innovation systems throughout their work. For instance, George Toye (PhD '90) founded wiTHinc with Ruth Kedar in 1998 to transfer what he had learned during his tenure at Stanford University. His research on innovation, design, learning and knowledge management processes laid the foundation for the creation of the online software product panFora, which supports online discussion forums. This software has been integrated into Stanford CourseWork learning management system, and allows students and faculty to interact and collaborate online. Another example is Scott Minneman (PhD '91); in his work as an interaction designer, exhibit manager and art director at Xerox PARC, Onomy Labs, and the Workshop Residence in San Francisco, Minneman has melded art, design, science, and engineering to create exhibits that are particularly physical, interactive and narrative, encouraging participants to interact, and collaborate in real time.

Several of CDR's most notable instances of design innovation came as the result of "spinoffs" from sponsored research. Louis Rosenberg (PhD '94), for example, was working on design research sponsored by NASA to support remote teleoperation of robot arms for the Mars Exploration Rover; he noted that people enjoyed using the force-feedback joystick that was used in the flight simulator experiments. Rosenberg and fellow CDR researchers Tim Lacey and Bernard Jackson started a company, Immersion Technologies, to develop consumer-grade haptic devices.

On the other end of the spectrum, many graduates of the Center for Design Research go on to highly influential design and technology positions in established firms. Numerous CDR graduates, for instance, now work for the software company SAP. Alumni Sam Yen (PhD '00) is Global Head of Design and User Experience and Sanjay Rajagopalan (PhD '00) works in the office of the President on design, innovation and technology strategy. Philipp Skogstad (PhD '09) is Head of Development Processes and Tools at SAP. John Tang (PhD '89) is a Senior Researcher at Microsoft Research and designs new user experiences to enhance collaboration and social information sharing. We also have had a longstanding relationship with NASA Ames, with many talented graduates going on the work there: currently, Larry Edwards (PhD '95) and David Lees (PhD '94) work on Robotics Research there.

Some researchers who were working on design methodology and representation in novel new areas ended up as founding members of new fields. These people are often founders or C-level officers in companies that are the vanguard of new industries where design is practiced. After a period working as a professor at Michigan Tech, Al Curran (PhD ’86) is now CEO of ThermoAnalytics, Inc, which provides leading edge infrared modeling and software development to support engineering design. Jesse Adams (PhD ’01) studied how to introduce nano-fabrication technologies to classrooms at CDR in the mid-1990s; this effort lead to a series of key publications and nanotech startups. Adams was a Professor at University of Nevada, Reno, and is currently CTO at NevadaNano. Krista Donaldson, whose 2004 PhD research focused on constraints to and opportunities for product design in East Africa is now CEO of D-Rev, which develops world-class products for low-income economies.

In all of these cases, the researchers involved performed and published novel and groundbreaking academic work in the arena of design research. However, in the process of developing that work, they often built systems, gained expertise and absorbed cultural lessons that made them *personally* impactful, human embodiments of a paradigm that looks for technological solutions that address the social interaction and innovation needs of designers.

2.2 Impact on Design Education

A significant contingent of Center for Design Research graduates go on to positions in academia. As academics, CDR graduates are usually characterized by discipline-crossing collaborations and applied research that lead to products. These hallmarks strongly influence the design thinking, teaching and learning practiced by former CDR denizens (Dym et al. 2005). Their impact on design practice occurs through their teaching of students, their research, which continues to be empirical, social, technical, and innovative, and through their design-research-informed influence on their respective fields.

Don Brown (PhD ’88) is an Associate Professor of Mechanical Engineering at University of Utah, and an adjunct Associate Professor in Computer Science. He has received several awards for parallel-motion tricycle that helps children with mobility impairments strengthen their muscles and improve the coordination needed to walk. He is also the founder and CEO of PartNET, a software firm that automates supply chain interactions.

Scott Minneman (PhD ’91) teaches as Professor in the interdisciplinary Graduate Design Program at California College of the Arts, as does Wendy Ju (PhD ’08). As core faculty in the emerging area of interaction design and working alongside graphic design and industrial design faculty, they are advancing the multidisciplinary CDR perspective.

Ed Carryer (PhD ‘92) is a Professor at Stanford University and teaches the Smart Product Design course series in the Design Division of Mechanical Engineering. He organized the first worldwide workshop on Mechatronic Design, and is one of the authors of Introduction to Mechatronic Design, which is one of the primary textbooks for this topic.

David J Cannon (PhD ’92) is a Professor in Industrial and Manufacturing Engineering at Penn State. His research interests include virtual tools and robotics, as well as human-machine systems in manufacturing.

Machiel van der Loos (PhD ’93), Associate Professor of Mechanical Engineering at the University of British Columbia, studies the design of mobile manipulation robotic systems. His interests in the design methods has extended into his development of “robo-ethics” for designers of robotic technologies to consider, and his interest in coaching in product development.

Margot Brereton (PhD ’97) is a Professor of Engineering and Interaction Design at Queensland University of Technology. She researches the human-centered design of ubiquitous computing technologies. For a decade, Brereton was Director of the Information Environments program, an innovative studio-based degree program that taught computer science and information technology as a design discipline.

Maria Yang (PhD ’00) is an Associate Professor of Mechanical Engineering and Engineering Systems at MIT. Her work focuses on the fundamental role of informal design representation in driving the early stages of the design process. Her work has advanced our understanding of how informal representations influence the way a design team engages in the process of design, and how they are linked to a design’s eventual performance.

Ozgur Eris (PhD ’02) is an Associate Professor in Product Innovation Management at Delft University of Technology. He conducts research in design thinking and theory, design informatics, and distributed product development. At Olin College, he participated in a large scale experiment in higher education by co-developing the design stream of a brand new engineering school. His current work focuses on identifying and supporting mechanisms for reaching shared understanding during sketching in design meetings.

Lawrence Neeley (PhD ’07) is an Assistant Professor of Design and Entrepreneurship at Olin. His research and educational efforts help designers rapidly imagine, realize and offer compelling real-world products; he has pioneered courses where students develop and manufacture products that are funded by Kickstarter.

Malte Jung (PhD ’11) is an Assistant Professor in Information Science at Cornell University. His research focuses on the intersections of teamwork, technology, and emotion. The goal of his research is to inform our basic understanding of technology supported teamwork as well as to inform how we design technology to support teamwork across a wide range of settings.

Micah Lande (PhD ’12) is an Assistant Professor in the Department of Engineering in the College of Technology and Innovation at Arizona State University. He teaches human-centered design innovation and researches how engineers learn and apply a design process to their work. In his most current work, Micah investigates the educational pathways of “makers” and hands-on learning through design in the “making community”.

2.3 Impact Through Cultural Diffusion

Beyond the impact of the people who are the "products" of the Center for Design Research is the contribution the CDR has to its community. The CDR has been part of a major design movement that has promoted innovation through hands-on, project based learning in collaborative teams. Those values have long been shared by the Masters degree-granting Joint Program in Design, the Design Division of the Mechanical Engineering Department, as well as other partners at Stanford University, such as the Human-Computer Interactions group, the AI Lab, and the School of Education's Learning Sciences Design and Technology program, the Rapid Prototyping Lab and Stanford's Nanofabrication facility. The cross-overs between these programs occur in some part to the porousness of Stanford's research and education community: graduate students are required to take courses from their department for their degree programs; researchers often belong to multiple groups and help to establish social ties between programs; funding opportunities within the University often promote cross-disciplinary collaboration as a condition of grant funding. While the CDR is part of the broader design-based community, it has played a leadership role in fostering matches among the Stanford design community, employing multidisciplinary techniques and technologies in its research, and focusing on design research throughout these activities.

The Center for Design Research was a leading funder for Stanford's Ambidextrous Magazine (http://ambidextrousmag.org), which was founded by members of the Center for Design Research and the d.school. (One of the authors of this paper was a founding editor of Ambidextrous; another, the first subscriber.) Ambidextrous was published sporadically from 2005 to 2010, and highlighted the people and processes involved in design. It advertised itself as "a forum for the cross-disciplinary, cross-market community of people with an academic, professional and personal interest in design." Over the course of its publication Ambidextrous had an international subscribership of hundreds, and promoted the ideas of design research in a format that was directed at a broader audience that included design practitioners. Within Stanford, Ambidextrous drew on the talents of volunteers from across the campus, and the surrounding community, and the editorial meetings helped to promulgate important debates and discussions about debate and how best to make impact.

Another cultural product that started from the Center for Design Research is PhD Comics (http://www.phdcomics.com), which is authored by Jorge Cham (PhD '02). PhD Comics began as a side project of Cham's when he was a PhD candidate advised by Professor Mark Cutkosky. Although Cham's dissertation focused on biomimetic hexapod robots, many of his colleagues and officemates were focused on design research, and he sometimes collaborated on design research papers (Yang and Cham 2007). PhD Comics attracts over 7 million readers a year. Some of Cham's most popular comics, which feature scientific-looking graphs that depict the ups and downs of graduate life, are humorous reflections of design research that sought to quantify many of the seemingly ineffable aspects of design activity and design education. Some of the on-running jokes about the wide range of activities and the interminable length of the PhD are based in the multiple method approaches and long residencies of the average Center for Design Research doctorates.

The Center for Design Research's PhD graduates largely receive their degrees in Mechanical Engineering, although there are often researchers from near-neighbor disciplines like Management Science and Engineering or Computer Science. However, the transdisciplinary character of the Center for Design Research also attracts researchers that would otherwise defy categorization. One example is Natalie Jeremijenko, a digital artist/engineer whose background includes studies in biochemistry, physics, neuroscience and precision engineering. Jeremikjenko worked as a research assistant at the CDR in the mid-1990s, and collaborated with researchers at Xerox PARC to develop works such as LiveWire, which used LED cables strung from variably oscillating fans to reflect the amount of internet traffic in a knowledge-work environment—this is considered by many to be a key work in the area of digital arts (Brown and Duguid 1994; Dourish 2004). More recently, members of the Center of Design Research have been working with dancer and choreographer Aleta Hayes to look at how physical movement and dance can free designers up in their thinking; this collaboration, for example, strongly influenced the research of Neeraj Sonalkar (PhD '12) to look for design parallels to the Laban dance notation to develop a visual language to annotate design activity.

The Center for Design Research also regularly sends researchers abroad and hosts visiting scholars largely from international universities and research centers. This has helped influence the research directions at CDR, such as the longstanding interest in global collaboration, the study of cultural factors such as body language in interaction, and the focus on how to generate cultures of innovation far afield of the Center for Design Research's home in Silicon Valley. Recently, many CDR research projects have been funded by the Hasso Plattner Design Thinking Research Program, which also funds related design research projects in the Hasso Plattner Design Thinking Research Institute in Potsdam, Germany. In socializing regularly with partners at our partner institution, we have benefited from having partners that we are sharing techniques and findings with, and the reflections prompted by the outside viewpoint on our research setting. CDR researchers Mabogunje and Sonalkar have also recently started the Real-time Venture Engineering Laboratory, to work with officials in various geographic communities to use an engineering design approach to build and study innovation ecosystems communities such as Nigeria and India.

Most recently, the promotion of hands-on innovation with interdisciplinary teams has been championed as the core of "design thinking" education by the Hasso Plattner Institute of Design (also known as the "d.school"). This multidisciplinary perspective reflects the common roots of the d.school and the Center for Design Research. While CDR is more technically focused, and d.school courses are generally focused on developing products and services, the collaborative, multidisciplinary and hands-on qualities of the design research and engineering education promoted by CDR are shared by the multidisciplinary teaching teams and forward orientation of the d.school courses.

3 The Future of CDR

As CDR enters its third decade, the realization that it is the people of CDR that are its true product comes as a bit of a surprise. In the course of collaborating on research projects, grappling with new technologies, running experiments, teaching seminars and publishing papers, the researchers at CDR gain valuable social, technical, and hands-on experience. The ways that these experiences transform people ends up having a far greater impact on the world of design practice than the specific projects we are working on in our course of time at the Center for Design Research.

In summary, the key lesson to be gleaned from the Center for Design Research's history is that people are the ultimate vehicles by which research is converted to practice. Some people take the ideas from their research and turn them into products, which are then sold to and used by thousands of people. Others employ the paradigms of the research mindset in their own practice, and thereby increase the use of qualitative reflection as well as data-driven empiricism in the design of goods and services. Finally, a good many people go on to share the ideas of design research by continuing to research design, and teaching students to research design, and diffusing the ideas generated by design research into the broader culture.

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Impact of Design Research on Practitioners in Industry

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Abstract Design research is well established within a lot of universities mainly within developed countries. It is hard to define the beginning of these research activities. Looking at Germany, about 50 years ago, a number of institutes were founded or existing ones moved to design research and teaching. With time, the interdisciplinary character of engineering design and design research became more visible. It is a good tradition in scientific communities to evaluate the impact of research activities, usually on a long-term basis. This chapter is based on experience and observations on a long-term basis. Further, research regarding the impact of design research is urgently required, although it is difficult because of long-term effects and a lot of influences that we cannot control.

1 Background of the Author and the Institute of Product Development

The author is looking back with more than 40 years of experience with design methodology, beginning as a graduate student, followed by the PhD-phase, using the skills learnt in academia for more than 15 years in industry and now as a Professor at Technical University of Munich (TUM).

The Institute of Product Development is a part of the Department of Mechanical Engineering. This Institute had been initiated by Prof. Donald Welborn (Cambridge University, UK) and Prof. Gustav Niemann (Machine Elements, TUM, Germany) and it started in 1965 with Prof. Wolfgang Rodenacker as the first professor, followed by Prof. Klaus Ehrlenspiel and since 1995 by me. Today, the team comprises of a Professor, three Postdocs, nearly 30 research assistants (pursuing their PhD), and supporting staff (secretaries and technicians).

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From the very beginning, there has been a long tradition of collaboration between industrial partners and the Institute of Product Development. Most of the industrial partners are developing and producing their own products and are active on the global market. They are large- as well as small- or medium-sized companies in different branches like automotive, medical devices, packaging, energy, etc. Most of them are located in southern Germany and the rest in different European countries.

Within the past 40 years, more than ten spin-offs successfully started their business as consultants, suppliers of specific software, engineering services or with their own products based on their experience gained during their studies and research in the Institute.

2 Students and Alumni in the Department of Mechanical Engineering

Within the Department of Mechanical Engineering of TUM, there are more than 5000 students (undergraduates and graduates) in addition to 400–500 research assistants pursuing their PhD. The students have to undergo a preselection procedure, which helps to reduce the dropout rate compared to earlier days.

The candidates after graduating with the Bachelor's degree may leave the department to start a Master's program at other universities; nearly zero percent is leaving for industry at the Bachelor level.

Most of the candidates (about 80 %) after graduating with their Master's degree take up a job in industry. The others join consultancy firms, start their own company or switch to a PhD program.

About 100–120 aspirants graduate with Dr.-Ing. (in some way comparable to PhDs) every year. Among these, about 90 % take up jobs in industry, while others join patent offices, consultancy firms, or start their own business.

3 Students and Alumni in the Institute of Product Development

Within the Bachelors program, the Institute offers a first-year course "Introduction in Product Development" to 800–1000 students from Mechanical Engineering (and about 300 from business science), which is obligatory for all students. The course includes a small project run in groups of 10–15 students. Further, the Institute also offers a course on "Product Development and Engineering Design" (similar to the Pahl & Beitz methodology for engineering design) for the third-year students and in addition, the Institute covers one-third of a course in "Modelling and Simulation", again for the third-year students.

Within the Masters programs, the Institute offers courses on “Methods in Product Development”, “Design to Cost”, “Managing Complexity”, and “Management of Product Development”. Additional exercises, practical courses, project work together with the lectures, constitute these courses. The number of students in these lectures is in the range of roughly 100–500 per year. Master students in their second year have to deliver a thesis after 6 months of project-oriented research under the guidance of a Professor and research assistants. Within the Institute of Product Development, about 20–30 master theses are supervised each year. Usually, these Master-level students work in the research projects of the institute. Nearly, 20 % of the Master-level students’ work in collaboration with colleagues and institutes situated abroad.

4 Our Typical Output Towards Practice

We produce peer-reviewed conference papers (mainly, 40–60 per year) and some journal papers. Reports and handbooks as a result of research projects are handed over to our research funding organizations or industrial partners. We write books or book-chapters, edit books, and give presentations.

We organize and run workshops for and with scientists as well as practitioners. Sometimes we do specific training courses and consultancy in and for industry beside our core duties.

There are joint research projects with industrial partners, financed by industry and/or public organizations, which include intensive face-to-face collaboration with practitioners. Nearly, all of our research projects have at least some kind of exchange with practitioners.

5 The Stakeholders Involved or Influencing the Degree of Impact

A broad range of different stakeholders are at least in some way involved in generating impact based on our research results:

- *Students in Master courses* often do small projects (in the range of 3–6 months) with the industrial partners involved. About 80 % of all graduates directly start their career in industry as M.Sc.
- *Research assistants* usually do their Dr.-Ing. (PhD) based on research projects, which quite often are run in cooperation with partners in industry. They have a contract with our university and besides research they are also involved in teaching.
- *Professors* in Mechanical Engineering usually spend five to 10 years in industry between finalizing their Dr.-Ing./PhD and starting a career as a professor.

- The *university* is supporting cooperation with international academic partners as well as with industry. The board of trustees of our university has a number of members being entrepreneurs or CEOs in industry. Members of the council of the university represent a broad range like majors of the different TUM locations, members of parliaments, administration or media. Within the TUM University Foundation, a number of companies and entrepreneurs are active supporters.
- The Institute of Product Development is integrated in the *scientific community* and holds membership of WiGeP (the German speaking scientific community), the Design Society (as the global scientific community), and the GfSE (the German chapter of INCOSE).
- *Politicians* decide on important boundary conditions like IP-rules for universities.
- After humans, the bridge to society is based on *media* like TV, Internet, newspapers, or the day of "open doors".
- *Practitioners* on a management level are eager to learn about new ideas and results coming out of research. Practitioners on an operational level look mainly for help to overcome their daily problems and obstacles. However, they are obliged to work on a state-of-the-art basis in their field of engineering. Selected practitioners may also be involved in specific teaching duties.
- *Industrial partners* within research projects usually look for a direct transfer of the technical or organizational results to solve their current problem. Sometimes methods and procedures or tools are transferred as a more general form of support. Industrial partners with specific problems or questions may look for an outsider's point of view or specific training. The human resource management in industry is looking for recruitment opportunities.
- *Consultants* try to take over interesting results.
- *Society* may accept and value the activities of a university on different levels.

6 Transfer Mechanisms

There are a number of possibilities to transfer results of academic research to industrial practice. Figure 1 presents a simplified overview addressing only the directly involved stakeholders. Looking at academia there is a specific culture within institutes, universities, countries, and disciplines formed by history and actual development of boundary conditions and goals. The situation in industry is similar if we consider different branches, companies, etc. There is an exchange between academia and industry with their stakeholders.

As experience shows, the most effective and sustainable way of transfer happens via people with their knowledge and competencies.

Looking at undergraduate students, within their bachelor courses some of them have a part-time job in industry or do their engineering-oriented internship. Because

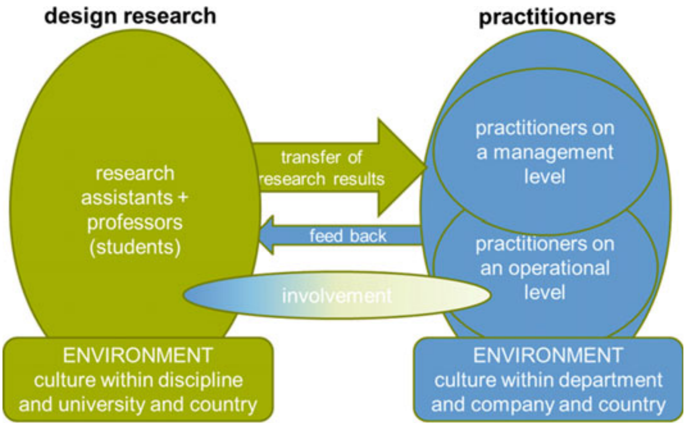

Fig. 1 Transfer between academia and industry, between research and practice

of the lack of experience and limited acceptance, their impact with regard to transfer is minimal. Nearly all of them continue studying within one of the master courses.

Looking at students within master courses, again they may have a part-time job in industry. A lot of them are involved in industry-related research projects, especially when working on their master thesis. After finalizing the master degree about 80 % of them leave for industry. The chance of an impact on this transfer channel highly depends on their experience and their personality as well as on the culture within industry and of the involved practitioners.

In the Institute of Product Development, research assistants start their work based on a Master's degree in Mechanical Engineering, some of them in Computer Science or Natural Sciences. Usually, their research including the preparation and finalizing of their thesis, required for their Dr.-Ing. (PhD) degree, takes around 5 years. Besides basic research, all of them are also involved in industry-related projects, which offer opportunities of an intensive exchange of experiences and knowledge in both directions. After finalizing the thesis about 90 % of them go to industry. The potential of an impact regarding transfer is high, as most of them start their career already with responsibilities for specific topics, a project, or a team.

Until now, all professors of the Institute used to work for more than 10 years in industry before becoming a Professor. This affords a chance to know and learn a lot of different insights about product development and engineering design, with specific boundary conditions as well as all the aspects of integration.

Another possibility of transfer mechanisms is the documentation and the distribution of information and knowledge.

The Institute is producing a number of documents each year. Going to conferences is helping the research assistants to build up international networks, present their thoughts and results, and receive critical feedback and insights within academia. Nevertheless, the direct impact of the scientifically oriented papers in industry is near to zero, as practitioners usually do not participate in academic conferences nor do they read these kinds of papers. Reasons are at first the efforts in time (usually several days), second the "scientific language" which does not always meet the requirement of practitioners, and third the findings of research usually have to be adapted to their specific needs and problems.

Research assistants often have first proven research results after around 3 years. Only then they are able to write a journal paper as first author. As the lead time until final publication is quite long, it seldom helps young researchers in finalizing their dissertation. Due to this situation, there are only a few papers written for scientific journals. The impact in industry is again near to zero, as practitioners do not read these scientific journals.

Books, book chapters, reports, or handbooks written for practitioners or for teaching Bachelor-/Master-level students have some impact, be it only to motivate further exchange with researchers. A similar impact can be observed when doing workshops, usual trainings, or simple consultancy. When switching to joint projects and joint work within the projects, the chances for having impact are more.

7 Goals in Academia Compared to Industry Are Different

In scientific communities, we try to pursue goals like high-quality research on topics, which follow rules of good scientific research in the sense of rigor and are highly relevant for the society. They are thus innovative in some way. We need funding, excellent researchers, and students involved and try to produce excellent publications including an exchange within academia. Based on research activities and results, research assistants write their dissertation, students in Bachelor- and mainly in Master-level courses get involved in research and therefore, create an impact on teaching content.

We try to prepare the students and researchers for their future career, mainly a career in industry. Another important issue is the intercultural competence and the development of networks not only at a local basis (typically alumni) but also at a national and international basis. A lot of Master-level students study for 6–12 months at foreign universities or do an internship in industry abroad. Research assistants go to international conferences and summer schools and visit research institutes abroad.

The overall issue is having sustainable impact in teaching, research, and industry. The last point requires an intensive exchange with industry and practitioners. This helps generating a specific culture in our academic environment.

Industry has a completely different set of goals compared to academia. Generating profit in a sustainable way is the key interest for surviving among competitors and different market segments. Due to dynamic development and changes within markets, they have to adapt their product portfolio, their organization including the set of competences, etc. and solve problems in short time with limited risks. They have to be innovative and effective as well as efficient at the same. Seeking chances and reducing risks, collaborating with others, protecting knowledge or developing competences, and keeping the fluctuation rate low are some of the challenges. The result is a specific culture in industry.

8 Basic Requirements for Impact in Industry

First of all, both parties industry as well as academia have to understand and accept that there are different sets of goals and cultures. Based on that researchers from academia have to be able to formulate their content, their messages in a way that practitioners are able to understand and are willing to accept. We have to supply clearly formulated instructions for a practitioners' operation supported by graphs and examples that show at least some relation to their set of problems and tasks. Practitioners prefer learning via case studies (or the like), whereas researchers are looking for theories and generic models.

Another aspect is the constellation of types of actors on the management and on the operational level in industry. Five different categories may be discussed:

A There is *a good chance* for a successful transfer via PhDs and MScs, if *management* and *operation* is seeing the necessity.

B There is a *small chance* for a successful transfer via PhDs and MScs, if *management* is not interested and *operation* is seeing the necessity.

C In case of transfer via MScs there is *a small chance*, in case of PhDs and joint projects there is a realistic *chance*, if *management* is seeing the necessity and *operation* is up to a certain extent at least interested.

D In case of transfer via MScs there is *no chance*, in case of PhDs *and* joint projects there is quite a *small chance*, if *management* has at least some interest and *operation* is seeing no necessity.

E Neither *management* nor *operation* are seeing the necessity, in this case there is *no chance* for successful transfers.

In projects or critical observation of transfer attempts, all these categories could be observed. There are, of course, a number of further important features of the individuals involved such as experiences of past attempts of transfers or the overall economic situation in industry.

9 Measuring of the Impact

Investing efforts in transfer attempts and activities requires possibilities to measure the real impact or at least identify indicators.

Reliable ways of measuring any impact requires a long-term analysis of changes, which again is difficult because of a large number of important influences that are difficult to control. This is why indicators will be discussed and only the positive aspects will be addressed.

9.1 People

- Excellent employment possibilities for MSc and PhD freshmen with design methodology as a background are given.
- Companies start looking for this qualification quite early and invest a lot of effort in this matter by offering awards or studentships for highly talented students, interesting internships, etc.
- Industry offers adequate salaries also for freshmen.
- Professors and researchers are invited for discussion, workshops etc. by industry
- There is an active alumni of former students and researchers.
- Successful spin offs can be observed.

9.2 Information

- Industry is asking for specific training courses or workshops.
- Industry is asking for consultation.
- Professional consultants are taking over research results.

9.3 Research Projects

- Industry is initiating joint research projects.
- Industry is willing to cover the cost of these projects.

If these indicators occur repeatedly, a very positive interpretation of the indicators is allowed.

10 Some Examples

Company A Relying on the advice of a friend, the owner of the company hired a PhD (Dr.-Ing.) with specialization in design methodology some 12 years ago. Following this first step, they have been hiring more PhDs and MScs with the same background during the following years. In parallel, they also financed a number of joint research projects. Businesswise, the company is very successful and the product department has managed a number of transitions. The company has nearly 10,000 employees and is a leader in the world market.

Company B About 12 years ago, this company hired the first PhD specialized in design methodology. The company is working in a field of high sophisticated technology and so far all the freshmen in the company had strengthened their knowledge in this specific technological field through university education. In the meantime, two more PhDs with a background in design methodology joined. The company is working on the global market with a few thousand employees.

Company C About 10 years ago, this company hired their first PhD specialized in design methodology. A few years later, the second one followed. Today, these two are responsible for two out of a total of four types of product lines. The company has roughly 1000 employees.

Companies D Within the past 6 years, the Institute worked in several research projects together with SMEs. Whenever we start a new project at least some of the former research partner tries to get involved in the new project again. Most of these companies are in the range of some hundred up to a few thousand employees.

Companies E These companies were established as startups originating from the Institute of Product Development, founded by one or more former PhDs. There is a broad range of products they offer starting with consultancy (processes, complexity etc.), software applications (big data, organizational, etc.), engineering services (design, computation etc.) up to specific mechatronic products and systems. Depending on the year they started in, their size ranges from a few up to some hundred employees.

Company F This company is a startup. In this case, it was founded and is run by a few students, some of them just started their master courses. They successfully offer engineering services like design, simulation etc. They try hard to work based on design methodology. After less than 3 years, they already started to internationalize their business.

Project X The Institute suggested a research project to an industrial association with mainly SME's as members. In the end, a project with a specific process-oriented topic in the context of product development had been initiated and financed by this association. For 2 years, several researchers had closely worked together with three companies. Results had been presented several times also to other members of the association and to their executive board, too. In the end, the key findings were documented in a handbook, written and structured in an industry-oriented way. The feedback was very positive and even a few years later, the Institute was asked for some more presentations of the results. On the scientific side, three dissertations and a large number of conference papers were generated.

Project Y The German Science Foundation supports collaborative research centers to do basic research. They may be active for a maximum of 12 years and may have an interdisciplinary background. In addition, there is a possibility to add so-called transfer projects. After a first period of research in one subproject, interesting results could be demonstrated and a transfer project could be started together with an industrial partner. Aims are evaluating specific results, getting new aspects and feedback to the basic research and of course generate some impact in industry. Within the runtime of 3 years, the involved researchers visited the industrial partner on a regular basis several times per month to collect data, understand the situation and needs in industry, present and discuss intermediate results etc. At the end of the project, the industrial partner was happy to get new ideas and views on their problem, to learn about new methods etc. Researchers had the chance to work on the basis of real-world data and to also generate an impact toward the overall collaborative research center.

And of course there are these large companies hiring staff with methodological background in engineering design; and there were and are wide-ranged projects of different types of collaboration.

11 Summary

All examples had some success based on people. During about 20 years of experience as a professor I do not remember any of our projects not having had any positive impact. Of course, there have been projects with difficulties or only small impact. In the end, we as academia should see the long-term effects since most of the learning is implicit by doing, reflecting, copying, improving, and gaining experience. This takes time. And sometimes standards like ISO 9000 and others help to foster the use of methods.

Rationalization Process for Industrial Production: Centres of Design Excellence and Prototyping

J. Lloveras

Abstract This article proposes a rationalization process of industrial production of consumer products with the structure of a possible solution. Moreover, its advantages are discussed. The application of a double filter to industrialize products is proposed. The filter would consist in an initial evaluation of innovation quality and design improvement, followed by an assessment of design excellence and production viability from the social point of view by an international entity. Centres of Design Excellence and Prototyping (CDEP) would not be related to manufacturing companies, which would compete to come up with the best design candidates for fabrication. Moreover, designers would have free design direction and a socially recognized status. This article also lists several doctoral theses and other research works on the enhancement of conceptual design and manufacturing processes of innovative products developed in UPC (Barcelona), within the framework of a common doctoral program by three Spanish universities, i.e. UdG (in Girona)—UPC—UJI (in Castelló), are the basis of the research here described. Most of UPC's research results could be used to implement improvements in the CDEP. The last section concerns the impact on practice of the Barcelona group's design research, and draws some conclusions.

1 Introduction

Current markets in developed countries offer a wide range of consumer products from which buyers can choose according to their desires and budgets. However, shortly afterwards and tempted by advertising, buyers purchase other similar products which include minor improvements (makeup). Another reason for change is damage or failure of the initial product, perhaps due to poor design or even intentionally poor manufacture (planned obsolescence).

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Despite its many virtues, the current economic model is somewhat inefficient because it offers an endless list of purchase items—sometimes advertised as if they were a must. This approach can lead to selfishness and tension between societies where products which require high consumption of material and energy resources are manufactured, not to mention its negative effects on the environment.

However, living a dignified life does not involve possessing a large variety of products, or always having the latest model. In fact, the unsustainability of the current economic model results in a waste of the finite resources of a planet where everyone has the right to a decent living. This situation poses an obvious challenge which could be solved by rationalizing the design and production of industrial products and raising social awareness.

2 Rationalization Process of Industrial Product Design and Production

In order to rationalize the design and production of consumer products, it is proposed that products designed for mass production go through two filters.

- The first filter, i.e. Standard of Excellence (SOE), would consist in the use of evaluation guidelines to determine quality in terms of innovation, excellence in performance, reliability, ergonomics, finishes, etc.

  Products obtaining a high score could be patented and move onto the next stage.

- The second filter would involve the democratic assessment of designs considering the technical, socio-economic situation by an international entity. This entity would be composed of a panel of international technical experts and non-technical professionals with no political or business affiliations. Based on the quality of design and public interest, the panel would decide what products are worth manufacturing.

Products approved for manufacture by the international entity would move to the next stage; namely that new products would be offered to companies interested in their manufacture. Companies would compete over details, cost and quality of products. Certain products would preferably be manufactured locally.

In the last step of the process, manufactured products would go through a quality control according to the design approved, as well as sales and benefits and correct distribution of all payments.

Note that, throughout the process, iterative flows between parts might be necessary and feedback would be provided.

Figure 1 outlines the proposed procedure, including CDEP. The SOE is shown in the first box. The following box contains the International Entity for Approval

(IEFA). MC-n refers to Manufacturing Companies that produce consumer products. The Control System (CS) is the last stage of the process. Finally, IF denotes Iterative flows between parts and Feedback of the process.

2.1 Centres of Design Excellence and Prototyping

The CDEP would be at the basis of this process and, unlike what is usually the case, they could be separated from the manufacture process. Designs from simple to complex of mass production products would be generated in these centres.

CDEPs would be places where incremental improvements of product designs are first conceived. After passing several iterative prototyping tests, designs would reach a substantial degree of innovative quality. The same final point could be reached if designs were based on path-breaking innovative concepts.

Manufacturing processes would also be conceived and tested in these centres, which would be small factories of creative prototype and test production where only designs would be sold.

CDEPs would compete to find the best results.

2.2 Designers

Apparently, designers only respond to the interests of those who pay them enough. They seem to be concerned about doing technically good jobs and are often detached from the reality around them. As a result, most designers have little social and environmental awareness.

Perhaps designers would play a more important social role if they detached their work from corporate guidelines. They could be key actors in a new economic model where they would produce and test their designs in prototype workshops until finding the "perfect" product, one which is a leap in technology.

That is why designers operating in engineering design and prototyping at CDEPs should be well chosen and have a creative capacity to produce conceptual designs worth manufacturing. The social worthiness of designers or design teams would increase significantly.

2.3 Expected Results of the Procedure

The rationalization process would allow only the best designs to be manufactured and rule out similar products of lesser quality. This should lead to more efficient consumption patterns, with a smaller offer of similar products and reduced frequency of product replacement by the industry, except for those products undergoing rapid technological development. Moreover, the use of fewer material and energy resources would result in reduced environmental impact. In this way, probably more people could enjoy these products.

Using filters for product rationalization must seem a source of problems, but not doing so could be worse. In fact, apart from those already met by most products, this procedure poses one more requirement, i.e. freedom of production of products that do not represent a specific substantial change is restricted. As a consequence, consumers would not replace a product until a new, truly innovative one came to the market.

There would be great freedom of design until excellent products were projected, as well as freedom of manufacture of approved products. The only requirement for products to be produced would be that their designs were a leap of technical innovation, with the quality required by the socio-economic circumstances of that time. Manufacturers would obtain more benefits by improving the manufacturing process.

Another advantage of this procedure would be the creation of jobs for highly skilled professionals in design-prototyping centres of excellence and in the above international entity.

Most of UPC's research results presented in the following sections could be used to implement improvements in these CDEP.

3 Research Work on Innovation of Conceptual Design and Manufacturing Processes Based on a Doctoral Program

This research work was initially conducted within the framework of an inter-university doctoral program, i.e. Technological Innovation Projects in Product and Process Engineering ("Projectes d'Innovació Tecnològica a l'Enginyeria de Producte i Procés"). Participating universities included the Universitat Politècnica de Catalunya (UPC) in Barcelona, Universitat Jaume I (UJI) in Castelló and the Universitat de Girona (UdG) (Girona) (on the Catalan and Valencian mediterranean coast). Said doctoral program began in the academic year 2002–03 as a continuation of another doctoral program entitled "Technical Innovation Projects", started in Barcelona in 1995.

Brief history of Barcelona research group Before the implementation of the Bologna process (Bologna Process 2013) in Spain, theoretical courses in doctoral programs took 2 years to complete. Students were subsequently required to go through a research phase and finally write their thesis. Later, in accordance with the Bologna process, master courses replaced doctoral program courses (last taught in the academic year 2009–10). The new European higher education system also put an end to the above inter-university program, whose activity in the Universitat Politècnica de Catalunya will also be interrupted in 2015. The program is currently integrated in a new, more extensive doctoral program, "Mechanical Engineering, Fluids and Aeronautics", where its original objectives have blurred.

Although the research carried out by the Barcelona group covered several areas, most of the work focused on conceptual design and product innovation issues. All the works below would contribute to the creation of CDEPs.

The following section lists several doctoral theses on aspects of conceptual design and the future manufacturing process, both of which are present in the early stages of the design process.

3.1 Some Doctoral Theses Developed by Barcelona Research Group

Now follows a list of some doctoral theses on conceptual design mainly developed by Barcelona research group:

- The analysis and adaptation of Creativity Software was chosen by (Chaur and Lloveras 2005) as his thesis topic.
- "How to empower the generation of new ideas in the creative phase of the technological innovation process in industrial engineering applications" is the title of Saiz MA's thesis (Saiz 2005).
- The title of Oscar Tomico's doctoral thesis is "Subjective experience gathering techniques for interaction design: subjective psychological exploration techniques based in the constructivism paradigm for informational and inspirational purposes" (Tomico et al. 2007; Tomico 2009).
- The title of Javier Rivera's thesis is "Generación y Gestión de la Innovación Tecnológica: Inteligencia Creativa Sistémica" (Technological Innovation Generation and Management: Systemic Creative Intelligence) (Rivera et al. 2009).
- Oscar González's thesis presents a methodological basis for consideration of differentiated geographic rating items in product ecodesign from an energy perspective (Gonzalez and Lloveras 2009).
- José Boccardo's doctoral thesis proposes a model of creativity from a complexity paradigm perspective (Boccardo and Lloveras 2010).
- "Wellness design: Engineering for emotion in human-device interaction" is the title of Sergio Gago's doctoral thesis (Gago and Lloveras 2012).

Now follow a few doctoral theses on manufacturing processes, which can be predicted in the design phase:

- Javier Munguía developed his doctoral research in the area of manufacturing processes. The title of thesis is "RMADS: development of a concurrent Rapid Manufacturing Advice System" (Munguía et al. 2007; Munguia 2009; Munguía et al. 2009).

- "Design Strategies Oriented to Prevent Product Assembly Failures: A Methodology to Design for Poka-yoke Assembly-DFPYA" is the title of Ph.D. thesis by Gabriela Estrada. This work focuses on the application of Poka-yoke principles in the conceptual design phase to prevent failures (Estrada et al. 2008; Estrada and Lloveras 2009; Estrada and Lloveras 2011).
- An expert system for selecting non-conventional processes for cutting metal sheets was presented by David Cortés in his doctoral thesis (Cortés 2015).

3.2 *Other Research on Conceptual Design by Barcelona Research Group*

Several traditional creativity techniques used in conceptual design were modified upon their application in research or in courses, for example:

- Brainstorming variant: After a short classic brainstorming exercise (Osborn 1993), time is devoted to reflecting in silence about arisen ideas, followed by a period of discussion on them (Lloveras 2001). This process, which is repeated several times, yields more satisfying results than classic brainstorming.
- Individual creative sessions using preferred creativity techniques for a certain time period (days). Ideas are then shared and discussed. This cycle is repeated until one or two selected working solutions appear (Lloveras 2006). During this process, the identity of the participant who had the seed of the winning solution is known. Should a patent be written, all members can be listed as inventors.
- Consecutive, or in-cascade, Mind Maps (Buzan 2000): a first level of possible solutions is provided without developing deeper levels, and one is chosen. From this solution a new mind map is started and developed at first level, and a solution (sub-solution) is chosen. The process is repeated at four or five levels, resulting in consecutive Mind Maps. This procedure is more appropriate for the initial conceptual phase of engineering design, and for solution of general problems, but it can also be used for specific problems by abstracting them to a general problem (Lloveras 2010).
- Rational order of creativity techniques: Order of description and use in a course of creativity techniques from less to more rational (Lloveras et al. 2010).

Three conceptual design phases are identified in the conceptual design process from the beginning until a viable solution is found. First, the conceptual design is directed towards a solution area (Directed design). Second, tasks to define the conceptual design more precisely are performed using various design tools such as search for state of the art, creativity, product architecture, ecodesign criteria or patent drafting… (Defined design). Finally, the viability of the design is discussed from a technical, economic and social standpoint (Viable design) (Lloveras 2011). The detailed design stage is then initiated.

4 Impact in Practice of Barcelona Group's Design Research

The impact in practice of the design research conducted by the Barcelona group is very modest. A few examples of general applied philosophy of technical innovation can be mentioned. Impacts are generally indirect, as pointed out by Dr. Udo Lindemann in the IDRP Workshop 2013, where he analysed the impressive results of his research group at the TUM (Technische Universität München).

The main results are indirect, mostly in the area of education. The activities related to the work conducted within the framework of the doctoral program provided students with research skills. Also, students may spread scientific and technical spirit in their home countries (Spain and South America, mainly). Our research has also contributed to improving the work of lecturers in undergraduate courses. For example, novelties for conceptual design were tested while preparing and teaching some undergraduate courses, like free elective courses (Lloveras 2007) about ecodesign, innovation and creativity, and aesthetics. Moreover, an UPC postgraduate training course in product and service creative innovation (Lloveras et al. 2010) was taught in a company as part of the training program for its new R & D department.

Several design practices and methodologies have been described to the scientific community through publications, but with little impact.

Additionally, various company-university agreements for new product development using the above design philosophy have been signed. Examples include writing of the patent of an improved measure tape (Carreño et al. 2006), or participation in the design of new MSW containers for the city of Barcelona (Lloveras et al. 2011).

5 Discussion and Conclusions

This paper proposes an evolution of the original concept of the role of design and prototyping in specialized centers, as published by the Engineers Association of Catalonia (Lloveras 2008) and exposed to UPC's Social Council, towards a rationalization of industrial production. But this original concept had a low impact.

The current trend in new product production involves extensive use of computers and robots. New products would be designed, calculated, simulated and tested throughout all stages of development, from concept to manufacture, at the CDEP. To do this, cutting-edge hardware and software would be necessary, as well as the performance of continuous research on design and manufacture software. Work would be completed by simulations and development of physical prototypes in an iterative manner until finding an excellent innovative product.

Two filters for the rationalization process for industrial production of consumer products stand out (Fig. 1): (1) analysis and evaluation of technical designs against a SOE and (2) approval for manufacture by IEFA. A SOE can also be applied by

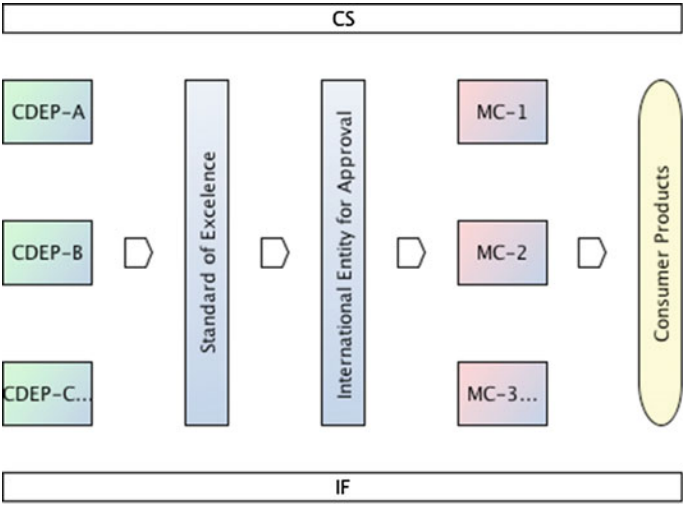

Fig. 1 Rationalization procedure of industrial production. *CDEP* Centres of Design Excellence and Prototyping; Standard of Excellence (SOE); International Entity for Approval (IEFA); *MC* Manufacturing Companies. *CS* Control System. *IF* Iterativity and Feedback

each CDEP to measure the quality of its designs. The key of this process is the IEFA organism and, if possible, the corresponding transition of production model, but the system's inertia and resistance to change would probably be significant.

By this rationalization process, some designs fail for industrial production, and only those representing a significant improvement of function, materials, quality and reliability are approved for manufacture by representatives of the society. Thus, current products with poor finish, a planned obsolescence date, or makeup would disappear. Moreover, rapid replacement of products, or consumerism, with its associated waste disposal problems and harmful environmental impact due to material and energy consumption, would be reduced.

In this scenario, the decreased offer of similar products would reduce the current choosing effort that causes so much confusion. Consequently, social stress and the quantity of advertising would be reduced. Only replacement products could be manufactured. However, large industrial production of an interesting novelty approved by IEFA would be possible. In general, less manufacturing capacity would be required, except for some periods of high production. It must, however, be noted that this process would need social agreement.

CDEPs, which could probably benefit from advice from academia, would compete to create the best design and manufacturing companies would compete to produce it.

This paper also presents some contributions (in the form of Ph.D. theses, courses and company-university agreements) to design research by the UPC Barcelona research group concerning conceptual design of product innovation and manufacturing. Nevertheless, the impact in practice of this research is low and mostly indirect in the form of educational benefits for future undergraduate, postgraduate and Ph.D. engineering students. Most conducted research could be used to implement improvements in CDEPs.

The proposed rationalization process is conceived for mass production, but it also finds application in individual or small-series manufacturing with 3D printing or Additive Manufacturing (AM). This Digital Manufacturing can use designs generated in CDEPs and approved by the IEFA because would meet all reliability and quality requirements. Also could be a basis for final product customization.

Future designers may gain increasing social importance compared to other less rational groups currently established, and produce designs of new products worth admiring because of their usefulness and beauty.

Summarizing, the research and contributions done are theses, courses and company-university agreements, mostly about conceptual product design, which some are published, but with a low impact. Probably Catalonia needs more organizational structure to effectively connect their industrial network with local universities, as well as with other EU universities and vice versa.

Finally, a rationalization process of industrial production is proposed, with CDEP, and two filters on SOE and IEFA.

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Facing Complex Challenges—Project Observations

M. Maurer

Abstract Today, the terms “complex” and “complicated” suffer from overuse—without providing a clear definition of these terms. This contribution shows the implementation of a practice-oriented definition for an industry project as a basis for a clear scope of action. Subsequently, it is clarified that increasing complexity in project management mostly originates from increasing system interdependencies. And knowing about these interdependencies allows solving complexity challenges with adequate strategies and methods. This contribution deals with the problem of steadily growing complexity and lack of its understanding in connection with missing solutions. Therefore, a research project was initiated for explicating the stepwise identification of types of complexity, promising strategies, and useful methods for managing complexity. Applied in the context of an industry project this allowed preventing the failure of premature selection of a specific method in case of insufficient transparency of the challenge. The contribution presents a straightforward process for identifying types of complexity, promising strategies, and useful methods in a project context. It is clarified why established methods of complexity management can result in insufficient solutions when applied in the wrong context.

1 Introduction

Today, the term “complexity” suffers from overuse. “Complexity increases” in almost all areas and “complexity is the most important challenge” of the future. Sometimes, descriptions of “complexities” appear. Apparently, the plural shall express a further increase of complexity. When asking the authors of such statements for a definition of the fundamental challenges, this often remains unclear. Declaring a question as being complex is often based on insufficient knowledge

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about the situation. Or in other words: If one describes a situation or question as being complex, he often means that the cause is not transparent.

Methods provide procedures and support systematic problem solving. Numerous methods exist for managing complexity—with different objectives. And declaring a question as being complex can be misleading when selecting a method. The reason for this is that the intentional selection of a method requires knowledge about the objective. However, if a "complex" problem is not understood (not transparent) it is hardly possible to determine a specific objective. Thus, if the declaration of complexity is directly followed by selecting a method for complexity management, the success of this method application is doubtful.

Successful complexity management requires the initial identification of complexity causes. Then the type of complexity has to be determined. After this, suitable strategies and methods can be selected.

In the following sections types of complexity and their causes will be detailed. These causes, complexity strategies and methods will then be integrated into a comprehensive process designed for purposeful management of complexity. The general layout of this process provides the possibility for understanding the different aspects of complexity management and their interaction. Thus, also the field of application for established methods like variant reduction or modular design will become clear. With this general process layout it gets easier for practitioners to identify a suitable method for solving a specific complex challenge.

2 The Challenge

A large and globally operating service company planned to renew its software systems. Services provided require processes to run permanently and therefore unbroken software system availability is mandatory. The pool of software systems used possesses many legacy subsystems, which are interconnected in historically grown networks. The software systems have been build up and are applied by several departments, whose mutual delimitation is also historical. Renewing the software systems can only be executed step by step, while maintaining the operability of the entire system. However, extracting a single system element means to break up (partly unknown) interconnections and to create new interfaces. And several departments may require a software element or interface, whereas the renewal is processed by one department only. The creation of news interfaces and the partial mismatch with the organization seems to even increase the system complexity that has to be managed. Initial attempts increased resources for better managing the complexity. However, this resulted in a further increase of complexity due to more general interfaces. This situation illustrated the need for an applicable process of complexity management.

3 Complex and Complicated Challenges

Research for a complexity management process started with the situation analysis: In the industry project considered here, project managers assumed that a high amount of complexity needed to be managed. The software-supported internal company processes should be renewed completely after being applied for more than 20 years. Several hundreds of software modules are interacting in daily processes. These modules are associated to different responsible organizational units and possess different needs for adaptation or replacement. Many interdependencies between modules are unclear to the project team—and so is the impact in case of displacement, implementation, and updating of single modules planned for execution during ongoing operation. With these facts in mind it is understandable that project managers of the enterprise described the situation as a complex challenge.

In everyday language the terms "complex" and "complicated" do often appear in the same context and are even used as synonyms. However, complex and complicated challenges differ in possibilities of solution. A short consideration of both terms helps to understand this:

Searching the needle in the haystack is an example for a complicated challenge. As well is the search for a number in a telephone book, in which the sequence of numbers and names is arbitrary. Both problems may be difficult to solve but can be mastered with effort (meaning time and resources), and investing more resources results in less time required for finding the solution. In contrary to this, predicting the further development of the world climate represents a complex challenge.

What makes the difference between complicated and complex questions as described in the examples before? First, a complicated question is a static one and can be subdivided, i.e., be reduced to several but less comprehensive questions. For the example of the telephone book this means that parts of the book can be searched in parallel by several persons, as long as the names and numbers stay in place (static system versus dynamic system). Subdividing a complex question is not possible, consequently time required for problem solving cannot be decreased by increasing resources.

In the industry project described before the project participants had to clarify if they have to manage a complex or a complicated problem, as this influences all further process steps. According to the explications above, project participants had to determine if the challenge could be subdivided into smaller questions; and if the challenge is based on a static or a dynamic system. In practice, the organizational layout of departments means a subdivision of the challenge, as each department is occupied with some aspects of the comprehensive system. However, analyses resulted in the fact that dependencies between software modules are often caused by distributed organizational responsibilities. The system also implies significant dynamics, as the project is executed in parallel to the continuous update and bug fixing of the product and process environment.

As mentioned before, the importance of distinguishing complex from complicated questions lies in different possibilities of problem solving. Whereas a complicated problem can be solved with effort (and even faster with more effort), this is not sufficient for solving a complex problem. As complicated problems can be subdivided, increasing resources can accelerate finding a solution. The same is not efficient for solving complex questions—but often applied in practice.

Project workshops on problem clarification resulted in the finding that the challenge on hand was a complex one. The clear differentiation from a complicated challenge did foster the understanding for the need of a new approach on problem solving. Next, the type of complexity and its origin has been investigated in detail. This is explained in the following chapters.

4 Types of Complexity

After the clarification of a complex (or complicated) situation the research focus was set to the possible types of complexity. The frequency of using the term complexity indicates that a multitude of complexity types must occur in practice. Clarification was searched for complexity in the context of product design and management. Of course, other disciplines know even more complexity types. In the project described here, complexity was considered as abstract phenomenon. However, a clear description was necessary for creating common understanding of the problem. Therefore, a classification of complexity by four mutually connected areas (see Fig. 1) was the basis.

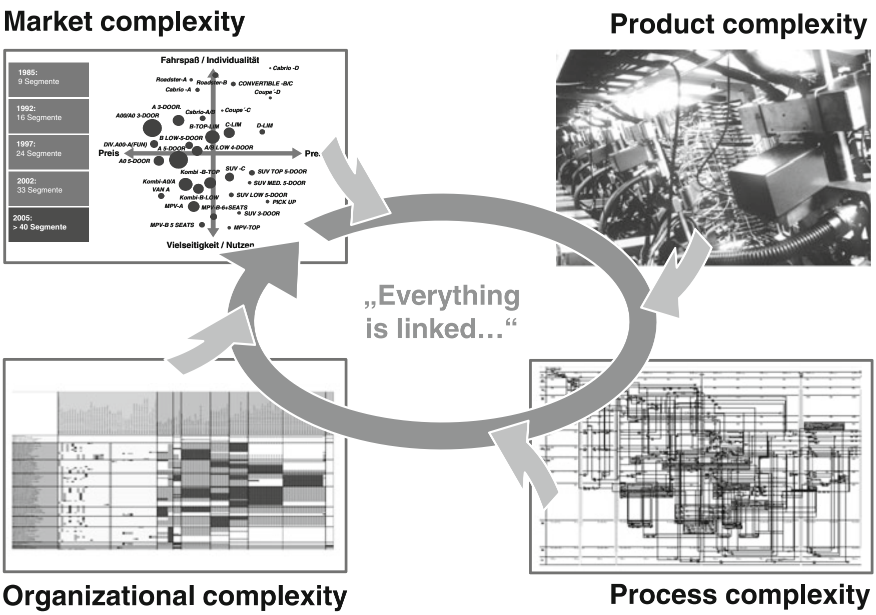

Fig. 1 Types of complexity (Photo: Tsgt L. Hernandez)

Market complexity represents a fundamental source of complexity issues, as market conditions and changes can hardly be influenced by enterprises. Market complexity emerges, e.g., by a variety of customer requirements. Further, boundary conditions based on, e.g., laws, regional, or linguistic characteristics can increase market complexity (also called external complexity for an enterprise).

From the point of view of an enterprise the external complexity is supplemented with internal complexity emerging from the offered product portfolio. This includes the variety and possible combinations of components, which are intended to serve the external complexity when assembled to product variants. Creating suitable modules, building blocks, platforms, and interfaces are examples for challenges in the field of product complexity.

Product complexity can cause process complexity. For example, the increase in products' functionalities can result in more partial processes (e.g., in development, production, and service) and the need for more intense synchronizing of these processes. Thus, process complexity can increase as a consequence of product complexity. Boundary conditions like shortened development times, globalized product portfolios, or distributed development activities contribute to this process complexity.

Organizational complexity is also interconnected with the already described types of complexity. Management of complex products and executing complex processes causes the need for adequate organizational design. In this context, "Conway's law" describes the interdependency between products and organizations within an enterprise (Conway 1968). Hierarchical or matrix-based forms of organization do often not meet existing product and process complexity.

Within the industry project it was required to highlight the interrelation between the different fields of complexity in order to identify and clearly describe the complex challenge. It was an important finding that the origin of complexity and its appearance do not have to be located in the same field. The enterprise did show a significant organizational complexity. However, intensive analyses brought up the fact that on the one hand this is a consequence of the process complexity the enterprise has to deal with. This was relevant for assessing the complexity's value for the enterprise. Of course, a complex organization itself does not possess any added value compared to a simple organizational design. The need for such a complex organization and its benefit only becomes clear when considering the process complexity, which becomes manageable with this organization.

On the other hand organizational and process structures both have been gone through evolutionary formation—partly independent from each other. For example, organizational departments have been defined initially, as processes of departments did not connect to other departments. Over time, processes have become more and more interconnected integrating more and more features of different departments. Thus, the organizational and the process network did show increasing mismatch, which increased complexity for any transformation approaches.

5 Complexity as Result of Interconnectedness

Whereas the field of origin of a complexity issue is often poorly considered in practice, the amount of interdependencies often becomes mentioned. In fact, in many cases complexity results from a multitude of highly interconnected elements. So, besides the pure amount of product components, process steps, or organizational roles the mutual links between these elements cause system behavior, which people perceive as being complex. Practitioners lack transparency of cause-and-effect chains, and systems often possess (undesired) momentum.

In the project described in this contribution such lack of transparency and momentum have not been regarded as main challenges of complexity. But these facts did cause the missing of a systematic approach for the reliable sequential design of an improved software environment.

When managing complex systems, people often make the same mistakes. These have been described by (Dörner 1989). For example, system analysis gets executed incompletely and subsequently only parts of the system are considered. Often the own personal focus guides a practitioner into concentrating on familiar system topics only. If, however, changes occur in non-considered parts of the system, impacts seem to happen accidentally—and practitioners lack explanations for that. Another typical mistake is the non-sufficient consideration of side effects. This can happen when practitioners rely on single key figures for managing progress in solving complex challenges. Then undesired effects are neglected but can have severe consequences to the complex system. As well, if unfavorable effects become visible in a complex system, practitioners tend to react with oversteering in order to compensate for the initial effect. Thus, people try to correct the effects quickly, for this reason resolute measures seem to be adequate. But lack of transparency and the associated lack of knowledge about interdependencies can lead to unexpected impact. In addition, short resources can reduce the available scope of action and the management often tends toward authoritarian decisions. People get the impression that the severity of the project requires a clear decision, even if the basis for a well-considered decision is not available. In such a situation people try to avoid discussions about alternative procedures.

All in all, it often seems to be impossible to solve a complex challenge systematically. This was also the finding of the project team in the considered industry project. For the successful management of complex challenges it is important to be aware of the mistakes described above. This is a prerequisite for a systematic approach for determining suitable methods of complexity management. Therefore, a process has been developed and applied to the industry project. This is further detailed in the following sections.

6 Strategies for Complexity Management

Strategies for complexity management are not in the focus of users. In most cases one wants to get rid of complexity. However, other strategies can be useful or even necessary. Here, this has been considered in detail. Complexity was perceived as being obstructive in the context of the industry project. For this reason, project participants asked for a strategy of complexity reduction or avoidance in the beginning. Then several workshops resulted in the awareness, that the type of complexity has to be known first, before strategies of complexity management can be selected.

Reduction and avoidance of complexity are not helpful per se, as the following example shows. As long as the company offers a multitude of customized services, the company has to deal with significant process complexity due to a multitude of customer requirements. This complexity could be avoided by implementing one simple measure: no offering of customized solutions anymore, instead offering standardized services only. Even if this measure would avoid complexity, also market chances of the company would be restricted significantly.

Of course, this example is rather trivial, but the conclusion is fundamental for managing complexity: If complexity is useful, e.g., in the example for realizing the company's success, then the pure reduction or avoidance of complexity is not

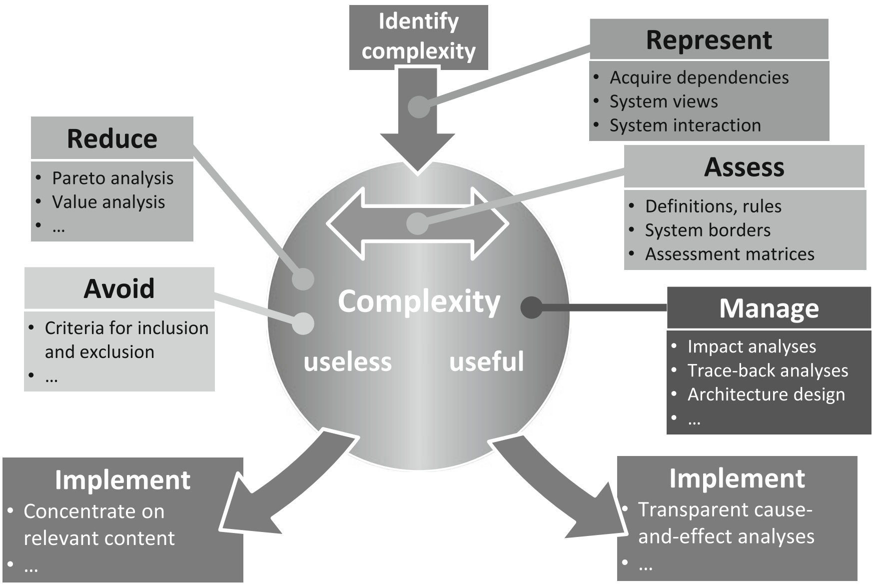

Fig. 2 Types of complexity, complexity management strategies and methods

productive. It is important to differentiate between useful and useless complexity—and apply the result for selecting an appropriate strategy of complexity management.

Figure 2 shows four general strategies of complexity management and assigns them to the two categories, useful and useless complexity. Basis for selecting the right strategy is the determination of the type of complexity. As described above, this type of complexity of often unclear to practitioners—as it was in the exemplary industry project. Several questions were used as guidance through project workshops for identifying the type of complexity with project participants: Where does complexity appear? What is the impact of the observed complexity? What can be identified as being harmful concerning the observed complexity?

Guided by these questions, the project team identified complexity as being useful regarding the company's success. Transparent representations of system interdependencies were applied extensively in workshops for obtaining this awareness. This will be detailed in the following section.

7 Generate Transparency by System Views

Many approaches exist for representing complex systems. Often graph depictions are applied, which are most suitable for highlighting the embedding of specific elements to a network. These depictions have been increasingly applied with the upcoming trend toward social networks and their analysis. Graph-based software tools apply several kinds of element alignment (e.g., force-directed graphs) and auxiliary information representation (e.g., size, form, and color of elements) for generating system transparency. Complex systems can comprise several thousands of elements and models cannot allow a complete depiction of such systems. With increasing amount of depicted information (e.g., the email communication of an enterprise) the visibility of details of the structure diminishes. Thus, showing large amounts of information only allows making vague and general statements (e.g., the interlinking of groups of people due to their email communication).

The application of specific system views is an option for generating transparent representations of complex systems. This is possible, as only a subset of system aspects gets depicted. This can be realized in two ways: On the one hand specific content, i.e., parts of a complex system can be isolated for being represented. Thus, this content gets extracted from the system while blinding out all other system parts. If, for example, the interactions within a large development department shall be depicted, one could concentrate on the exchange of documents between people. Centrally located people as well as closely interacting groups of people then can be identified in a graph representation of the structure. When applying this approach it must be assured that the extracted system part allows meaningful conclusions—and that the possibilities of interpreting the results are limited. This is important as the number of interconnections in complex systems makes it difficult to extract partial aspects without neglecting significant aspects.

On the other hand, interdependencies can be concentrated into a specific system view in order to generate transparency for a complex system. Hereby, system content becomes aggregated. For representing, e.g., the interdependencies between people in a development department, different interdependencies like documents' exchange between people or component responsibility shared between people become superimposed (represented by one interdependency). The single cause of interdependency gets lost in such a representation, in return the amount of information to be depicted decreases—without disregarding any content. A systematic approach toward the creation of system views is described by Lindemann et al. (2009). The transparency, which can be obtained by this approach, provides a better system understanding for practitioners as well as improved possibilities of interaction with the complex system.

In practical application both possibilities for creating transparent system views got applied. Isolated partial views are often created on a technical working level. This is because each expert possesses a clearly defined view on his tasks and responsibilities. In the industrial project example, resulting views on system content were still very extensive, despite the constraint to partial system aspects. Several hundreds of system elements and up to several thousands of interdependencies had to be managed. Therefore, intensive use of expert software tools was required and also necessitated training for technical experts.

Aggregated views on a complex system are mainly created for being used by the project management. By extensive aggregation of system content the amount of elements and interdependencies could be decreased significantly in this system view. Consequently, those views did not allow deriving specific decisions on details but allowed appointing significant development trends. Aggregation was done in terms of time as well as topics. For example, one system viewed showed dependencies between main modules of major software releases. This allowed identification of modules with highest impact to up- and downstream releases. An aggregation by topic was based on the existing organizational structures. This way system views were available, which corresponded with a valid and familiar form of classification.

8 Useless or Useful Complexity?

As already mentioned, complexity should be classified regarding the characteristics "useful" and "useless," In the project mentioned here, complexity was initially perceived as being negative, and therefore project participants aimed at avoiding it. This one-sided perception and direct conclusion can be observed very often. However, a simple example can show that complexity is not always a hindering system attribute.

Anderson (2006) describes in his book “The long tail” the phenomenon of increasing importance of individual and small product sales. He provides an explanation for the fact that the famous “80:20 rule” is no longer a general principle. It has been a rule in conventional industries saying that 80 % of sales are made with only 20 % of the product portfolio or product variants. But Anderson explains with numerous examples that since several years the amount of products with low sales numbers can add up to a significant ratio of all sales. If one would declare this “long tail” as being useless without any detailed analysis, a company offering these products would probably lose a large part of achievable revenue.

Regarding the example, assessing complexity represents an important step in the process of successful complexity management. Assessment rules have to be case-specific and general requirements can delimit the possibilities of decision significantly. In the context of the industry project, standardized decision tables have been created. These tables made it possible to classify complexity by several criteria and to make this decision process repeatable. As assessment criteria, e.g., technical competence concerning the module content and relevance for customers were applied. As well, relevance to the fundamental platform strategy and resource requests were taken into account.

9 Reduce or Avoid Useless Complexity

The type of complexity within the industry project has been identified as product complexity. A multitude of system modules possess a very high quantity of mutual interdependencies. Therefore, the management of the continuously changing product environment is extremely difficult. The cause of the product complexity could be found in the market, which has to be addressed. This market shows many individual requirements and can hardly be influenced by the company. Negative consequences of the product complexity mainly occur in the company processes. These processes have to be robust and range over several product interfaces. The initial complexity has been declared as being useful. So the basis for defining a suitable complexity management strategy was the systematically elaborated analysis that provided.

Figure 2 shows three strategies. Hereby, reduction and avoidance of complexity are both well established and can be applied successfully to useless complexity. Especially, variant management has to be mentioned in this context. Because of its popularity, it is often stated synonymously with the comprehensive expression of complexity management. However, variant management represents only one strategy of complexity management. Its benefit is the reduction or even avoidance of useless complexity. But when applied to useful complexity it results in undesired effects. Then the limitation of variants can mean the limitation of beneficial customer offers.

It is often helpful to define entrance barriers for the implementation of product or component variants in order to avoid the creation of useless complexity. Companies that are not aiming for customization can avoid that every variant becomes integrated into the product portfolio without even considering its profitability.

One possible strategy for reducing complexity is based on the Pareto analysis focusing on profit-related contributions of products. Products with a contribution below a specific (individually defined) value can be filtered. For example, products with less than previously defined sales figures or above specific production effort can be excluded from a portfolio. Value Analysis and Target Costing provide similar possibilities. Here, it is of major importance to set the right assessment criteria.

10 Manage Useful Complexity

In the industry project considered here, complexity has been identified as being useful considering the company's objectives. Therefore, a strategy for reducing or avoiding complexity could not be applied but the management of existing complexity was required. The better useful complexity could be managed, the more complexity the company could handle—and this allows increasing the company's success.

Amongst others, cause-and-effect analyses have been identified as effective methods for managing useful complexity. Therefore, the method has been implemented into the company processes. This allows identifying required measures in case of adaptations to the complex environment of software modules even though manifold interdependencies exist.

Modularization of products is often mentioned as method of complexity management. This becomes clear in the context of useful complexity and consideration of system structures. With the focus on structure development, modularization means the assembly of highly interconnected system parts and standardization of interfaces between these parts. Platforms, building blocks as well as differential and integral design can be seen as methods for managing useful complexity by system design. In context of the industry project modularization meant new design of the software environment. Analyses led to the insight that enormous benefit could be achieved by this. However, the effort required for the fundamentally new modularization would exceed the project scope in terms of time and budget.

The lack of transparency, which results from interconnected system elements, is often the reason for negative consequences from complexity. In such a situation, decision-making based on simple cause-and-effect chains is hardly possible, because these chains cannot be clearly identified. Acquisition as well as modeling of all elements and interdependencies cannot be executed for the entire scope of typical complex systems. In this context, we could clarify that decisions in the industry project have often been based on incomplete system descriptions so far.

Usually, people create their own models (consciously or unconsciously), which contain relevant information. Thus, the challenge of managing complex systems is to integrate the required information into a model for decision-making—and not to provide as much system information as possible. For this reason, the initial clarification of existing types of complexity is of major importance. Insufficient or wrong determination of the complexity type can result in building unsuitable models. One distinct measure in the industry project was the definition of basic system views, training project members in using these system views and to create a process for updating and distributing these views.

Visualizing the required models allows discussing implicitly known aspects within the system context. And interpretations are created more easily. Often matrix and graph representations are applied for visualizing system views, e.g., by means of standard office software. In our industry project also, a tool solution provided by a specialized software developer was implemented to the management process. Representations in condensed form of diagrams have been customized for the regular management reports. Especially, influence portfolios have been applied for visualizing the embedding of cost intensive and risk carrying software modules into the software environment.

11 Impact of Research Findings to Practice

The elaboration of a complexity management process could be implemented successfully into practical application. Users could better classify approaches toward complexity and understand the sequence of process steps required as well as necessary inputs and obtainable outputs for those steps. This way, the phenomenon of complexity became better manageable.

Based upon the general process layout the project team of the company recognized that the previously applied approach on complexity management was inadequate. So far, methods for overcoming complexity were selected and implemented first—before even the problem was clearly identified. With the new general process the reliable identification of the prevailing type of complexity could be systematized. This identification is followed by categorizing complexity with the categories "useful" and "useless." Therefore, standardized representations for the complex system in question were defined and attached to the general process. These representations were used at relevant milestones and provided the basis for discussions and assessment of complexity issues. Results of complexity assessment were decisive for selecting the suitable strategy of complexity management. Only with the clearly approved strategy on hand one or several methods of complexity management were finally selected and implemented.

All in all, the research findings of a general process layout for complexity management were implemented reasonably for gaining access to the phenomenon of complexity. The sequential process enabled a step-by-step understanding of problem causes. Proposals for solutions based on strategies, methods, and required tools became assessable in the context of these clarified problem causes.

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Faceted Browsing: The Convoluted Journey from Idea to Application

Chris McMahon

Abstract This article describes the development of a team's research in engineering applications of faceted classification and search over some 20 years, from early experiments in novel information systems to routine use and development of a growing body of knowledge about how the techniques may be applied. It is intended as an illustration not only of an outcome from design research that has influenced practice but also of some of the socio-technical patterns that may be observed in the development and exploitation of research outputs, which is important to understand if we are to best exploit the results of research.

1 Introduction

This article is not a description of a body of work in engineering design research and its application in industry but is about the gestation and development over about 20 years of an idea—a computational technique—that has been an important part of the author's work on information management in design. The topic is proposed as a contribution to the IDRP 2013 workshop as an example of the often quite convoluted patterns of research and knowledge transfer that take place in the development of new ideas and tools. It is also an example of an area in which developments in design research interact with developments in computing and information management more generally.

The 'idea' in question concerns computational approaches to faceted classification, which the author first worked on a little over 20 years ago (without knowing at that time what it was called) and then returned to at the end of the 1990s as part of a large research project. We attempted to commercialise the software that resulted from that project, with some initial success, although ultimately the commercial venture failed. In the 2000s we did applied research trying to learn how best to use the technique in design and to expand its range of application in engineering.

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Meanwhile, in parallel with our work, a number of others have contributed to the development of the techniques, and computer-based browsing of faceted classifications has been applied in a number of domains (La Barre 2006).

Faceted classification has been around in library classification for many years, but it is only in the last 20 years or so that it has begun to be widely used computationally to assist in information search and discovery. The research teams at the Universities of Bristol and Bath developed approaches to computational faceted classification at broadly the same time as a number of research teams around the world, so it is difficult to say where the approach first originated. But by 2012 the British Computer Society was saying that it had become a default approach for user interaction in e-commerce (Russell-Rose 2011). This pattern of simultaneous discovery in many places has been observed in other fields, as indeed has the pattern of early experiments leading to interesting ideas that nevertheless do not initially develop further. In this paper therefore, as well as reviewing the history of the development of our research in faceted classification, a commentary is made at each stage on general lessons that may be learned about the development of new ideas, tools and methods and of their transfer into industry.

The structure that will be adopted in the rest of the paper is as follows. Section 2 will present the early origins of our ideas in what came to be known as the *Review* software system. In Sect. 3 the research that developed the core of our work on faceted classification and browsing, conducted as part of an academic/industry research programme, will be described, together with experience with trying to commercialise the code through the spin-out company Adiuri Systems. In Sect. 4 our applied research developments of the past 10 years will be outlined, together with the wider progress in faceted browsing as a general tool for information access. Section 5 will provide some general comments and concluding remarks.

2 Review

In the late 1980s we were involved in projects on expert systems application in engineering, but quite frankly we struggled to make good progress in implementing systems that went beyond trivial cases. At the time we had a research grant to explore expert systems applications with very few constraints on the research to be done within the grant. In research team discussions we began to ask, if expert systems were not very promising, what approaches might be helpful in supporting knowledge-intensive design. From these discussions we explored what might be the characteristics of computer systems to support engineering teams in their information and knowledge management. We saw hypertext as a potentially valuable approach, using tools such as Apple's Hypercard, first introduced in 1987,[1] and proposed that a future engineering information system should have the ability to:

[1] http://en.wikipedia.org/wiki/HyperCard.

- View arbitrary engineering objects (text, graphics, CAD files and so on) in a standard viewing environment
- Index those objects using arbitrary collections of attributes
- Annotate objects and create hyperlinks between objects

Our view was that, rather than expert systems doing the work of the engineer, engineers would be helped in their work by the ability to browse, view and navigate useful collections of engineering information. We outlined the requirements listed above in about 1989, and in doing so we anticipated many of the capabilities of a modern computing environment—viewing arbitrary objects, hyperlinking, metadata and tagging.

We implemented our ideas and more over the period 1989–1993 in a system which we called *Review* (McMahon et al. 1993, 1995). Annotation and hyperlinks were implemented in a foreground layer through which we viewed engineering objects (or which could stand alone). Direct hyperlinks were possible but also hyperlinks which searched for matching entities (and which could use the values of associated attributes as the basis for the search). We also implemented a feature whereby the user could search for entities by making a series of attribute/value selections. After each selection the available attributes and values would be pruned to just show values appropriate to the current selected set of entities. Figure 1 is the figure from McMahon et al. (1993) which illustrated how this would be done for the case of selecting bearings from a catalogue. Without being aware of it we had implemented faceted search.

At the time we were working on *Review*, and many others were also experimenting with hypermedia, Tim Berners-Lee was also working on a hypertext system. And of course crucially he implemented his approach in a networked environment and that was the important disruptive leap. The rest is history. Berners-Lee's Hypertext Transfer Protocol (http), Hypertext Mark-up Language (HTML) and in-line hyperlinks in separate hypertext files have been a dominating force in computing for 20 years (Berners-Lee et al. 2000).

So what are the general lessons to take from our work on *Review*? First, if you want the opportunity for radical developments, do not constrain researchers too closely. Allow them the freedom to pursue their hunches and to reject conventional wisdom. Second, while the ideas may only properly take root if they are particularly timely, they all form part of the knowledge base of the research team, perhaps to be picked up again at some later point.[2] Third, and we will return to this point later, in the early days of any field, lots of ideas will be tried out from which one or a small number will often emerge as dominant (the so-called 'dominant designs' (Anderson and Tushman 1990)). This seems to be the case with hypertext and it has recently been argued it was the case with the Internet (Campbell-Kelly and Garcia-Swartz 2013).

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[2]And as an aside we published in engineering journals and conferences and in doing so we were perhaps less influential than we would have been if we had published in computing publications.

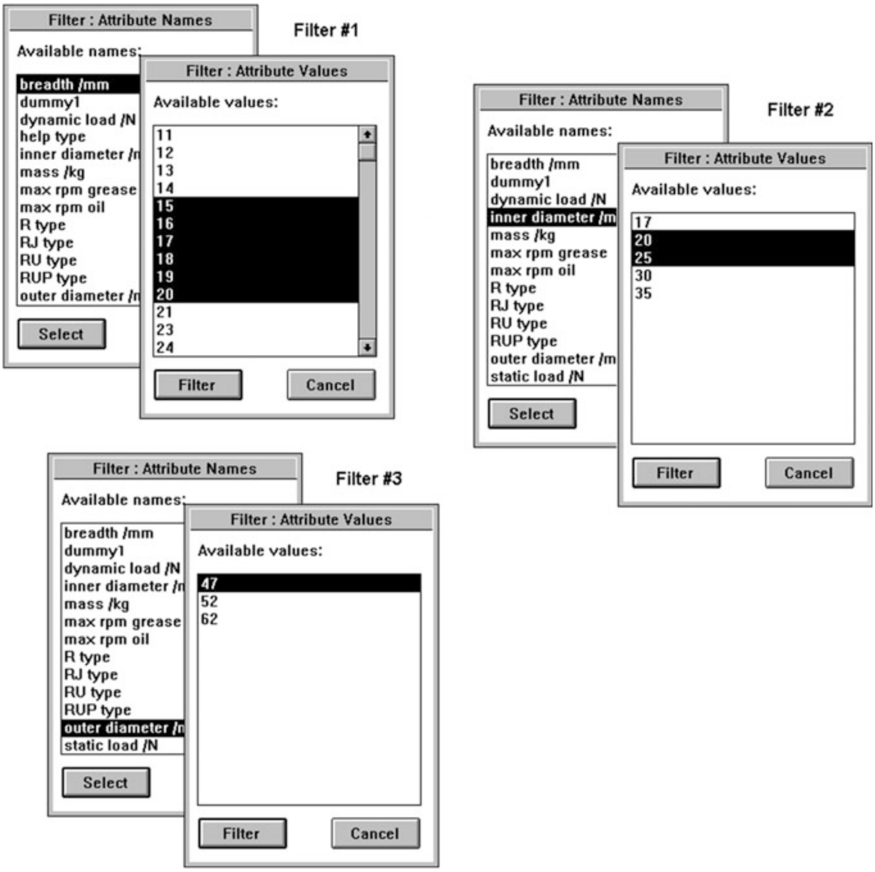

Fig. 1 A filter sequence from the *Review* software (McMahon et al. 1993)

3 Faceted Classification

At the end of the 1990s we were working with the University of Bath, Airbus, CSC and Lucas in a project sponsored by the EPSRC looking at information support for design engineering in aerospace.[3] We were able to observe a variety of practices used by engineers to assist in organising and finding information, and from those observations we identified the need for them to be able to organise information into computational knowledge organisation structures. But when hierarchically decomposed (directory) structures were used often only those who had created and populated the structures could easily find material. Furthermore, it was clear that no unified structure could be identified to serve all of the professional groups in a company.

[3]EPSRC Grant GR/L90170/01, IMI: Information for Design Engineering in Aerospace.

Our solution was to allow multiple organisational structures to be applied to the same information and for each structure to deal with one particular aspect of the information (e.g. was it about aircraft types, parts of the aircraft, technical disciplines, supply chain, etc.?). We also did the assignment of objects to positions in the structures automatically by pattern matching (e.g. if the document contains text 'A340-600' then assign to class *Long range:A340:A340-600* in the organisational structure based on aircraft type). We were effectively associating metadata with the objects but now instead of attribute values the metadata described nodes in a hierarchy. We implemented the ideas in a computer system, now with the capability to be used in a Web environment and with an integrated free text search also. As in *Review*, the user would search for information by making selections from the displayed metadata (but now hierarchically organised). When any selection was made, all the displayed metadata would be updated such that any further selection would refine the search and would not lead to zero matches (we called our approach 'No-zero Match' (NZM) based on the observation that with conventional database search users often entered combinations of search terms that led to zero matches) (McMahon et al. 2002).

In developing NZM we had developed faceted classification and browsing although at that stage we still only had a partial understanding of how our work related to other work in the research community. Nevertheless, we felt that we had discovered a new way of searching and browsing for data and information, and we set out trying to interest end users in the technology. Our industrial partners were very constrained in their ability to carry out experiments with new, non-commercial software. We tried to interest the e-commerce community but this was the time of the dot-com crash they did not want to take risks with the use of novel user interfaces (ironically, the websites we approached have now disappeared and the market is dominated by companies offering the capability we demonstrated 12 years ago). We did, however, manage to obtain seedcorn funding from a University Enterprise Fund and we set up a company called Adiuri Systems to develop and market our software, described in McMahon et al. (2004).

3.1 Adiuri Systems

Adiuri Systems was initially quite successful. Rolls-Royce selected the company as a partner in the IPAS project on the basis of its state-of-the-art approach to knowledge organisation[4]; we obtained contracts from, among others, a naval supplier, a large oil company and the website Arkive[5] (which still today uses faceted search but not from Adiuri). We developed in this way a good empirical understanding of the way to build faceted classifications and the interfaces to them, and we learned about the capabilities and limitations of our automated classification

[4]http://www-edc.eng.cam.ac.uk/ipas/.

[5]http://www.arkive.org/.

approach. But as a very small company it was difficult to be seen as sufficiently stable to be a software supplier for software tools in large companies, and venture capital companies were not keen to support a company whose income was based on project sales—they wanted a financial model based on a regular income stream. We tried to establish such a model based on selling access to information on corporate social responsibility (CSR) but without success (and in the process being distracted from project sales). After about 3 years in operation the company went into receivership and the ownership of the software reverted to the Universities of Bath and Bristol. The lesson here is that as academics we need a good understanding of the organisational and financial constraints on the exploitation of our work, and perhaps we need some different rules and mechanisms from those we have at present.

3.2 Other Developers of Faceted Classification

We were not the only research team that had developed software tools that took the same approach as ours. Giovanni Sacco of the University of Genoa had called the approach ‘dynamic taxonomies’ and had published in 2000 (Sacco 2000). In 2000 the University of California at Berkeley had a new project called Flamenco (FLexible information Access using MEtadata in Novel Combinations) working on faceted browsing (Hearst 2000). Flamenco when we first saw it was very impressive, but very much slower than our system. Travis Wilson’s Facetmap from 2002 was another example (La Barre 2004). Sacco seems to have been the first to write about dynamic manipulation of **hierarchical** taxonomies, although we had used dynamic manipulation of metadata a number of years before. The point here is that there were a number of research groups around the world working on the same principle. And it was not only in computation that the approach was gaining ground —in the library community there had been interest in faceted classification for decades (a 1955 paper suggested that there was a need for a faceted classification as the basis for all methods of information retrieval (Classification Research Group 1955)) and researchers such as Kathryn La Barre and Vanda Broughton were leading a renewed interest (La Barre 2004; Broughton 2006). Research has been described as like being in a thick fog that gradually lifts so that the world around can be seen. That was what it seemed like to us at the time—we very gradually became aware of pockets of interest around the world in this approach called faceted classification.

More generally, we can observe that what happened in faceted classification mirrors what happens in many other technical domains: a development occurs in multiple places almost simultaneously because it is timely. Constant (1980) notes this in the context of gas turbine engines with simultaneous invention in Germany, Sweden and the UK. Campbell-Kelly and Garcia-Schwarz write (2013) that the

ARPANET network, conventionally thought to have led to the Internet, was one among a myriad of (commercial and non-commercial) networks that developed from the late 1950s. They assert that integration of these networks into an Internet was likely to happen, whether ARPANET had existed or not.

4 Developing the Approach

During the past decade faceted classification has become the default approach to user interaction in many e-commerce sites, for example for car advertisements[6] or hotel room bookings.[7] The ACM Special Interest Group on Information Retrieval (SIGIR) held workshops on faceted search, and books on the topic began to appear (Sacco and Tzitzikas 2009). But while there was a lot of excitement in some quarters about faceted classification, it was also clear that there was a lot to learn about how to use this new technique. La Barre asked (2004) if faceted classification was ‘a brave new world or a world of confusion?’, noting the plethora of tools emerging but also the lack of guidelines for their use. In our research we could see the potential of the approach but putting our ideas into practice was challenging. We developed the software to be more firmly based on open source software (the software suite is available on Sourceforge[8]) and carried out a number of experiments in different application areas, including manufacturing process selection (Giess et al. 2009a), the management of in-service information (Goh et al. 2009) and of business data (Giess et al. 2009b). Most recently, we have explored its application to design for emotion (Reader and McMahon 2013). But perhaps the most important work that we did was to explore approaches to facet analysis and classification in different domains with a view to developing guidelines for engineering use (Wild et al. 2009). In this work we drew especially on experience from the library community and on its different approaches to the identification of appropriate facets and facet values in facet analysis. In particular, the community uses the notion of ‘warrant’ (the justification for action in the facet analysis). ‘Literary warrant’ describes the practice of constructing a classification scheme based upon the specific content of the literature being classified; ‘user warrant’ describes using user preference or need or the frequency of occurrence of a term and ‘scientific warrant’ uses structures defined by experts within the field as the basis of the categorisation. This work provided a more solid basis for classification in engineering, but our study showed that tough, teachable guidelines do not yet exist: differing interpretations of the notion of facet exist and there is still an assumption that facet recognition is unproblematic and that the process is either top-down or bottom-up. In common with many computing applications, simplistic

[6]E.g. http://www.autotrader.co.uk/.

[7]E.g. http://www.laterooms.com/.

[8]http://sourceforge.net/projects/waypointfct/.

domains are used as exemplars and it is often not clear how to scale these approaches to address the issues found in industrial applications. In the next phase of work we need to develop further a body of teachable principles of classification within a general framework of information management approaches, work we have recently started in conjunction with colleagues in Cambridge (McMahon et al. 2009).

5 Concluding Remarks

This paper has described the development of our work in faceted classification and browsing in terms of a series of phases: generation and test of ideas from a process of exploration and trial; development of similar ideas in multiple communities as they become timely and reflect the developing state of the art; emergence of a preferred approach and broad agreement about the core features of the technology/approach; application in straightforward example domains ('low hanging fruit') and then development of a deeper understanding of the benefits and limitations of the approach through detailed research over many years. These phases reflect patterns that may be observed more widely in design and in technical development—the epistemology of engineering as 'variation and selective retention' described by Vincenti (1990), the emergence of dominant designs from early experimentation and then their development through 'normal engineering' (Anderson and Tushman 1990; Constant 1980).

The development of our work over 20 years also illustrates the way in which engineering design research and applications draw on and in turn influence developments in other domains especially in computing applications, as we see for example in the origins of computer-aided design in the development of graphics facilities for airborne early warning in the 1950s (Machover 1994) and in recent developments in design rationale capture exploiting earlier work in Issue-Based Information Systems (IBIS) (Bracewell et al. 2009). Machover reinforces the point about the interactions between domains but also about the time taken for technologies to be adopted to new applications when he says, in the introduction to his paper (1994), "In a 1978 retrospective on computer graphics I wrote that the field was still sometimes called 'a cure for no known disease'. In 1994, computer graphics is probably viewed more as 'a cure for every known disease'". If we are going to understand well how research ideas are taken into practice we need to have a deep understanding of such socio-technical patterns in technological development.

Finally, the main messages that might be drawn from this work for the transfer of research results into practice may be summarised as follows:

1. It is important in any collaborative research between an academic team and industry to try to have a portfolio of work from short term to more speculative, and to use each type of work to inform the other.

2. A research team should be continually monitoring the technical maturity of its research outputs, for example using 'technology readiness level' (Mankin 1995).
3. Research teams need a very good understanding of the mechanisms for commercial development of research through venture capital, seedcorn and other early stage funding. Equally, industrial partners and users of the research outputs need to be aware of the influence that they can have with early stage funders and especially the benefits to the research team of targeted support for commercialisation efforts.

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Successful Industrial and Academia Cooperation in Technology Industry

A. Riitahuhta and H. Oja

Abstract Finland activated its R&D funding through the establishment of the governmental Technology Development Agency TEKES in 1983. At that time the former Federation of Finnish Metal Industry (nowadays the Federation of Technology Industries) started technology development and cooperation with universities. Since the 1980s TEKES and Technology Industries created several technology development programs, e.g., Mechatronics, Computer Aided Design, and the latest one Digital Product Processes. These technology programs have been the most important platform for industrial and academia cooperation. The technology programs have also worked as bridges to international cooperation. Through programs it has been possible to participate in the global research program, namely Intelligent Manufacturing Systems-IMS, to send researchers to foreign research groups like Denmark Technical University, Stanford University, MIT, NIST to mention a few. Technology programs have invited foreign professors and consultants to present their studies and methodologies. Namely, Creativity technics as Synectics, TRIZ; Generic Design Methodology; Design Structure Matrices—DSM; Quality Function Development QFD; Expert Systems; SA/SD methods; Product Life Cycle Management were adapted by Finish research and teaching. However, we see that the brought methodologies and platforms shall be developed forward, because industry is doing business in a global, networked environment. New business models impacting the product development of many high volume consumer products have transformed to Original Design Manufacturers (ODM). Universities are also in worldwide cooperation and competition at the same time. There is a quest for new type of discussion forums, of which is the NABC model

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(NEEDS; APPROACH; BENEFITS and COMPETITION) created and taught by Stanford Research Institute (SRI 2012), which is very beneficial, while we discuss with funding agencies and companies. In this article, we present some approaches and their benefits in academia and industry cooperation.

1 Introduction

Technical university education in Finland was started using European university teaching as an example. Because the education model was imported it was possible to select the successful education models also from the top US universities. Finland was a fast adapter in technologies and technical education. One example from an agile technology transfer was that a Finnish textile company was the first company utilizing electric lightning in Nordic countries and the second one in Europe. The same agility continued because university professors usually had industrial experience from abroad.

From that background it was natural that the industrial academia cooperation continued even stronger when the Federation of Finnish Metal Industry started an R&D function. There were two assemblies: Industrial Advisory Board (IAB) and Product Development Council (PDC). Members of IAB were mainly top business managers and members of PDC R&D directors and university professors. PDC created research program concepts and IAB organized the funding. This working model was very strong from the 1980s until this decade when Finnish technology industry developed very fast. The funding of the research was granted by TEKES, a governmental funding agency, established in 1983 and participating companies. In the area of Design Science and Manufacturing there was the Mechatronics program at the beginning of the 1980s followed with several others, namely Computer Aided Design until the latest Digital Product Processes (TEKES 2013).

In this paper, we consider industrial academy cooperation using the NABC model created by Stanford Research Institute. The model was not used that time but it seems to be an explaining model. N stands for needs, A for approach, B for benefits, and C for competition. As an example, we use the efforts of the Tampere University of Technology and especially its Integrated Product and Production Development Group (IPPD). In the area of IPPD, there are three professorships, two lectureships, three research doctors, and two senior researchers, with about 20 members of staff. The research areas are presented in Fig. 1, especially the product development related research.

All research areas are linked to one another. However, sustainability is still at the starting position.

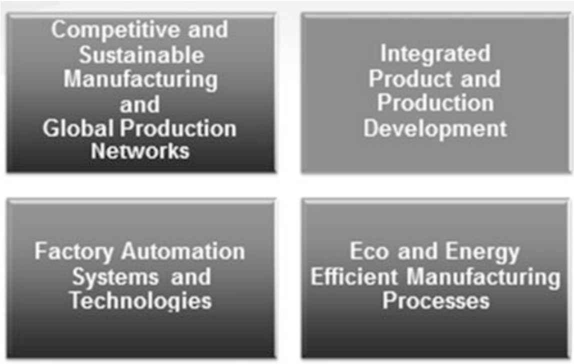

Fig. 1 Strategic research areas of TUT production engineering

1.1 Industrial Needs and Related Research Areas

Companies' top management has been involved in defining the needs and goals of technology programs as members of IABs and PDC. Some industrial managers have interest in design sciences, so much so that they have started to join university Ph.D. studies. In discussion groups between industry and academia, research on new design science agenda has evolved (Table 1), but we require more open social media discussions. However, the results of discussion have to be formulated and we see that universities provide excellent platforms to develop defined needs for industrial implementation.

Industrial needs have varied through the times as the products get multidisciplinary, customized, and the manufacturing distributed into networks—similar to needs, the research focus has moved away from being disciplinary centered (Riitahuhta 1988; Pulkkinen 2007).

1.2 Approach

The research and discussion with the different types of industry (large international corporations, SMEs, investment, and consumer business) have emphasized us to construct the Open Product Development Model, Fig. 2.

The eco-cycle model is very important, because industrial companies need different types of focus and methods depending on their size, type, and situation. Industrial research can be classified into three phase areas:

- Proactive strategy-based Product Development knowledge
- Fast and efficient Product Development
- Product Life Cycle

Companies work in the dynamic internal and external environment. Caused by changes companies go to Eco Cycle presented in Fig. 2. We have created research supporting companies in different situations. For instance, if a company's product

Table 1 From machine element centric design toward future design methodology

Description	Theory, method, tool
Design of a gear box, clutch, instrument	Machine elements
Vehicle design	FEM, machine dynamics
Improved systemization of power plant design	Pahl & Beitz method, VDI2221, VDI2225, Integrated Product Development
Development of parametric 3D design	Pahl & Beitz
Expert system of engineering configuration for process plant design	Model-based and object-oriented knowledge representation, theory of technical systems
Modularization, platforms, configuration	Theory of technical systems, product structuring, design for configuration
Dynamic modularization, product life cycle management, change management	Design Science, theory of technical systems, product structuring
Conceptual_DFMA, optimization of variation and flexibility of combination of product, process, and network	Integrated product and production design, matrix methods, DFX, DFMA,
Innovation, radical innovation, incremental innovation	Radical innovation by design (RID), incremental innovation method for multidisciplinary product
Simulation-based design, early design with combining simulation and TRIZ	Parametric Design, TRIZ
Verification & validation	Set based concurrent engineering, systems engineering
Strategic-based product and production system development	Company strategic landscape
DFMA	C_DFMA, augmented assembly, virtual reality

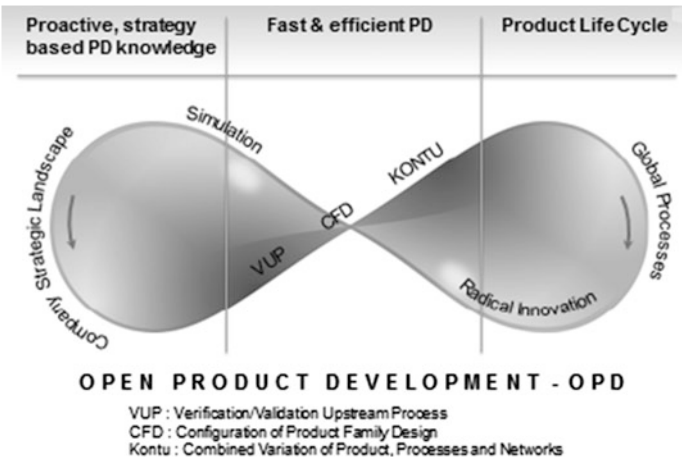

Fig. 2 Eco-cycle of the open product development

variants exceed its capability to manage variants' life cycle, we suggest that the company makes Company Strategic Landscape (CSL) analysis. Consequently, if company's products have no attractive features, we suggest use of the TRIZ method for increasing innovativeness. In Eco Cycle, the mentioned methods are managed in our team on good research and application level.

As example, we present two methods created by our group and implemented in industry.

1.3 CSL-Company Strategic Landscape

The framework model—CSL (Lehtonen 2007; Lehtonen et al. 2007)—defines the elements related to the product development operations and the production of the company. The relations between these elements are dominant and thus important (Fig. 3). In research aiming at the development of operations, measures must be directed to the management of the guiding relations, as these will guide the entity in reality. Elements related to funding (investment capitals etc.) are not presented in the following figure.

The CSL-framework model (Fig. 3) describes the key issue entities for structuring of the product and the contents of the relations between them. The product structure itself is in the top left corner. In this figure, the "structure" of the product

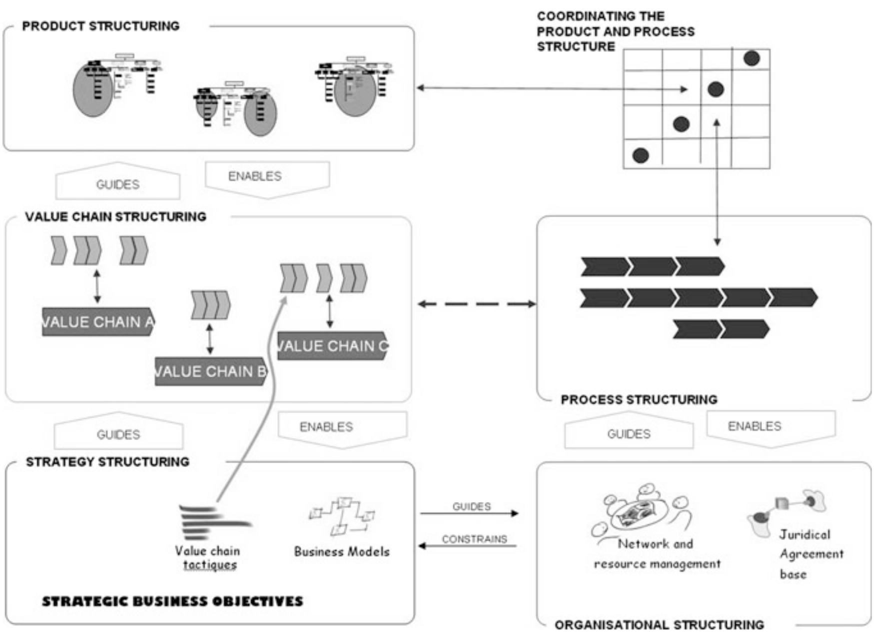

Fig. 3 In the CSL-framework, business operations are seen as an entity

does not refer to the mere assembly structure and a list of parts, as a product assembled of the same parts may be divided differently from the viewpoint of product structure management.

The structuring of the product is guided by a value chain (the structuring of the value chain) where the product must operate. On the other hand, the properties of the product structure also enable and limit the number of the possible value chains. The value chains, in turn, are determined according to the business goals (the structuring of the strategy).

The sales, design, and production processes of the products and services to be delivered are shown in the middle on the right-hand side. In their background, we can see the structure of the internal resources and the network (the structuring of the organization) and the selected methods (operative interfaces). The structuring of the organization and the business goals exist in a reciprocal guiding and limiting relation to each other.

The key idea in CSL-framework model is the relation between the internal structure of the product and the delivery process. In principle, the product structure and the delivery process can be selected separately and are usually examined one at a time by approving the other as a static background data. When optimizing the operations, these two are no longer seen as separate, but they must be synchronized.

The points in the table on the top right corner indicate the product structure/delivery method pairs that are "good points" or combinations in which the operations are carried out rationally according to the *selected goal*. In the figure, the points are located on the diagonal line merely as an example. The points do not necessarily form an unambiguous vector—good points are not necessarily found at all. We must note, however, that the ability of the various delivery methods in order to support the set *goals* differs drastically. Let us interpret the figure: a certain design process defines the product structure that supports set goals. The product structure, in turn, only enables certain value chains that only correspond to certain business goals.

1.4 Incremental Innovation in Multidisciplinary Product Process

The integration of different domains has been a starting point of the Mechatronics Paradigm. As a reference, container handling equipment in ports is a good example of multidisciplinary technology applications. Oja (2010) presents how integration over disciplines enables technical concept development incrementally.

The development of existing products and technical concepts in an incremental way aims for product value improvements in two viewpoints: for the users and for the manufacturer. The first looks for increased value with features, performance and life cycle costs, as the latter attractiveness to the market and decrease of the cost of value creation.

Most of the product development methods focus on the development of the new product or dynamic concepts. The development of existing products or static concepts can be approached by more specific methods. The primary objective is to capture and understand the design conditions and physical phenomena during function execution. For the innovative process, the sources for opportunity identification can be found in the interaction between the disciplines rather than within the disciplines.

The functionality of the port equipment is controlled and executed through programmable logic controllers (PLC). As the control system governs the controller inputs, actuators, and sensors within the chain of the functional execution, it also plays a major role in how the purposeful behavior (performance) and internal and external consequences (loadings, impacts) are experienced in reality. It is clear that the designed function in practice is not delivered only by mechanical structures and mechanisms—it is the result of multidisciplinary integration.

The incremental concept development aims to capture the differences between the design and reality domains and utilize that in analyzing the interdisciplinary relations within the function execution chain as shown in Fig. 4. The difference between the design and reality domains can be identified in function execution by the delay from the user action to execution starts and response slip after the user action.

Three aspects direct the context sensitive analysis for the methodology:

- Describing, defining, and analyzing functional interfaces, and the interdependence that exists and impacts that occur between technologies and disciplines.
- Identifying the real function execution chain, which activates the transformation process from initiation to the end state.

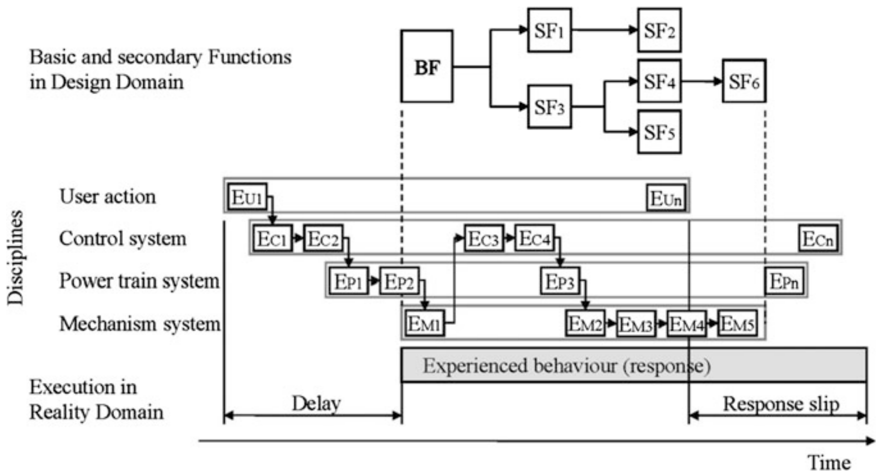

Fig. 4 Function execution chain in design and reality domains

- Identifying and describing experienced behavior, e.g., how and with what consequences the transformation process performs.

The same functional structure in the design domain (above) can result in differences in the reality domain (below) depending on the execution chain integration across disciplines. Accordingly, within the incremental development, concept development shall focus more on how the function, properties, and performance characteristics are realized. The realization of functions refers to the operational principle, which enables us to distinguish between the product variations within a product class, actually as different technical concepts.

With this approach, only the technical system of a product has been taken under evaluation, and other business, product originating process, and use viewpoints were excluded. This distinction enables the identification of opportunities within modern multidisciplinary products and highly integrated systems by approaching development from subsystems and their interactions.

The method fosters opportunity identification for static concepts and include four specific phases after the recognition of the value viewpoints:

- Initiation and current concept analysis:
  - The recognition and analysis of the experienced behavior of the function in the reality domain. Identification of the different disciplines in the transformation process.
- The seeding of solution alternatives:
  - Identification of the function execution chain through different disciplines. With this the consecutive events on the timeline are developed within the development team enabling the communication between specialists and understanding the function response in the reality domain.
- The identification and selection of opportunities:
  - The exploration and identification of interactions by means of multidisciplinary mapping between function execution events and properties in each discipline. The selection of the events is affected by properties from several disciplines.
- Solution development and incremental innovation:
  - Identification of the properties and control which affect the selected events and developing solution alternatives, which change the operating principle of the function.

The identification and utilization of the function execution chain provided a tool for sharing information within a development group and expanding design team knowledge according to the chief engineer's competence and viewpoint.

The analysis is followed by organizing the information into a format, which supports intuitive and creative thinking that provides ideas for further improvements in an existing concept. Visualization of the interactions within the concept is provided with the interaction mapping.

The interaction mapping visualizes the experienced behavior environment, where the correlations to system (product) behavior can be identified and used for further idea processing with the development team. The team may use the chart to foster idea processing or development, but also to generate different what-if scenarios to test and communicate how the changes affect—or even generate new ideas to change the operating principle. As the opportunities have been identified, the development tools can then be directed toward concrete items instead of free associations on a conceptual or functional level.

2 Benefits

The deep cooperation and discussion between industry and academy grants that we can use real industrial problems in our teaching, e.g., in Design for X course we have a whole hoisting machine, the manufacturability and assemblability of which is studied by students in the workshop, and for the final reporting seminar the product manager from this industry is invited.

Our students work within the following areas:

- Problem-based learning, real industrial problems
- Candidate theses, literature studies on new interesting research areas
- Master theses, a theory framework and an industrial solution
- Doctor theses, a novel theory validated with industrial examples.

Totally over 300 masters theses have been made in the area of product development since 1991. Besides teaching material, industrial doctors support the creation of the research agenda as IAB and many of them participate in teaching specific parts of courses. One result of this kind of cooperation is a book covering Design for Manufacturing and Assembly in the conceptual stage of the design.

An important benefit is funding for research. The demand is set by TEKES that, certain industrial funding is necessary for the governmental research grant. Because industry is getting knowledgeable staff, concepts, and phenomena models through cooperation, it is possible to get research funding. This kind funding is sometimes considered too industrially oriented and a question is how scientific agenda will be maintained. To avoid this we use external evaluation by internationally respected researchers.

3 Competition and Risks

Competition is an important part of the NABC tool. Due to strong connections and involvement with industrial directors we have not considered direct competition and threats. We see the following changes in research climate as competition:

- Many top universities have developed strong centers for industrial cooperation (Stanford: CDR, CIFE; Cambridge University: EDRC; Denmark University of Technology: IPU; etc.)
- University research is commercialized: Material Selection Research at Cambridge University has been transferred to Granta Ltd; and Modular Function Deployment method to Modular Management consultant company.
- World leading companies are transferring production to emerging countries, earlier to benefit from lower manufacturing costs, but today closer to faster growing markets. Research and development are also searched worldwide to implement demographic requirements into products.
- Funding agencies are changing their policy, funding is directed more on new more ambiguous technologies and became more project type rather than platform type, e.g., knowledge accumulation and transform between projects is becoming more challenging.

By analyzing the competition, we can find weaknesses and threats in our research management. The most important are listed in following:

- We try to cover too wide a scope with too few researchers. It means that our publications are mainly Ph.D. theses and conference articles. In Ph.D. theses, we emphasize that validation must be scientific, but also industrially significant. We have found that too industrially related research agenda prevents scientific proficiency.
- We have developed methodologies during research projects which have been verified successfully in industry, but we have not succeeded with the wider international implementation of methods mainly due to lack of branding of research results until recent years. Without brand names, we are not visible to worldwide companies.

In discussions, e.g., within Design Society, we have found that many research groups do similar analysis. There are various interesting activities developed internationally. MIT and Stanford have made teaching material to web. They also organize big web courses which can be reached by thousands of students. There are global curriculum development efforts as CDIO. Singapore has invited several researchers to SUTD-MIT International Design Center, DTU invites international researchers to work as Professors. Industry develops Competence centers.

Based on the above-mentioned analysis we have also started organizational developments as a part of wide restructuring. One of the interesting developments is to create integration between research groups. The research will be more agenda based than organization based.

4 Conclusions

Industrial cooperation has enabled us to successfully identify, understand, and solve real problems. Implementation of research results has been acknowledged by enterprises, but wider publicity has been modest due to lack of methodology branding. Despite having strong industrial impact, we have maintained the scientific agenda by using external international evaluation.

We have used Stanford Research Institute's NABC model as a framework and found that it worked well. The multidisciplinary research and integration of different domains are crucial for technology industry. Funding models change, competition for funding is already fierce. New types implementation platforms are needed.

We have suggested a Future Design Methodology, Open Product Development-OPD. OPD is as follows:

- The basic structure and visualization of methodology are clear and simple but methodology allows a wide and deep working by an expert according to stage of design
- In the methodology, business drivers and constraints play an important role
- The methodology supports the design of product families
- Governing properties in design are knowledge management, variation and life cycle management, the optimization of manufacturing processes and networking, quality management through verification and validation processes at design stage
- Efficient methods of incremental and radical innovation and their use facilities are created in the methodology
- Roles and responsibilities of design director and product architect are applied from the best practices of architecture.

OPD's part methods have been developed, verified, and validated by our research group. OPD totality has been conducted from our group's research work, and experiences in the industry with the constructive research method. Our goal for consolidate OPD utilizing our own but also Design Society research as well as new type education and research attempts as SUTD-MIT IDC. We have also realized that more agenda-based integrated research is needed to respond to needs of the industry.

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Changing Conversations and Perceptions: The Research and Practice of Design Science

Cassandra Telenko, Ricardo Sosa and Kristin L. Wood

Abstract Although design science is a relatively young field, the impact of design research upon industry is evident in the literature, in the practice of design by academics, and in the experience set of the authors. This chapter provides evidence of impact from three sources, two studies of design literature, and one survey of design researchers. It is found that more than one third of design research articles, despite focusing on theory, include engagements with industry, and, complementarily, a majority of design researchers have patents, industry experience, or both. These studies of design literature and design researchers change our perceptions of the impact of design research on practice and initiate a new conversation. In the context of research findings and models of transferring general fields of research to practice, design research impacts practice in a variety of tangible and long-lasting ways. Building upon these analyses, we develop a first set of guidelines for transferring design research to practice. These guidelines are illustrated by selected examples and outcomes from the authors' experiences. The frontier of design science, especially the impact on practice, is exciting and filled with unlimited potential. Changing conversations and perceptions is a critical first step in building the community's tremendous past successes. Through proven guidelines, we may realize our potential and create a sustainable ecosystem of transferring design research to practice.

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1 Introduction

The belief that design research has little impact on practice is persistent. On the one hand, this criticism is often applied to all academic research efforts; on the other hand, it is largely a matter of perspective based on limited assumptions, narrow definitions, and stereotypical views. Few of such statements are clarified by a holistic consideration of the roles of design research, design science, and industry. How does knowledge transfer relate to our definitions of design science and design research? What are modes and rates of knowledge transfer? Does design research need to be commercialized to be successful, or is its impact on the education of the next generation of design practitioners more significant? As we reconsider these expectations and perspectives on design research, the impact upon practice becomes clearer.

The term "design research" refers here to the scholarly inquiry that seeks to advance design by studying and improving it in systematic and scientific ways. More specifically, design research is the means to expand, test, and operationalize the findings of design science. It includes both art and science, and is clearly identifiable in fields related to the applied sciences and the social sciences (Frankel and Racine 2010). Distinguishable communities of design research include engineering and industrial design, architecture, urban and interior design, design computing, interaction design, and product and innovation management. Across these fields, varied perspectives exist as to the meaning and usefulness of design science (Gill and Hevner 2011; Hevner et al. 2004; Järvinen 2007). To summarize these perspectives, a general description of design science includes the following features:

i. Applying the scientific method to study design and its epistemological elements as a practice, process, and human endeavor.
ii. Improving design practice and learning through the study of design principles across disciplines, including a stratification of formalisms, such as design rules, heuristics, and guidelines.
iii. Creating long-lasting knowledge and theoretical foundations from which design methods, processes, and tools may be developed and advanced.
iv. Integrating knowledge from disciplines, such as cognitive science, social psychology, anthropology, and sociology.
v. Connecting research, practice and technology development by integrating the above features.

Design research has no logical or natural mapping to the traditional perspective introduced by Bush (1945) that research can be characterized as a linear spectrum from basic to applied research at the opposing ends. More appropriately, we adopt the alternative representation of research as a 2D space, defined by an axis for advancement of knowledge (basic research) and an axis for immediate application (applied research) (Stokes 1997). The resulting space reveals four quadrants of interest: one for non-research, one for purely basic research, one for purely applied research, and one for research that advances knowledge and provides immediate applications. It can be seen as the ideal of design research to exist in this latter quadrant, contributing to both design practice and science.

One key implication of this representation is that bridging research and industrial, commercial, or entrepreneurial applications is a two-way relationship. Very often new systems, products, and processes spur, support, or enable new fundamental questions that reveal new and valuable understandings. We consider here numerous examples of design research influencing practice from education and professional development to incubation and collaboration with industry partners. We define impact and influence as transfer of knowledge between design researchers and practicing designers. Knowledge transfer is not necessarily measurable and direct; it may take many forms, involving people, products, and partnerships.

1.1 Learning From Others

Since design research is a relatively young field, we can learn from other traditions where the connection between research and practice is of special interest, such as medicine, management, and education. Some main challenges in medicine include obstacles that health practitioners face in approaching the scientific literature, assessing the validity and practical relevance of new knowledge, and incorporating the appropriate results into their practice (Greenhalgh 2010). These skills are considered the basics of *evidence-based medicine*. The gap between what is known and what is done in medicine has also been linked to the overuse, underuse, and misuse of research output (Glasziou and Haynes 2005), with studies showing that research that should change medical practice is often ignored for years. Even when best practices are well known, they may be poorly implemented. Thus, there are several structural and systemic factors across health education, research, practice, and regulation that result in insufficient support for research-related activities with practitioners (Embi and Payne 2013).

In management, scholarly research has become less conceptually and instrumentally useful to executives, managers, decision makers, and teachers as demonstrated by a recent study that tracks top academic journals to identify articles with findings that are actionable by practitioners. The results of the study confirm a sharp decrease in the proportion of top journal articles that generate actionable knowledge from 1960 to 2010 (Pearce and Huang 2012). In education, dissemination approaches have been identified as a key weakness, creating the ongoing research-to-practice gap (Cook et al. 2013). These studies show that current dissemination methods fail to resonate with or influence practitioners due to the misalignment of outlets, including venues that target narrow communities of academic researchers and broader publications intended for practitioners.

Other relevant areas to analyze the impact of design research on practice include university–industry research collaboration (Jonsson and Levén 2012), knowledge transfer and diffusion (Fiddaman et al. 2013), academic entrepreneurship (Grimaldi et al. 2011), and design policy (Raulik-Murphy 2010). Frameworks and models for transferring academic research to practice capture stages such as exposure, adoption, implementation, and practice of new interventions (Simpson 2002), or, as based on another model, awareness, acceptance, application, agreement, and adherence (Glasziou and Haynes 2005). Recently, Tabak et al. (2012) produced an inventory of 61 models to enhance dissemination and implementation of research in practice, categorizing them by construct flexibility, focus on dissemination or implementation, and a socio-ecologic framework that locates barriers at various levels: system, community, organization, and individuals (Holmström et al. 2009; Green et al. 2009; Lenfant 2003).

To apply research findings in practice, companies need to perceive the competitive advantage of new knowledge. However, studies show that only a few companies tend to introduce new products or services. SMEs are highly vulnerable to competition and usually are the largest employers of new knowledge; however, multiple barriers prevent SMEs from investing in design, including management structures and lack of financial resources (Raulik-Murphy 2010), low capacity to absorb risk and uncertainty (Johnson et al. 1990), a mind-set of efficiency, and cost-cutting and incremental changes (von Stamm 2004). Currently, several countries have developed programs to help companies develop design capabilities. These programs aim to raise awareness through promotional activities such as seminars, exhibitions, awards, and publications (Raulik-Murphy 2010).

In summary, (a) the research-to-practice challenges in design are shared by other fields and have been extensively studied; (b) despite notable exceptions, knowledge transfer can take up to 20 years; (c) challenges and opportunities result from structural characteristics at various levels including research fundings, industry strategies, market demands, academic promotion, and educational models; (d) professionals are likely to face obstacles finding, assessing, and applying relevant information given the existing means for knowledge dissemination; (e) valuable research findings are likely to exist but have not been applied or are applied poorly (i.e., the gap between research and practice); (f) a wider range of models and guidelines are needed to cover the varied conditions in the design research–practice relationship; (g) strategic policies and incentives are needed to build bridges between design research and practice; and (h) different terms are used across cases and areas of study to refer to overlapping categories such as stakeholders including: industry, practitioners, nonacademics, partners, clients, and public.

The following sections provide quantitative results from sampling the design research literature and surveying the practical experiences of design researchers. The chapter concludes with guidelines for establishing and developing working relationships between practicing designers and design researchers and provides specific case studies from the authors' own research experience.

2 Context From Sampled Literature Analysis and Surveyed Researchers

Because many of our perceptions are founded in impressions from the literature and academia, we begin with three studies of design research. The first study considers the authorship of industry professionals across the design research literature within the last 2 years, a sample of over 192 publications. The second study samples 134 publications in the same design journals since 1990 to determine the number of publications with industry involvement and the types of knowledge transfer occurring in design research. The third study provides a survey of the design experience of engineering design researchers in academia. The data from these studies support the encouraging view that there is a significant connection between design research, design researchers, and design practice.

2.1 Investigating Author Affiliations in Research-to-Practice

We begin by evaluating close partnerships between academia and industry as evidenced by authorship affiliations of recently published articles in five top design research journals: Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM), Journal of Engineering Design (JED), Research in Engineering Design (RED), Journal of Mechanical Design (JMD), and Design Studies (DESSTUD). While the main mission of each journal is primarily to present advances in design science, four explicitly include some industry relevance in their scope:

AIEDAM: "The journal is also interested in comprehensive review papers, as well as in *practicum papers* that describe original, major applications of state-of-the-art techniques to important engineering problems."

JED: "The journal publishes *pioneering best industrial practice* as well as authoritative research, studies and review papers on the underlying principles of design, its management, practice, techniques and methodologies."

RED: "The journal is designed for professionals in academia, *industry and government* interested in research issues relevant to design practice."

DESSTUD: "The journal publishes new research and scholarship concerned with the process of designing, and in principles, procedures and techniques *relevant to the practice* and pedagogy of design."

These mission statements include business and government as part of their audience, but limit their scope to research, with only one adding practice as a subject for publication. One could hypothesize that few authors are practicing professionals outside of academia, with the exception of recent graduates. We argue that a promising number of authors are practicing professionals.

For each journal, the 50 most recent papers, or two most recent volumes (years) were analyzed for authorship affiliation. The final sample size was 192 design research publications. Authors from industry, the military, certain government agencies, or hospitals evidence the relationship between design research and practice and were tallied as industry professionals. Authors affiliated with a university or co-authoring with their academic advisors were tallied as academic professionals. While 174 papers were authored exclusively by academics, 18 had authors from industry, the military, government, or hospitals.

This total of 9.4 % of papers (for JMD up to 14 %) represents strong partnerships, as publishing in academic journals is not a typical component of design practice. The fact that approximately one in ten papers within the academic venue is written by authors affiliated with nonacademic organizations is significant. We assume that this percentage of published research is of *high* relevance to industry, but recognize that authorship is just one indicator of practical relevance. The connection between practice and research exists in many forms, and the next section analyzes multiple indicators on a more holistic scale.

2.2 Sampled Literature Analysis: Research Transfer to Practice

This section considers evidence from the same five design research journals as the authorship affiliation study. With the perspective that archival publications are primarily an academic venue, we consider that authorship, case studies, acknowledgements, and other in-text references to applications of the research are indicators of knowledge transfer between industry and research. Following from the sample of recent authorship and the nature of design research, the hypothesis for this analysis was that substantial knowledge transfer exists between research and practice. Figure 1 illustrates the procedure used to undertake the study, from sampling articles from the literature to analyzing industry connections.

The publications were randomly sampled from each journal and from volumes published in 1990 or later. The year 1990 was the first year all five journals co-existed. The number of samples from each journal was chosen to be proportional to the number of search results within each journal given the terms “design theory and methodology”. For example, AIEDAM yielded 297 search results, while JMD yielded 159, RED yielded 248, JED 217 and DESSTUD 376. The lower proportion of JMD articles makes sense as JMD has a longer history of archiving research in mechanisms rather than design science. The final breakdown between journals was 16 JMD articles, 26 RED, 22 JED, 31 AIEDAM, and 39 DESSTUD for a total of 134 papers. Since 1990, these journals have archived over 5,000 publications with the keyword “design,” and a statistically significant sample would be 96 articles.

After collecting the samples, each paper was sorted into one of two categories. Articles with no evidence of knowledge transfer between design and practice were sorted as belonging to the general sample set. Articles that implied or explicitly described knowledge transfer were considered to be part of the smaller, “industry

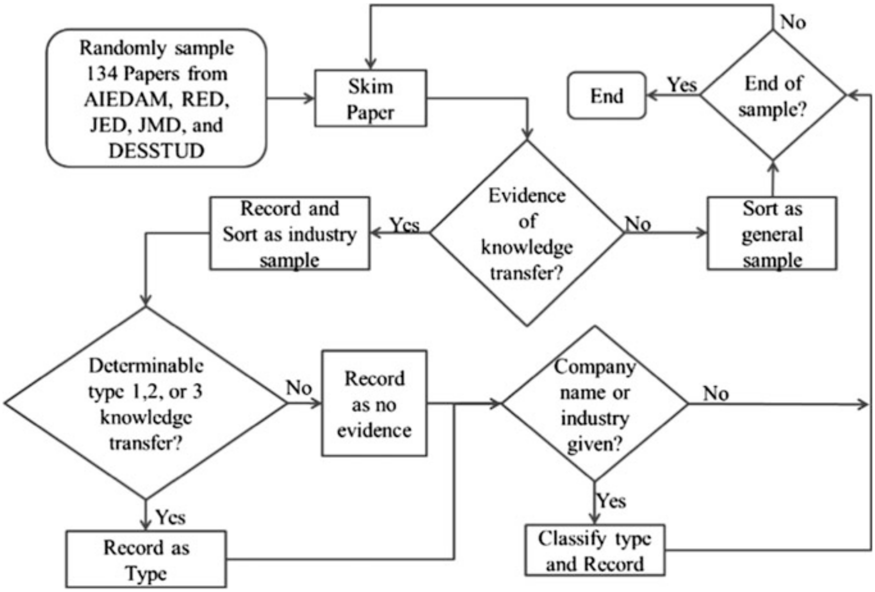

Fig. 1 Sampling procedure for determining knowledge transfer

sample." Similar to the authorship affiliation study, industry was defined as any non-university author, participant, collaborator, advisor, or sponsor.

Three directions of knowledge transfer between industry and research are possible and were classified as one of three types: Type 1–practice informs research; Type 2–research informs practice; or Type 3–research and practice inform each other. Practice informing practice and research informing research are not considered. Since this sample represents archival publications within the academic research realm, type 2 knowledge transfer is difficult to determine from the literature. Academic journals are necessarily transferring knowledge to academia, nominally being read by reviewers. Examples of type 3 are described in Sect. 3.2.3 regarding the authors' own research with Ford and DTM. In fact, type 2 knowledge transfer may be fairly common but is, at times, only evident in the acknowledgements of publications.

Evidence of knowledge transfer was found in one of three ways. First, if an author was affiliated with a business, defense or non-university institution, the paper was considered to exhibit type 3 knowledge transfer, regardless of the authors' academic ties. Second, if the text referred to a study of practicing design professionals, applying a technique within a company, or consulting with expert designers, the paper was considered to exhibit type 1 or type 3 knowledge transfer. Finally, if the acknowledgements of the paper mentioned a business, defense or non-university institution as a sponsor or consultant, the paper was considered to exhibit type 1, type 2 or type 3 knowledge transfer.

After sorting the samples and classifying the types of knowledge transfer, the type of industry was noted to discern trends in the types of industries that design addresses. A few industry references within the texts and acknowledgements did not specify the companies or fields. These were not considered.

Using these definitions and sampling procedure, it was found that 39 % of articles in the top five design research journals exhibit evidence of knowledge transfer between research and practice. Given the sample size, the 95 % confidence interval for this sample is ±8 %, meaning that between 31 and 47 % of published research is shared with industry. In comparison with our findings from other research fields, and the consideration that publications are primarily academic in nature, this number shows substantial collaboration between the supposed "silos" of research and practice. Furthermore, the variety of industries engaged in design research is encouraging. Although a third of the partnerships were with defense, aerospace or automotive applications, consumer products, industrial products, electronics, banking, electronics, and software were all represented in the two-third majority.

Given the three types of knowledge transfer, 11 % of papers were type 1 knowledge transfer (studies of designers), 20 % were type 3 knowledge transfer (practice and research inform each other), and 7.5 % were undeterminable as type 1, 2, or 3. Most type 1 knowledge transfer was evident within the text as part of the experimental methodology. We argue that studies of designers can influence design practice directly, because participation in an experiment becomes part of a designer's experience and experimental procedures can teach new methods. Nevertheless, a conservative approach was taken in considering these interactions, limiting the transfer to type 1, practice informing research.

For type 3 transfers, many of the samples included industry authors. Of the 124 articles, 22 (17 %) were authored by nonacademic professionals. Five articles (3.7 %), some with purely academic authorship, explicitly mentioned that their research application was part of the development of a commercial or industrial product. Even if we consider that nonacademic authorship does not indicate immediately applied research, one in 27 publications features research that describes a completed industry application. These results are in addition to the type 2 knowledge transfers (research informs practice) not reported within the literature.

Our definition of practice includes application-driven government agencies such as the department of defense (but not NSF), and nonacademic research labs. One could impose an alternative, conservative definition of practice that is restricted to businesses and manufacturers of commercial products. If we revisit the findings from the previous sections under this definition, the authors' examples would omit interactions with NIST to create standards for practice and application. As evident in the guidelines, standards are an important aspect of practice. If we remove government and other research agencies, such as the US Army Research Institute, US Army Corps of Engineers, NASA, and the Office of Naval Research, from the sample of journal articles evidencing knowledge transfer, the percentage of papers with knowledge transfer reduces from 39 to 33 %. Type 3 knowledge transfer reduces from 20 to 14 %. The changes are relatively small and within the margins of error because not all papers reference government agencies alone. Many include consultation, authorship, or funding with other commercial business partners who design and manufacture products for the government, such as Bechtel or Lockheed. It is difficult to separate defense funding, research labs, and agencies like NASA or NIST from commercial companies. These agencies are strongly linked, if not responsible for technology readiness and industry practice. It is important to note that connections to design practice are not always central to communicating results of design science and research. From the literature, the transfer of design knowledge between academia and industry is often paired with clear impact on marketed products or processes, and the exchange of expert designers, either as new hires or authors. In Sect. 3.2.1, an example is given of total knowledge transfer; a graduate student is hired by the partnering corporation and immediately asked to train the rest of the company in the newly devised methodology. In reported results, only the dollar savings of the research case study are mentioned, and only in one sentence of the article. The implications are at least twofold: the value of design research to practice is not typically conveyed within academic venues, and academic literature provides a conservative representation of the impact of design research on practice.

2.3 Study of Design Researchers and Practice

This section considers ways that certain cross-sections of leaders in the engineering design field are engaged in design practice. The stereotypical hypothesis is that academics, and more specifically professors, lack practical experience. This study provides evidence to refute this hypothesis. The basis of the study is a set of demographic and technical questions that were not intended for this anthology (Krager et al. 2011). The participants were leaders in the field and were asked to complete a survey as part of the application process for a past National Science Foundation (NSF) Civil, Mechanical and Manufacturing Innovation (CMMI) sponsored workshop on individual and team-based innovation. These participants represent a set of domain knowledge experts in engineering design, and, as such, provide the possibility for key insights into understanding the current state of innovation, at least within this knowledge domain. The technical questions as part of the study include Likert-scale agreement and disagreement queries, in addition to a set of short answer questions. These multifaceted questions support analysis by both quantitative and qualitative research methods. These questions were developed through a collaboration among the authors and participants of a workshop which included experts in the fields of cognitive psychology, social psychology, and engineering design. Through this approach, the intent is to investigate an individual's perception and knowledge of design research and methods across demographics.

Three categories define the study's construction: (1) demographics of the participant group, (2) technical components with quantitative assessment, and (3) short answer questions. The first section of demographic questions, shown in Table 1,

Table 1 A sample of the NSF CMMI survey questions and responses

Survey question: Profession		Survey question: I have consulted for companies on their engineering design work…	
Engineer in Industry	0 Respondents	Never	10 Respondents
Professor	34 Respondents	Less than 1 year	5 Respondents
Lecturer	0 Respondents	1–5 years	13 Respondents
Research scientist	3 Respondents	More than 5 years	9 Respondents
Other	1 Respondents	No response	1 Respondents
Survey question: I have worked in a company doing engineering design work…		Survey question: I am a named inventor on patents…	
Never	5 Respondents	Never	17 Respondents
Less than 1 year	9 Respondents	1 time	5 Respondents
1–5 years	21 Respondents	2–5 times	12 Respondents
More than 5 years	1 Respondents	6 or more times	1 Respondents
No response	2 Respondents	No response	3 Respondents

included characteristic data as well as the participants' professional histories, and is the focus of the inquiry here.

The survey was administered to 42 participants with 38 completing responses. The results indicate that the backgrounds of participants were broad, but the vast majority is well-founded in design education. Approximately 90 % of the participants were engineering professors. The participants were well distributed by age. The largest group, 42.1 %, was in the range of 30–40 years old. Nearly as many participants aged 40–60 years (38.9 %) were represented, while 18.4 % of those surveyed were in the 20–30 year range.

The experience-based questions provide interesting insights into the professional activities of the participants. Fifty percent (50 %) of those surveyed are named inventors on patents. This number is high compared to the percentage of named inventors across engineering faculty in general. A large number of participants had consulting (71.1 %) and industrial experience (81.5 %). Additionally, 71.1 % have taught a product design course, and 63.1 % have developed tools for innovative design. These results indicate that the participants were well-versed in the range of activities, research, practice, and education, typically engaged by design researchers in academia. The participants included markedly high experience of design practice in terms of consulting, industrial experience, and the development of intellectual property. They also were heavily engaged in developing tools for innovative design. Indirectly, these results indicate a strong association of design practice and design research. The participants appear to practice design as an integral component of their academic work, which should correlate to a higher potential of transferring their research to practice.

The evidence from this survey and the literature samples debunk a number of myths. Researchers do engage industry. Industry professionals do participate in academic venues, despite practical time constraints, and other commitments. Furthermore, many design researchers have experience in practice as consultants, industry employees, or both. Section 3 addresses the impact of design research on practice more generally, from the perspective of guidelines and with more specifics from case studies.

3 Findings: Transferring Design Research to Practice

In this section, we describe a set of cases where design research has been successfully transferred to practice. These cases represent just a few of the experiences of the authors, and include the goals of the design research, details of outcomes for practice, and insights derived from the experiences for developing impactful transfer of design research to practice, including any of the three types of transfer as discussed in the previous section. These examples were selected to illustrate a number of guidelines and mechanisms for impacting design practice.

3.1 Guidelines and Platforms for Impacting Design Practice

To begin our discussion of actual findings and cases, a collective assessment of design research and the platforms for meaningfully engaging industry and practice is carried out. We begin this assessment by identifying similarities across the sample of academic papers. Building upon these findings, we assemble the results from literature findings, workshop studies of design researchers, and the experience of the authors, and provide the list of guidelines shown in Table 2. Guidelines here suggest specific courses of action that can meaningfully result in long-lasting and sustainable transfer of research to practice, and are but a first step based on decades of activity within the design research community. The first column in Table 2 lists each guideline, where the lexicon is an action to be undertaken on the part of the design researcher and in concert with partnerships in practice. The subsequent columns of Table 2 list known and expected outcomes from each guideline, in addition to suggested mechanisms for implementing a guideline. The adaptation of multiple guidelines creates a portfolio of rich connections for deep relationships in practice. Combinations of implemented guidelines across and between international design programs have the potential to build on past successes of design research and develop an ecosystem of even more dramatic innovations for the grand challenges at the community, national, and global levels.

Table 2 Guidelines and platforms for design research engaging design practice

Guidelines	Outcomes	Mechanisms
1. Connect direct value	New products, services, systems, profits, markets	Collaborative development, residency, consulting, sabbatical
2. Partner with product development firms	Transfer of knowledge, talent	Employee, intern, residency, sabbatical
3. Assess industry processes	Diagnostics, trust/relationships, strategy	Consulting, intern, residency, sabbatical
4. Incubate companies	State-of-the-art, design-driven companies	Research lab, incubators, technology parks, hack-a-thons, exhibitions, contest, space, fabrication labs
5. Invent within design research	Product, case study, accessible research in the language of practice, enterprise, process, material	Thesis, dissertation, industry sponsored project
6. Collaborate with industry partners as PIs	Funding, joint investment/commitment, new methods	Employees, graduates, grant agencies, challenges, industry fair
7. Practice design	Recognition, portfolio	Competitions, installations, IP, exhibitions, awards, consulting, sabbaticals, advisories, charette
8. Commercialize methods and techniques	Products of design research, such as finite element analysis (FEA), failure modes and effects analysis (FMEA), design for manufacturing (DFM), design for assembly (DFA), House of Quality (HoQ), Six Sigma, Design for Six Sigma (DFSS), Lean Design, computer-aided design (CAD), Optimization, Theory of Inventive Problem Solving (TRIZ /TIPS), Rapid Prototyping	Companies, software, certification
9. Brand and disseminate	Accessible research in the language of practice, brand, awareness	TED talks, periodicals, blogs, social media, books, manuals, standards
10. Develop standards in design	Verification, assessment, endorsements, expert judgment, standards, guidelines, taxonomies, ontologies	Expert witnessing, testing standards, government grants
11. House practitioners on campus	Relationships, ideas, immersion of practice in research	Chairs, industry labs, donations, residency, advisory panels, industry days, seminar series, industry consortium, hiring adjunct faculty, project advisors/judges

(continued)

Table 2 (continued)

Guidelines	Outcomes	Mechanisms
12. Engage practitioners in professional development	Transfer of skills, trust/relationships, reputation	Continuing and lifelong education programs, targeted at the module or degree-level, internal industry education programs, joint Masters programs, reverse-residency/sabbatical, MOOCs (Massive Open Online Courses)
13. Immerse students at all levels in design-based learning	Next-generation design engineers, loyalty/pride/identity, strong design fundamentals, graduates with skillset that maps design research to practice, exposure to real world settings	Design education programs at the levels of K-12, undergraduate, graduate, professional Masters, PostDoc, and research assistants, MOOCs, UROPs, capstone, service based learning, student groups/clubs, field visits (O Lab), company visits

3.2 IDRP Cases

Building upon the guidelines and platforms described in Table 2, we selected five particular cases to illustrate successful integration of design research and practice (IDRP for short). These cases provide details on how a subset of the guidelines and platforms listed in Table 2 may be realized in publishable and nonpublishable ways. We begin with a case of an automotive partnership in which an industry need was met by developing new design tools. Then we consider the development of fundamental design language that was applied to reverse engineering, automotive design, the design of manufacturing machines, and international standards. Finally, we also consider the value of cases with educational elements. One research project realized value in training future air force leaders in design research thinking while others include curricular and extracurricular experiences. All of these cases were part of the development of commercial products, and a list of research articles developed out of these efforts are shown in Table 3.

3.2.1 Design Methods Development and Transfer: Automotive Industry

In this case, we consider the guideline (#1) of connecting, initially and directly, with the bottom-line business of original equipment manufacturers (OEMs) and part suppliers of the automotive industry. The outcome of this case was the development, testing, validation, and transfer of design methods to practice. The research project began by identifying design processes and particular products which the industry identified as critical to their business and in need of radical, innovative

Table 3 Design practice cases and associate design research

IDRP cases and further reading
Design methods development and transfer: automotive industry
Greer, J., Wood, J., Jensen, D., and Wood, K. L. (2002) Guidelines for Product Evolution Using Effort Flow Analysis: Results of an Empirical Study. In: Proceedings of the ASME IDETC/CIE2002, Montreal, Quebec, Canada, Sept. 29-Oct. 22, 2002
Greer, J.L. (2002) Effort Flow Analysis: A Methodology for Directed Product Evolution Using Rigid Body and Compliant Mechanisms. The University of Texas at Austin
Greer, J., Jensen, D., and Wood, K. (2004), Effort Flow Analysis: A Methodology for Directed Product Evolution. Design Studies, 25(2):103–214
Lefever, D. (1995) Integrating design for assemble-ability techniques and reverse engineering. Master's thesis, The University of Texas, Austin
Lefever, D., and Wood, K. (1996) Design for assembly techniques in reverse engineering and redesign. In: Proceedings of the ASME IDETC1996
Professional development and design theory/method transfer program: example with the US air force
Camburn, B., Guillemette, J., Crawford, R. H., Wood, K. L., and Jensen, D, J. (2010) When to Transform? Development of Indicators for Design Context Evaluation. Proceedings of the ASME IDETC/CIE 2010, Montreal, Quebec, Canada, August 15–18, 2010
Singh, V., Krager, J., Walther, B., Putnam, N., Koraishy, B., Wood, K. L., and Jensen, D. (2007) Design for Transformation: Theory, Method and Application. In: Proceedings of the ASME IDETC/CIE2007, Las Vegas, NV, September 4–7, 2007
Singh, V., Skiles, S., Krager, J., Wood, K.L., Jensen, D., and Sierakowski, S. (2009) Innovations in Design Through Transformation: A Fundamental Study of tRaNsFoRmAtIoN Principles. ASME Journal of Mechanical Design, 131(8)
Singh, V., Walther, B., Wood, K. L., and Jensen, D. (2009) Innovation Through tRaNsFoRmAtIoNaL Design. Tools for Innovation 1(9):171–195
Singh, V., Wood, K. L., and Jensen, D., et al., (2006) A Novel Exploration into Gust-Resistant Operation of MAVs /UAVs through Transformation. MAV06 Conference and Demonstration Proceedings, Eglin Air Force Base, Eglin, FL, October 31, 2006
Skiles, S., Singh, V., Krager, J., Wood, K. L., and Jensen, D. (2006) Adapted Concept Generation and Computational Techniques for the Application of a Transformer Design Theory. In: Proceedings of the ASME IDETC/CIE2006, Philadelphia, PA, September 10–13, 2006
Wang, D., Kuhr, R., Kaufman, K., Crawford, R., Wood, K., Jensen, D. (2009) Empirical Analysis of Transformers on the Development of a Storyboarding Methodology. In: Proceedings of the ASME IDETC/CIE 2009, San Diego, CA, August 30–Sept. 2, 2009
Weaver, J., Wood, K.L., Crawford, R., and Jensen, D. (2010) Transformation Design Theory: A Meta-Analogical Framework. ASME JCISE 10(3)
Design languages: government standards organizations
Chakrabarti, A., Shea, K., Stone, R., Cagan, J., Campbell, M., Hernandez, N. V., and Wood, K. L. (2011) Computer based design synthesis research: An overview. ASME JCISE, 11(2)
Grosse, I. R., Milton–Benoit, J. M., & Wileden, J. C. (2005) Ontologies for supporting engineering analysis models. AIEDAM, 19(01)
Kitamura, Y., & Mizoguchi, R. (2004) Ontology-based systematization of functional knowledge. Journal of Engineering Design, 15(4):27–351

(continued)

Table 3 (continued)

IDRP cases and further reading
Kurfman, M., Stock, M. E., Stone, R. B. Rajan, J., and Wood, K. L. (2003) Experimental Studies Assessing the Repeatability of a Functional Modeling Derivation Method. ASME Journal of Mechanical Design 125(4):682–693
Little, A., Wood, K., and McAdams, D. (1997) Functional analysis: a fundamental empirical study for reverse engineering, benchmarking and redesign. In: Proceedings of the ASME IDETC1997
McAdams, D. A., Stone, R. B., and Wood, K. L. (1999) Functional interdependence and product similarity based on customer needs. Research in Engineering Design 11:1–19
Stone, R. B., and Wood, K. L. (2000) Development of a functional basis for design. Journal of Mechanical Design 122(4):359–370
Stone, R. B., Wood, K. L., & Crawford, R. H. (2000) A heuristic method for identifying modules for product architectures. Design studies 21(1):5–31
Stone, R. B., Wood, K. L., & Crawford, R. H. (2000) Using quantitative functional models to develop product architectures. Design Studies 21(3):239–260
Wood, K. L., and Greer, J. L. (2001) Formal engineering design synthesis. In: Function-based synthesis methods in engineering design: state of the art, methods analysis, and visions for the future, Cambridge University Press, New York, p. 170–227
Product innovation and new companies
Cárdenas, C., Rivera, Y., Sosa, R., & Olvera, O. (2011) TRIZ-Based Design of Rapid 3D Modeling Techniques with Formative Manufacturing Processes. INDUSTRIAL DESIGN–NEW FRONTIERS, 173
Sosa, M. E., Eppinger, S. D., & Rowles, C. M. (2003) Identifying Modular and Integrative Systems and Their Impact on Design Team Interactions. Journal of Mechanical Design, 125(2), 240
Sosa, R and Gero, JS (2005) A computational study of creativity in design: the role of society. AIEDAM, 19(4) 229–244
Sosa, R and Gero, JS (2008) Social structures that promote change in a complex world: The complementary roles of strangers and acquaintances in innovation,. FUTURES, The journal of policy, planning and futures studies, 40(5):577–585
Sosa, R; Gero, JS; Jennings, K (2009) Growing and destroying the worth of ideas. In: Proceedings of the 7th ACM Conference on Creativity and Cognition 2009
Design courses and experiences
Bonaglia, F., Goldstein, A., and Mathews, J.A. (2007) Accelerated internationalization by emerging markets' multinationals: The case of the white goods sector. Journal of World Business 42(4):369–383
Sosa, R., Dorantes, A., Cárdenas, C., and Martínez, V. (2010) On the impact of systemic thinking in sustainable design, Design & Complexity, Design Research Society International Conference DRS 2010, Montreal

improvement and advancement. This case illustrates an actual design method transfer, developed and marketed products, and the process by which these results were realized.

Methods for design for assembly, novel part combination, and part reduction were developed as part of a Masters' thesis project and graduate internship, motivated by direct relevance of the authors' research lab's interest in developing methods for redesign and innovation, and, our industrial partner, Prince Corporation's desire to simplify and reduce assembly costs for their systems, such as a slide-out auxiliary visor (SOAV) (Lefever and Wood 1996; Greer et al. 2004). The SOAV was part of an overhead ceiling unit produced at high production volumes for a luxury automobile manufacturer. The SOAV unit supplemented the traditional fold-down visor by allowing the driver to shield light coming from both the side and front of their vehicle. While the traditional fold-down visor, in the swiveled position, shields light coming from the side, the SOAV, being contained above the headliner, translates out and rotates down to block incoming light.

Prince Corporation was originally requested, by the automobile OEM, to design this automotive subsystem, complete through tooling and preproduction, in a period of 2 months. This very short cycle time provided very little time for iteration. None-the-less, Prince undertook the project, and produced a very robust, reliable, and mechanically novel SOAV, while following sound design principles, such as top-down assembly of all components and internal force symmetry to provide a self-balancing and antibinding slide-out system. After the initial design and first-run production, the SOAV assembly consisted of 40 parts, more than necessary to carry out the required functions and a ripe opportunity for reducing manufacturing cost, developing innovative redesigns, and production time savings.

Prince Corporation and the authors developed an agreement to undertake this project in terms of design research and product development, where the goal was to affect the bottom-line business of the company. The outcomes of the research project were fourfold: significant cost savings in the form of a redesigned SOAV (guideline #1 and #5), creation of two new methods for novel component combination and parts reduction, introduction to and training of engineers at Prince automotive (guideline #12), and education of over 4,000 graduate and undergraduate engineering students at the University of Texas at Austin (guideline #13). These outcomes exclude the students and practitioners outside of the University of Texas at Austin who are taught the reverse engineering methodology in Otto and Wood (2001).

Two methods were developed as significant extensions to Boothroyd and Dewhurst's (1980) Design for Assembly (DFA) method and integrated into a reverse engineering and redesign methodology being constructed by the authors. Boothroyd and Dewhurst's (1980) DFA method was well known at the time for evaluating the ease of assembly of a product. Although methods for DFA existed, there was little work on extending the evaluation of a product to redesign possibilities. The project therefore fit well into the researchers' long-term goal of creating a reverse engineering and redesign methodology and toolkit.

Information about the processes and methods developed to accomplish the task of part reduction are well documented in the literature. The account here serves to provide the reader with an overview of the academic results, especially in terms of actual design research transfer to industry and implementing guidelines for meaningfully accomplishing this transfer.

One method added to the toolkit is referred to as the subtract and operate procedure (SOP). Many products are composed of redundant parts or solutions that can be eliminated. The SOP is a five-step procedure for removing individual components of the product assembly, operating the product through its full range of functionality with the component missing and analyzing the resulting operability. The procedure is then repeated by replacing and removing components, combinatorially, one component at a time, and discovering redundancies in the system. The type of redundancy describes whether the component or part can simply be removed or replaced by parametric redesign of another component.

Another method added to the reverse engineering toolkit is referred to as force-flow (or effort-flow) analysis. Force flow (or effort flow) diagrams represent the transfer of energy, effort, or force through a product assembly. Each component is represented as a node connected by arrows indicating the directional flow of forces. Wherever flows require relative motion between components, an R can be placed to denote the edge of a group of components. A group of components surrounded by "R"s then become candidates for part combination.

For Prince Corporation, the results of this research produced an SOAV redesign with 15 fewer components and identical functionality. Force flow analysis alone can be credited with nine component combinations, part reduction, and novel component redesigns. The part combinations and reductions also reduced manufacturing and vending costs while allowing assembly workers to be shifted to other assembly lines. The result was millions of dollars of savings for manufacture of the SOAV alone.

The established cost value of this work led to the hiring of a lead graduate student from the research lab after completion of his thesis. Within 2 months of working at Prince, this graduate had trained the remainder of the engineering team at Prince in the reverse engineering and redesign methods being developed at the University of Texas. This application of guideline #12 was initiated by Prince.

The Masters and PhD students who developed these methods and associated tools were not the only means of transfer of this knowledge to daily practice. The reverse engineering and redesign methods were also included in the development of a textbook for Product Design. The relevance of such work is vastly important, if we consider the University of Texas alone trains over 250 engineering students in these methods annually.

3.2.2 Professional Development and Design Theory/Method Transfer Program: Example with the US Air Force

In this case, we describe an outcome of performing and transferring design research with a variety of organizations as part of the United States Air Force. The primary mode of transfer was in the form of combined sponsored research and professional development programs (guideline #12), where industry professionals directly applied the design methods as part of their technology development projects. Other modes included university-level education programs and fundamental design research projects with the research entities of the Air Force.

The project was initiated through the contact of the authors with a chief scientist office in the US Air Force Research Laboratories (AFRLs). A meeting was arranged to pitch recent advancements by the authors in design research. During the first meeting, design research results were shown, and their impact described with industry examples and outcomes in the commercial marketplace. While the first meeting generated good discussions and intellectual interchange, the core of the design research did not resonate with the needs of the AFRL chief scientist, and there was a general decision not to pursue the proposed work. However, the chief scientist invited the authors back for another meeting the following day, where the authors would be afforded another opportunity to rescope the ideas, especially in the context of the applied missions of the AFRL. The authors mapped the understood missions of the directorate, and realigned the design research and associated research methodologies. The idea of Transformation Design Theory was born (Singh et al. 2009), and pitched to the chief scientist as a fundamental design research project, an applied development initiative of innovative systems, and a professional development project to train and transfer potential findings to various groups in the Air Force. This project was welcomed, and a 7-year research relationship began between the collaborators.

Transformers research is a collaborative project between the University of Texas at Austin (UT), the US Air Force Academy (USAFA) and the Air Force Research Labs (AFRLs), such as the Munitions' Branch in Eglin FL. The Air Force was interested in this research for three advantages, (1) transformers present an exciting opportunity for innovative concepts (2) working with the air force academy ensures training of the next generation of officers in both technical and creative aspects of problem solving (3) the collaboration resulted in new micro air vehicle (MAV) designs. Through the first 2 years of collaboration, a transformer design theory was developed, where "transformation" is defined to be the act of changing state in order to facilitate new, or enhance an existing functionality. Based on this definition, a "state of a product" is defined as its specific physical configuration in which the product performs a primary function(s). Ultimately, three fundamental principles and a number of critical facilitators were presented and illustrated. These principles and facilitators form a budding theory of transformation in design (Singh et al. 2009).

Building on the theoretical findings of transformation, a number of design ideation techniques were developed, as well as realized MAV systems. Two exemplar MAV design objectives were to develop a gust-resistant wing and a stowable MAV. The MAV is a replacement for current unmanned aerial vehicles that weigh 1 kg or greater, and is equipped with autonomous navigation and cameras with real-time video transmission. Before implementation of transformer techniques and the collaboration of USAFA and UT students and researcher, the MAV was highly susceptible to wind gusts and originally versions included a rather large stowage cross section. The application of the transformation principles allowed the MAV to remain lightweight, have a compact collapsible structure, be able to complete hundreds of missions, and remain inexpensive enough to be expendable.

The gust-resistant wing concepts improved resistance to wind gusts by over 50 %. Three concepts were developed and tested using experimentation and analytical modeling: (1) ported wings, (2) elastically hinged spoilers, and (3) variable dihedral angle. The ported wing concept consists of "ports" or small cutouts spaced out along the wing span acting to reduce lift by separating air flow. These mitigate the effects of common upward gusts of wind through either passive or active mechanical actuation. The elastically hinged spoilers concept consists of multiple sections of hinges on the trailing edge of the wing. These flap-like spoilers can be lifted independently of each other by the wind gust reducing the area of wing creating lift, resulting in separations similar to the ported wing's cutouts. The dihedral angle would be in combination with each of the other concepts. By raising the wing tips above the wing's root, the stability of the MAV can be increased. Each of these concepts was implemented in wind tunnel testing and flight tests. All concepts improved gust resistance of the MAV. The addition of rectangular ports located close to the trailing edge of the airfoil have been shown to reduce the lift associated with vertical gusts by as much as 50 % while reducing overall drag of the MAV.

A number of stowable MAV concepts were developed using the transformer theory and associated ideation techniques. As one example, a stowable MAV design applies the analogy of a slap bracelet, creating a bistable wing structure. In its active state, the wing is spread at the full wingspan. In its stowing state, the wing is coiled tightly. The "Slap Bracelet" concept offered multiple benefits: ease of use, speed of deployment, low weight, feasibility, and novelty. The redesigned wing has two stable configurations: (1) fully extended in the shape of a wing and (2) coiled alongside the fuselage. The bistable, carbon fiber wing is constructed such that a natural curvature exists in both the transverse and longitudinal directions. Because the wing can only curve in one direction at a time, the wing is always at a high-energy state in one dimension. The wing, in this view, is always stressed in either the longitudinal or transverse direction. The transition between states occurs when the wing's cross section is flattened in one direction.

These example applications of the design research in practice are but a few that resulted from the collaboration. Through the development of fundamental design theory, associated design methods, and working systems at the core missions of the partner (AFRL), a long-term trusting relationship was developed. In fact, this relationship expanded to a number of other Air Force entities, including professional development programs for Air Force personnel. These professional development programs focused on a wide range of design processes and methods, including transformer theory and ideation techniques. They also included rapid response development through the Air Force's Commander's Challenge Program, the teaching of Air Force officers, and civilian personnel in this program, and the teaching of cadets in various United States Air Force Academy programs.

3.2.3 Design Languages: Government Standards Organizations

In this case, we consider collaborations between various academic groups carrying out design research and the collaboration with counterparts in government standards organizations, such as the National Institute of Standards and Technology (NIST) in the United States (guideline #10, as well as guidelines #1, #6, and #12). The outcome for this case concerned the aggregation of different efforts of design research to develop a more comprehensive taxonomy and language for design that could be expressed as a working standard with greater exposure and connection to industry.

The authors' work with NIST, Ford Motor Company, and Desktop Manufacturing (DTM) Corporation originated from a National Science Foundation (NSF) Young Investigator Award, the observations of a Masters' student's research, and networking through the design research community. The NSF award required industry sponsors to support the research. Ford was interested in design for six sigma training, development of advanced manufacturing approaches, and the design of innovative automotive subsystems; and DTM wanted to model solutions to their novel additive manufacturing technology, the selective laser sintering process. Both companies were interested in modeling their products and connecting these to functional requirements and customer needs to create more innovative and robust designs. These goals fit into the long-term dream of the investigators to create design methods and techniques, but the first step was not obvious.

Step zero was to review the functional knowledge available. A Masters student and doctoral candidate set about studying a wealth of products and recorded functional models available at UT, the archive of student reports from senior-level design courses and design work with industry. After studying and analyzing these reports, the investigators were struck by the lack of coherent language between reports to describe products and their functionality. A common language was missing and would greatly aid in verbalizing, visualizing, sharing, architecting, and analyzing designs. The functions and flows could then be reliably connected to functional requirements, customer needs, and the creative generation of design solutions.

The resulting research goal was to create a common design language with a focus on the mechanical and electromechanical domains. This language, termed a *functional basis*, consists of a set of functions and flows with the intention of comprehensively describing the mechanical design space (Hirtz et al. 2002). The functional basis has been shown to increase the repeatability, consistency in detail, and correctness of functional models created by a variety of designers.

As an example of industry application, the functional language was presented by the authors as part of a 5-day design for six sigma training course at Ford Motor Company. The functional basis further enabled Ford to relate customer needs to functions and identify modules requiring increased robustness. Functional modeling was received with great enthusiasm and the results showed that the functional basis is useful for modeling the large-scale systems developed by Ford.

At DTM Corporation, the need existed to evolve process and machine subsystems as part of solid freeform or layer-based manufacturing. The functional basis was used to model system-level processes, subsystems, and components, ultimately leading to new subsystem concepts and improvements in precision surface control. After 2 years of development of the functional basis, it was presented at the American Society of Mechanical Engineers (ASME) International Design Engineering Technical Conference (IDETC). A NIST researcher, Simon Szykman, was presenting similar work to create a language for functional models of designs to be used in software. A collaboration was developed between the researchers from academia and NIST, where there existed a willingness to combine efforts.

Working with Ford, DTM, and researchers at the University of Missouri-Rolla, a large number of product models were completed over a 3-year period. The NIST taxonomies and the original functional basis were intended to support manual- and software-based applications of functional modeling methods. After joining forces with NIST, the research team reconciled their existing models and language to create a standard functional basis and obtained funding from NSF under NSF: DMI-9988817 to create an online repository of functional models. Today, this repository consists of 184 products and 6,906 artifacts and is available through the Design Engineering Lab website at Oregon State University. The functional modeling research has continued to be fundamental in a number of research initiatives since the completion of the original joint research projects, and has been applied with numerous industrial partners over a ten to 15-year period.

3.2.4 Product Innovation and New Companies

In this section, we describe successful cases of guidelines #4 and #5 for incubating companies and designing within research. At Tecnológico de Monterrey (Querétaro, Mexico) one of the authors led the school of industrial design from 2007 to 2011. In those 5 years, more than a dozen design studios and companies were created by graduates of this school, such as: Mooid (mooid.mx), Dandelion (dandelionlab.com), Moxo (moxo.com.mx), Arroz con Leche (arrozconlechemama.com), Xarzamora (xarzamora.com), IbarraChacho (ibarracacho.com), Olab (o-lab.com.mx), GaloBertin (galobertin.mx), CGN (casagutierreznajera.com), Dix (dix.mx), Somos Diseño (somosdiseno.com), Urnas Sacbe (urnassacbe.com), Fabrica Ecologica (fabricaecologica.com), Pata de Perro (patadeperroestudio.mx), Art68 (art68.com.mx), etc. In three specific cases, graduate research theses constituted the basis for incubating or accelerating such companies, namely: Ecopilia (ecopilia.com.mx), Materializadora (canastasdemimbre.com), and Relement (relement.mx).

In the case of Ecopilia, Prof. Victor Martinez and his graduate student Gabriela Gutierrez developed an innovative composite material and a low volume manufacturing process with the sustainability principle of cradle-to-cradle. The name of the company derives from the words *oikos* (home in Greek) and *copilia* (return in Nahuatl), i.e., “take back home (nature) all we have taken from it.” The research project produced a patent for the composite material based on corn and paper fibers, which is biodegradable, compostable, and recyclable.[1] The process itself is carbon neutral, using custom solar ovens and processing equipment. The material was subsequently applied to the development of new products substituting materials of high embodied energy such as glass fiber and MDF. Ecopilia entered the local business incubator in 2009 and continues to grow today.

Juan José Navarro had previously co-initiated Materializadora as a spin-off of a student club in the school of industrial design. The company set to develop innovative products by transforming low-value handcrafts, such as nondescript baskets made of woven natural fibers. Their business plan followed a “fair trade” model where local artisans receive training in design techniques and manufacturing processes and are compensated fairly for their work. The first products offered by Materializadora were original designs by peer undergraduate students. In 2010, as a graduate student in the Master of Design, Manufacturing and Innovation, Juan José worked under the supervision of one of the authors in the development of new rapid modeling and prototyping equipment based on wire-bending techniques. This cross-disciplinary project was conducted by industrial designers and mechatronic engineers, resulting in three Masters’ theses. First, the impact of using wire for model-making during idea generation was modeled as compared to other conventional materials used by industrial designers in the early stages of model-making and prototyping including cardboard and clay. This was followed by the design of rapid 3D modeling techniques with formative manufacturing processes (Cardenas et al. 2011). Lastly, the wire-bending machine was built and its impact on idea generation evaluated experimentally, including in participatory design processes by cross-disciplinary teams. From this work, new product families were added to the company’s portfolio, which today offer 34 products in six product lines with eight choices of materials.

Estefania Juarez and Alba Sanchez co-founded QuieroAire in 2009, renaming it Relement in 2011. This start-up was initiated as a result of an elective design research and innovation graduate seminar created and taught by one of the authors. In this seminar, teams of engineers and designers worked with local companies in order to identify latent problems and opportunities for design-driven innovations. Based on the author’s studies of creativity and innovation processes, students applied a situational approach to identify potential for radical improvements, where the target was a change of one order of magnitude—so as to go beyond optimization or continual improvements. Creativity and innovation were managed in three complementary dimensions in these projects: the creative individual (the team of students and change agents identified within and beyond the company), the field (the departments and divisions involved in the design and engineering of the products and processes being analyzed), and the domain (the established practices, norms and the general culture of the company).

[1] http://www.itesm.edu/wps/wcm/connect/snc/portal+informativo/news/patentbioixim4mar13.

By applying the principles and techniques covered in the seminar in real settings in local companies, five teams identified a large number of factors, barriers, and leverage points in proposed innovation strategies that ranged from original revenue models for scrap materials to new applications of advanced technologies, and, in the case of Relement's founders, to new opportunities given by the industry practices related to the use, management, and disposal of refrigerants and air-conditioning equipment. The seminar concluded with teams receiving feedback from the partner companies on the originality, feasibility, and value of projects. In this particular case, the company failed to identify the value of these ideas arguing that although interesting, they were incompatible with the established growth strategies. However, the students received very positive feedback from professionals, academics, and government officers who encouraged them to enroll in the local business incubator; it was initially named QuieroAire. A few months later, the project secured two separate grants, one from the local government and one from a private bank. Since then, Relement has refined the original definition, vision, and mission, and today it offers sustainable solutions to reduce the footprint of air-conditioning and provides consultancy on environmental management of greenhouse gases and lifecycle analysis.

The three cases presented here had quite dissimilar starting points and motivations. In fact, none of them were actually initiated with the explicit aim of incubating a company. The fact that more than a dozen design-related companies were created during this time, suggests that an entrepreneurial culture was being shaped. But the cases of Ecopilia, Materializadora, and to a greater extent, Relement illustrate that design research can easily find valuable applications in practice, whether by commercializing a patentable material, introducing novel model-making and prototyping techniques to accelerate the growth of a company, or pursuing innovation projects identified and framed with novel design approaches. It is noteworthy that these three companies have survived the always problematic first years of a new venture, and they continue to grow after 4 years. It is also of interest that these three companies have very strong foundations in sustainability, a core value of the school of design at the time. Ecopilia was a research project initiated by a faculty member and was developed systematically as a graduate thesis. Materializadora was an existing company that incorporated knowledge and techniques from a chain of graduate theses, including that of one of its founders. Relement is a remarkable case of an innovative company originated as a student project with clear potential that was overseen by the original partner, but strongly supported by knowledgeable industry experts.

3.2.5 Design Courses and Experiences

In this final section, we consider cases under guideline #13 for immersing students at all levels of design-based learning. As the head of the school of industrial design at Tecnológico de Monterrey (Querétaro, Mexico) from 2007 to 2011, one of the authors oversaw initiatives leading to the establishment of close partnerships between companies and design studio courses across the undergraduate curriculum. These partners ranged from multinational corporations to small and medium enterprises, as well as government and nongovernmental organizations: Campbell's México, Hafele Mexico, Creapack, Guaily, Imbera Cooling, Fundación Bertha O. De Osete, Mexico Tierra de Amaranto, Centro para Adolescentes San Miguel de Allende, Mars Mexico, etc. In these cases, students from semesters 1–8 developed new product designs coached by faculty and based on briefs provided by the client. Capstone projects in particular led to innovative designs that were frequently incorporated into the company's product strategy. In two particular cases, design research had a clear impact in practice: Mabe Mexico (www.mabe.cc) and Delegacion Miguel Hidalgo (miguelhidalgo.gob.mx).

The capstone projects with Mabe Mexico in 2008 and 2009 had two main themes: next-generation refrigerators and washing machines. This course was led by the author, Victor Martinez and Joel Gaona. The most promising product designs developed during the semester were selected by the design director of the company, and the group of students received a 1-year internship at the R&D department of the company to continue the new product development (NPD) process including detail design, user-testing, and feasibility studies. Several solutions presented to Mabe identified clear opportunities for design and technology innovations in response to unique social and market conditions in Mexico and other Latin American countries. The university–industry link here defies the conventional transfer of academic research into design practice: highly creative product designs were produced by students at the conclusion of their studies, and these ideas served as inputs to the R&D process of the company, one of the main private centers of research in the country.

The project with Delegación Miguel Hidalgo in 2008 was motivated by the increasing systemic problems associated with solid waste disposal in one of the busiest areas of Mexico City. With more than 20 million inhabitants and 650,000 tons of daily waste that ends up in landfills, the team led by Victor Martinez and Pablo Herrera applied design tools and techniques developed based on sustainability and systems thinking. The outcomes of this project included innovations in waste management equipment, public policy, and business strategies ranging from food packaging to local recycling and biogas plants. The *Waste Recovering System* project became an Award Finalist at the Index Awards of 2009 (designtoimprovelife.dk). This design project validated a cross-disciplinary study of practices across the schools of business, engineering, and industrial design (Sosa et al. 2010). Regarding systemic reasoning, our studies had suggested that the distinctions between disciplinary and multidisciplinary teamwork are weaker than what is usually expected. The fact that this team of last-year product designers produced such remarkable results applying techniques of high-order systemic thinking, further confirms our initial research findings.

3.3 Discussion

The overarching themes of Sects. 2, 3.1, and 3.2 debunk perceptions commonly held by industry professionals and academics alike. Although many believe that few academics practice design and engage industry, our studies indicates that many design researchers have significant design experience and intellectual property. Although many believe that design research is carried out in a silo, separate from business and industrial R&D, it seems that more than a third of design research, as reported in academic research journals, not periodicals from practice, contributes to business and industrial R&D. Furthermore, the effect of educating undergraduate and graduate students in design science is severely underappreciated, as shown by many of the IDRP examples. From considering these successful interactions, an extensive set of guidelines and mechanisms materializes, as shown in Table 2, for impacting practice. Given the amount of evidence we have presented and the limitations of these sources, we argue that impact upon of design research on practice is quite extensive and even greater than can be discerned from the literature.

First, let us consider the relationship between archival publications and practicing designers. Only one of the five top journals in design research, the Journal of Research in Engineering Design (RED), specifies industry professionals as the audience for their publications. In general, archival publications are not written for practicing designers, who have little background information and limited time to read 10-page or longer articles. Outcomes for specific applications are often implicit, ancillary, formed through relationships, developed through hiring and professional development, or fostered through method transfer, design research products on the market, or actual projects that directly affect a business' bottom line. Research articles, on the other hand, focus on the design research theory and development. Design research is published with the intention of advancing knowledge through revisiting the literature, and publishing research methods and results. Industrial professionals are not, nor should they be, the intended audience for academic journals.

Given the time required to produce journal-quality publications, the fact that 9 % of design research published in the past 2 years was authored by a nonacademic professionals is astounding. It is encouraging that nonacademic professionals have the time and interest to read, let alone write, design research publications. More appropriate mechanisms for creating accessible research in the language of practice are found under the guidelines of branding and disseminating (9) and engaging practitioners in professional development (12). For example, dynamic and engaging videos, periodicals, blogs, and continuing educational programs, provide the essence of actionable knowledge without the verbose discourse of research questions and procedure.

The estimate, from our analysis, that one third of design research involves knowledge transfer might underestimate the true impact of design research on practice. A severe limitation of relying upon archival journals is that true impacts of design research on practice are often unpublishable. Most obviously, IP issues and proprietary information present just one set of conditions preventing publication of industry and research collaboration. Additionally, many interactions between industry and research occur outside of the publishable research, through consulting, workshops, and in the trenches of design. If we consider the IDRP case with Prince Automotive, no publication related the fact that the graduate student involved was hired by Prince to train very senior and experienced design engineers in the techniques he developed. In the case of the functional basis development, contributions to Ford through workshops, product development, automotive and platform design, and partnership and contributions to DTM through design modeling and system evolution were omitted from the journal articles. Such outcomes of partnerships are, typically, left to brief acknowledgements, where the primary audience seeks to push the research frontier through the rigorous academic process.

Second, the focus on archival journals and academic venues limits our perspective to the side of academia. Optimistically, many interactions exist outside of these venues. For example, students, beyond the classroom and research lab, bring knowledge from their coursework to their new job and change practice either immediately or over time. Pessimistically, the impact of the research could be overstated. Perhaps funding from a source was allocated to a side project unessential to the funding agency's interests. Additionally, papers that report high industry impact might only enact short term results and not long-term change in practice. Additionally, research may never be read by the funding agencies. Such situations are possible, but not in keeping with the authors' experience. In the authors' examples of IDRP, successful interactions often lead to long-term partnerships and change.

Writing from an academic perspective, leaves many industry-side mechanisms and guidelines unconsidered. A separate and complementary set of guidelines can, hopefully, be derived from the other chapters within this anthology. Similarly, we envision that the guidelines in Table 2 could be restated from an industry perspective, or as industry undertaking the actions. For example, guideline #11 for housing practicing professionals on campus could be translated as housing academic researchers at corporate offices through sabbaticals and internships or advisory boards.

With the perception that design research is quite successful in impacting practice, the conversation changes focus and we can consider opportunities for capitalizing on the existing strengths of design research in academia and existing mechanisms for bringing design research to practice. The power of the guidelines presented in this chapter is that they are successful and proven strategies. The associated mechanisms are actionable, not only individually, but in combination, creating more opportunities for engaging practice in design research than can be reasonably enacted. These guidelines span from the initiatives of individual researchers to departmental and campus-level initiatives. The examples provided in this chapter of IDRP are but a small sample of the authors' experiences, and the reader is encouraged to refer to this set of guidelines when reading the other chapters within this anthology.

Although many of the guidelines and much of this chapter focus on published studies, consultations, and workshops, the most powerful mechanisms for transferring research to practice engage students. Education of future designers and industry leaders is one of the most important tools for bringing research to practice. Design thinking is a culture and approach to problem solving that must be learned. University curricula are important mechanisms for transferring ownership of the knowledge created by design research. All research outcomes of the IDRP examples within this chapter have been integrated into university-level curricula and practiced by thousands of engineering students. If one author is responsible for the education of over 4,000 professionals, then a community of design researchers, as educators, has undeniably significant impact.

4 Conclusions and Contributions

Conversations of the important linkage of design research and design practice are natural and important. Perceptions of the degree to which design research has impacted or made a difference in design practice are equally important. However, this chapter seeks to change, or at least call into question, stereotypical conversations and perceptions of the relationship and measures to which design research has significantly affected the practice of design.

Basic research in design should be highly valued, savored, and encouraged. As a scholarly field with the objective of contributing intellectual merit and long-lasting knowledge, a design research community cannot exist without basic research. Likewise, our community must have strong ties to practice and ultimately impact practice through the transfer of processes, methods, tools, and technology that lead to innovations for societal need and the development of the next generation of design leaders for an innovation economy.

The general studies presented in this chapter are encouraging. Whereas, some may believe that very little impact results from design research, an analysis of the literature and a survey of a segment of design researchers show that design practice is embraced and pursued. These findings are a starting point and basis for evaluating the impact of design research on practice.

Building upon these foundations, we have presented in this paper a collective set of guidelines and platforms for engaging design practice from design research entities. These guidelines and platforms are discussed completely through a set of cases where design research has been successfully transferred to industry or related organizations. Guidelines and platforms of this type will enrich the design research community's pursuit of growing and evolving design as a science and the practice of design, collaboratively with design practitioners across many fields, institutions, and national borders.

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Development of Function Modeling and Its Application to Self-maintenance Machine

Y. Umeda and T. Tomiyama

Abstract This chapter discusses the impact of design research on practice by taking two cases; function modeling and self-maintenance machines deployed from the function modeling research.

1 Introduction

The impact of design research on practice is not always obvious. While the effectiveness of design support tools at the detail design stage is nowadays obvious, including CAD, CAE, PLM, and design optimization tools, the effectiveness of design research focusing on conceptual design or design activities deeply related to creativity is especially unclear. In order to stimulate the discussion on the impact of design research, this chapter illustrates two cases; function modeling research and the development of self-maintenance photocopier, which is deployed from the function modeling research.

2 Self-maintenance Machine Project

In 1988, T. Tomiyama and H. Yoshikawa started two research projects. One was intelligent CAD project, which aimed at the development of a prototype of intelligent CAD and the development of a theory for constructing intelligent CADs. This resulted in, for example, 'knowledge intensive engineering framework (KIEF)' [e.g., (Tomiyama et al. 1994, 1996; Yoshioka et al. 2004)]. The other was self-maintenance

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machine project, which aimed at the proposal of framework of self-maintenance machine and the development of its design methodology, its reasoning system, and its prototypes. The authors led this self-maintenance machine project. We proposed design methodologies for control type self-maintenance machine and function redundancy type self-maintenance machine [e.g., (Umeda et al. 1991, 1992, 1995; Umeda and Tomiyama 1999)]. Besides theoretical development, we started to develop a self-maintenance photocopier under the collaboration with Mita Industrial Co., Ltd. in 1989. The first self-maintenance photocopier was shipped into the market in 1994 (Shimomura et al. 1995). Through this self-maintenance machine project, one of the most important achievements was a function modeling scheme 'Function-Behavior-State Modeling,' firstly appeared in 1990 (Umeda et al. 1990) and expanded into, e.g., (Tomiyama and Umeda 1993; Umeda et al. 1996).

3 Function-Behavior-State (FBS) Modeling

Clarifying the concept of 'function' and modeling function in a computable manner were critical for both of the intelligent CAD project and the self-maintenance machine project. On one hand, since the main target of the intelligent CAD is conceptual design support, 'function' is the main concept to be manipulated. On the other hand, the goal of maintenance or reliability theory is to keep or recover functions of a machine and we set the objective of the self-maintenance machine to maintain its functions rather than to repair physical structure of the machine. Function had become the central target in designing the self-maintenance machine.

The objective of this subproject was to model function in a computable manner and to apply the modeling scheme to conceptual design support and the design of the self-maintenance machine.

After surveying various definitions and representation schemes of functions, including the transformation between inputs and outputs in Pahl and Beitz (1995) and "to do something" in value engineering [the survey is summarized in (Umeda and Tomiyama 1997)], we concluded that function is a subjective concept representing user's expectation to a machine from the viewpoint of user's value (or designer's presumption of user's expectation to a machine from the viewpoint of presumed user's value). And we decided to represent a function in terms of "to do something," because this is the most flexible and natural representation.

Next question was to what concept function is to be grounded. Since "to do something" is just a symbol in a computer and this is not computable, we wanted to map the function concept to something objective and to systematize functions by this mapping. We chose 'behavior,' because we were in mechanical domain and we recognized that function is performed through behavior.

Finally, we defined function as "a description of behavior abstracted by human through recognition of the behavior in order to utilize the behavior" and modeled the relationship among function, behavior, and state as shown in Fig. 1 (Umeda et al. 1990, 1996). As shown in this figure, each function symbol, i.e., "to do

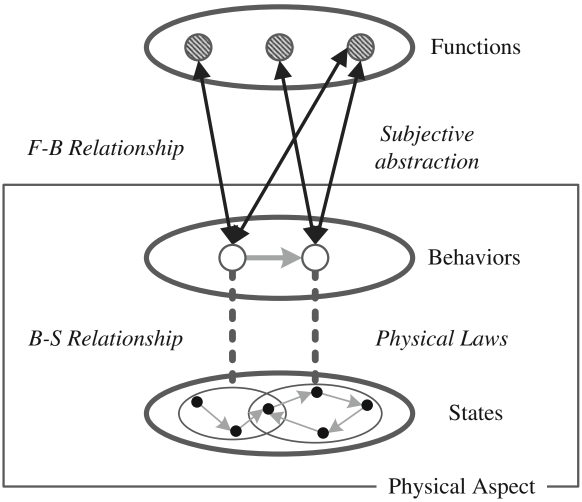

Fig. 1 Relationship among function, behavior, and state (Umeda et al. 1996)

something," is related to its actualizing behavior through F-B relationship, which represents human recognition and abstraction. In turn, behavior is defined in this model as a sequence of state transition ruled by physical phenomena. We call this relation B-S relationship. Here, the representation of behavior may differ depending on the physical situations of the current interest. To model such difference, we introduced *aspect*. Each aspect is modeled as a collection of relevant elements of state description [i.e., entities, attributes, and relations (Umeda et al. 1996)] and physical phenomena of the current interest. Then, we also modeled that the hierarchical structure of a machine is constructed through human recognition as shown in Fig. 2. This is based on our assumption that human recognizes a machine hierarchically especially for understanding its mechanism and, in the same manner, a designer designs a machine by decomposing the top required functions into subfunctions as Pahl and Beitz said (1995). This figure indicates that the designer should concurrently describe symbols of functions and their actualizing behaviors with appropriate aspects in a hierarchy. Because aspects are physically related with each other, consistency among aspects and consistency of behaviors and states in each aspect can be maintained by a computer with sufficient physical knowledge. For example, we have proposed metamodel mechanism that manages relationship among aspects (Tomiyama et al. 1996). We call this function modeling scheme "Function-Behavior-State (FBS) modeling."

We implemented this FBS scheme as "FBS Modeler" (see Fig. 3). FBS Modeler employs the qualitative reasoning system developed by the intelligent CAD project. By using this system, which is based on Qualitative Process Theory (Forbus 1984), we constructed a knowledge base of physical behaviors in the form of physical feature. By using this qualitative reasoning system with the physical knowledge base, a designer constructs a behavioral model of a design object and runs

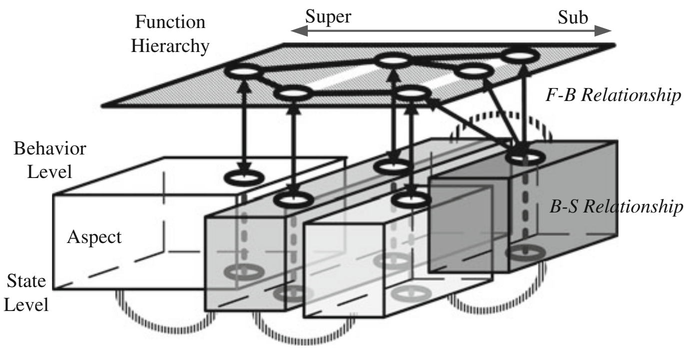

Fig. 2 Product structure (Umeda et al. 1990)

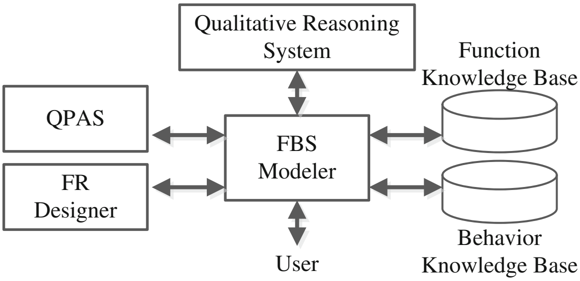

Fig. 3 Architecture of FBS modeler (Umeda et al. 1992)

behavioral simulation. In this process, a physical feature works as a building block for constructing the behavioral model.

We developed FBS Modeler for supporting function modeling and functional design. The functional design process in FBS Modeler consists of six steps (this basically follows Pahl and Beitz's design process (Pahl and Beitz 1995), but computerized): (1) specification of required functions, (2) functional decomposition supported by searching through the function knowledge base, (3) embodiment of functions supported by searching through the function and behavior knowledge bases, (4) construction of behavior network (i.e., behavior model of a design object), (5) execution of behavior simulation, and (6) evaluation of functions.

The strong points of FBS modeling are summarized as follows:

- Combination of the subjective part and the objective part: the concept of 'function' was not clear and may include subjective part of users, potential users, and designers, and objective part. FBS modeling clearly distinguished these two parts and combined them. This achieved both of the flexibility of representation in the subjective part and the computability of the objective part by grounding it on the physical behavior.
- Implementation: We have the working implementation that demonstrates the power of FBS modeling; i.e., FBS Modeler supports functional design not just

by representing functions in the form of symbols in a computer. A designer can find out subfunctions and embodiments by searching though the function and behavior knowledge bases and, by executing the behavior simulation, he/she can check whether each function is performed or not and the possibility of side effects.

- Applications: We had good applications of function modeling. One is, of course, functional design support. The other is the self-maintenance machine described in the next section. These applications helped potential users of FBS Modeler to understand advantages and merits of FBS modeling.

4 Self-maintenance Machine

A practical application of FBS modeling was the self-maintenance machine. We defined a self-maintenance machine as “a machine that can maintain its functions for a while even though faults occur” (Umeda et al. 1995). In other words, we focused on *functions* rather than *structure* and maintain functions *for a while* rather than *eternally*. Function modeling was indispensable for two reasons:

- We proposed ‘function redundancy’ as a self-maintenance strategy. Function redundancy recovers functions of a machine by using potential functions of existing parts in a slightly different way from the original design, when the machine becomes faulty and loses some functions. Function redundancy requires function modeling and operation. Indeed, we developed a design support tool for function redundancy on the top of FBS Modeler. Figure. 4 shows an example of function redundancy in a photocopier (Umeda et al. 1992). In this example, when the main charger is broken, a photocopier cannot perform the main function ‘to take a copy.’ If this photocopier is equipped with the function redundancy with the transfer charger, the transfer charger substitutes the function of the main charger since the behavior of the transfer charger is same as that of the main charger.
- The prototype self-maintenance machine we developed is equipped with the knowledge-based system that executes fault detection, diagnosis, repair planning, and control sequence program generation. All of these tasks are related to ‘function.’

In the collaborative development of the self-maintenance photocopier with Mita Industrial Co., Ltd., we, as academia, developed various reasoning systems and two prototype machines; control type, and function redundancy type. On the other hand, the company understood the concept of the self-maintenance machine, its theory, and the design methodology for it, and then they developed their own machine to be shipped to the market. Our main interests for prototyping included the verification of the framework and the methodology, where generality, wide applicability, and logical soundness were critical. On the other hand, practicality including the

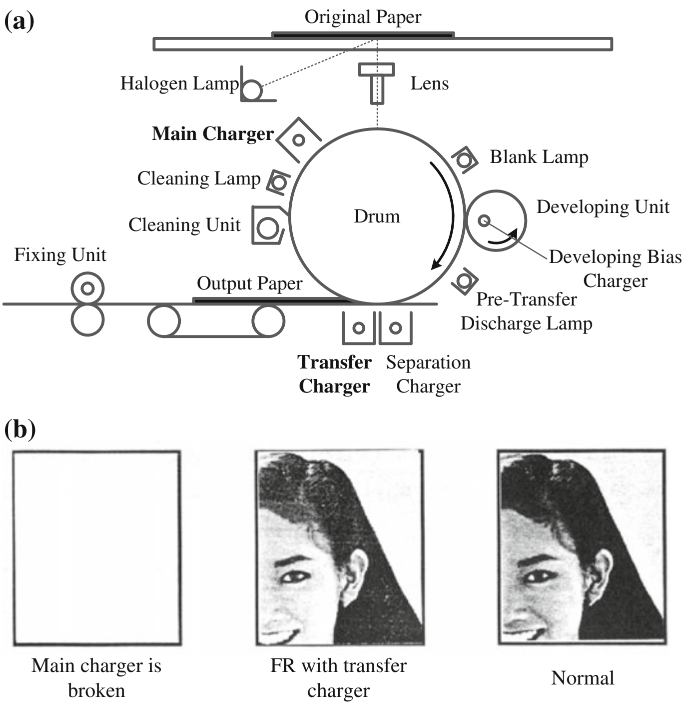

Fig. 4 Example of functional redundancy (Umeda et al. 1992) **a** Structure of a photocopier, **b** output images

accuracy of the reasoning, the reliability of the machine, and the speed of the self-maintenance, was essential for the company in developing the practical machine. They therefore developed their own reasoning system for the self-maintenance function by employing case-based reasoning and fuzzy logic, which increased the practicality, rather than just using our reasoning system. In developing the practical machine, the project leader of the company, who also belonged to the academia, played the very important role including;

- understand the difference of missions and objectives between academia and industry,
- understand the basic concept, the framework, and the methodology,
- translate them into practical form (this requires technological development filling the gap between academic theory and practice), and
- set the project target and run the project.

5 Discussions on Influencing the Practice

Through our experience in studying the functional design, we can discuss some points on influencing the practice.

- FBS modeling or FBS Modeler has not directly been used in practice (i.e., the real product development). Actually we have executed several seminars on FBS Modeler for industry, but they were for enlightening engineers rather than for practical use. Even now, conceptual design support is not practically applied. But, the research results worked as a working normative model that encouraged engineers and designers to understand function modeling, function reasoning, and functional design support (e.g., how the Pahl and Beitz's design methodology can be implemented in a computer).
- More importantly, in early 1990, different research efforts focusing on function modeling and functional design appeared (such as Gero's group (1992), Goel and Chandrasekaran's groups (1989), and AAAI/IJCAI Function Reasoning workshop series). In combining with them, our work contributed to open the research domain of function modeling, function reasoning, and functional design, which is still active.

The self-maintenance project was really practical, although it was just *an* industry-academia collaborative project. In other words, it did not arrive at the situation where many companies are developing self-maintenance machines. But, we can point out several reasons of the success of this project:

- Feature of the target machine: The target machine, i.e., photocopier, has structure suitable for adding the self-maintenance function. The target photocopier was highly modularized and the behavior of the whole machine was controlled by a sequence program. This enabled the reconfiguration of the sequence of module activation just by changing the sequence programs. This reconfiguration was indispensable for realizing the function redundancy described in Fig. 4. Moreover, since a photocopier is composed of various technologies including mechatronics, chemical processes, and electrostatic technology and is far from an optimized and sophisticated machine, the photocopier has a lot of potential functions, which expands the possibility of the function redundancy. In general, a large and complicated system may have many potential functions that can be used for the function redundancy. One of our contributions was to formalize and computerize the utilization of the potential functions by FBS modeling and the function redundancy. This results in enabling a designer to search such potential functions during functional design.
- Features of the after sales service: Another advantage of the photocopier came from the fact that it is a service intensive machine. A photocopier cannot continue to work for, e.g., a year without periodical maintenance. In 1990s, the photocopier of this company required maintenance much more frequently than nowadays. And, fortunately, safety requirements of a photocopier are not so

severe as an elevator or an escalator, which also require periodical maintenance. Therefore, our self-maintenance strategy, i.e., to maintain its functions for a while (until a service personnel comes) when faults occur, fit to the photocopier quite well. Since such products exist everywhere even in these days, the self-maintenance strategy is still a promising strategy for increasing added value of products. For example, this strategy may fit well to "product service system" (Tukker 2013).

- It is very important to share the basic concept (i.e., the self-maintenance machine). The demonstration of the research results and the prototype machines was effective to transfer the concept of the self-maintenance machine from the academia to the industry. Moreover, in developing the commercial self-maintenance photocopier, we identified "quality of the output image" as the target function to recover. This target setting was successful, because this function is one of the most important functions and there are many means to control this function, which means we have many candidates of repair operations. Since the academia and the company arrived at the consensus on this target at the early stage of the project, we could avoid reconsidering the target and regressing.
- The key person was the project leader who mediated between the academia and the industry. Moreover, he succeeded in translating and deploying the framework and the methodology into practical system. This was the key step in the project.
- Above all, the support of executive is indispensable.

6 Summary

This chapter discussed the impact of design research on practice by taking two cases; function modeling and self-maintenance machines, which is deployed from the function modeling research.

The framework and design methodology of the self-maintenance machine had direct impacts on practice (i.e., the development of the self-maintenance photocopier). The important points include common understanding of the concept and goals between researchers and practitioners and existence of the mediator that can translate the framework and the methodology of the academia into practical form (this requires technological development filling the gap between academic theory and practice).

Our functional design research had indirect impacts on practice; on one hand it contributed to open the research domain of function modeling and functional design, on the other hand, it may have contributed to educate, increase knowledge, and stimulate design thinking of practitioners. Many practical tools such 3D-CAD, CAE, design optimization tools, and PLM were not useful just a decade ago. We can expect functional design support tools will be practical in near future.

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Part III
Experience from Practice

Experience with Development Methods at Three Innovative Hidden Champions

Gerd Fricke

Abstract Innovative industrial companies are lead successfully by CEOs directly responsible also for product development. The strategic plan of those companies includes product development directions, which can be efficiently worked out using a lean scenario technique. It helped that all new product ideas were collected centrally in an idea pool and evaluated together with top management giving definite priorities but not cancelling too "digital" ideas with a good chance of benefit. A roadmap should visualise all finally planned projects including feasibility studies and it should contain all relevant economical and technical features. The roadmap is the essential basis for efficient multiproject management. It must be actualized regularly accompanied by priority setting and consequent decisions. Head of each project is a project leader who must be mandated with formal authority supported by top management. The distinction was extremely purposeful between a market specification product profile and derived from that a technical specification document; both product specifications have to be signed by sales and development top management. Methods were success promoting when pragmatically improving communication in the project, finding technical solutions or optimising quality and costs. Methodically educated employers supported obviously the development success, this is often underestimated also during the embodiment phase. Teaching those development methods must be intensified in university and professional education. Intensive research is necessary in real industrial environment investigating how to improve the practical use of academically well-known methods and how to optimise the product development processes on management and on project level.

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1 Product Development in Industry

Engineering design (on product level) is interweaved with most activities of the industrial development process (on project level) which itself is reciprocally depending on settings and processes on company and market level. Design methods in its narrow sense must be looked at also on a wider view. The findings are based on 20 years of experience in product development from project leader to CEO and Chairman at three international market leaders. All companies recognise their innovative leadership and product development as an important core competence. This function is represented by a direct link of the development areas to the CEO and separate R&D directors. The product development departments are located close to the headquarter.

Two organisations have been “tested” over the time: Function-oriented (i.e. separate departments for research, mechanical design, electronics, testing, project and product management…) as well as product-oriented organisations (all development disciplines including purchasing, production preparation, QM etc. are present at each “product centre”). The latter organisation is only efficient when the product centre’s portfolio and turnover is big enough to have always success-promising projects in the pipeline but not enough resources. This avoids “self employment” or homeless fragmentation.

The employees’ qualification ranged from PHD engineers to technicians with a few methodically educated only. Unfortunately, the latter is the typical situation. To implement development methods it helps to employ at least a critical number of methodical educated engineers and then convince others implanting simple methods on management, project, and product levels for solving low hanging fruit problems at the beginning. This encourages the application of other methods next time.

2 Company Level

2.1 Strategic Planning and Product Portfolio

For leading an innovative company successfully, you need long-term goals and a strategy with clear guidelines for product development resulting in a StrategyPlan (Table 1).

Experience: A neutral expert educated in management methods should be used for moderating the discussion focusing on important goals and strategies, avoiding “goals for everything” but reaching a comprehensive picture of the aimed future including visions of new product fields. These visions could be abstract descriptions of solutions for customer needs. It helps to get out of the box (location outside the company). In 2 × 2-days workshops, a simplified scenario technique was applied for forecasting the future of certain Product-Market-Constellations with surprising

Table 1 StrategyPlan

StrategyPlan — Status: 30.09.13

1= runs as planned | 2= runs uncertain | 3= runs bad

Strategic Pillars				2013				2014				2015				
1	LEADERSHIP	Who?	Link	QI	QII	QIII	QIV	QI	QII	QIII	QIV	QI	QII	QIII	QIV	Remark
1.1	Strategy A	Paul		2	2	2										
1.2	Strategy B	Smith		1	1	1										
1.3	Strategy C	Jones		2	2	1										
2	MARKET SUCCESS	Who?	Link	QI	QII	QIII	QIV	QI	QII	QIII	QIV	QI	QII	QIII	QIV	Remark
2.1	Strategy D	Paul		2	2	2										
2.2	Strategy E	Jones		2	1	1										
2.3	Strategy F	Carl		1	1	1										
3	PRODUCTVITY	Who?	Link	QI	QII	QIII	QIV	QI	QII	QIII	QIV	QI	QII	QIII	QIV	Remark
3.1	Strategy G	Dean			2	2										
3.2	Strategy H	Smith		2	2	2										
3.3	Strategy I	Jones		1	1	1										
4	PRODUCT INNOVATION	Who?	Link	QI	QII	QIII	QIV	QI	QII	QIII	QIV	QI	QII	QIII	QIV	Remark
4.1	Detect needs (inno priorities & inno push in retail)	Paul		1	1	1										IDEAPOOL
4.2	Efficient New Product Developm. & Product Enhancement	Jame		1	1	1										ROADMAP
4.3	Elektronic Plus	Lance		3	3	2										MEASURES
4.4	Life cycle (product optimization, end of life) - added 7/13	Jame				2										ROADMAP
4.5	New Business Development - Inno products pushing turnover	Paul		2	2	2										IDEAPOOL
5	SUPPORT	Who?	Link	QI	QII	QIII	QIV	QI	QII	QIII	QIV	QI	QII	QIII	QIV	Remark
5.1	Strategy P	Carl		1	1	1										
5.2	Strategy Q	Smith		1	1	1										
5.3	Strategy R	Carl		2	2	1										

proximity of the forecasted picture and the reality 3–5 years later. The scenario technique has helped enormously for decisions of general product development directions: e.g. the application of a new energy source was predicted as crucial but not having the relevant competence in house—as result own expertise was build up and a new device was developed securing the market leadership 4 years later.

Visualising the results in a 9- or 4-field matrix (The Boston Consulting Group 1970) focuses the planning for potential new products. Brainstorming (Osborn 1957) was the preferred method when searching for new product fields or goals completed by visualising the ideas to improve associations and to expose contradictions. No more than 12 persons should participate in such strategic meetings and they should be of different character and responsibility but discussing at eye level. At least one of the directors should be educated and practically experienced in applying those methods if no methodical expert is available.

The findings must be explained personally to management and employees. Product development-related goals should be distinguished between product and process goals. A general product roadmap must be part of that StrategyPlan. The StrategyPlan was used for a monthly check up on director's level. A simple validation ("according plan", achievement unsecure", "running bad":—in the latter case, measurements must be defined immediately) supported keeping the company and the product development on the right track without too much formality.

2.2 Idea Pool

Product ideas from employees (from product centre, new business development or others) or from outside the company should be centrally filed in a summarised form. All ideas for new products or innovative features are centrally collected in one standardised table and regularly evaluated in a small cross functional team including management. This evaluation leads to a comprehensive but focused list of product ideas, each stepwise judged towards standardised criteria with "+", "?" or "−" (Fig. 1).

A product idea should be cancelled in case of only one minus for one of the criteria "according strategy", "convincing customer benefit", "realize efficiently"or "profitable market potential" (Fricke and Lohse 1997). This method was improved further in order to avoid cancelling too digital but with a need for clear priorities. Remaining ideas achieve a "chance value" after its assessment. Each idea is rated between 0 and 100 % in respect to "strength of customer need for getting that product/feature", "fitting strategy", "low hanging fruit (effort versus benefit for the company)", "knowledge about principle solution", "competence and novelty (Ansoff-matrix)". The result is an average chance value.

Experience: The R&D and Sales Director as well as the CEO have to be a member of the evaluation team because the outcome is important for the long-term success or failure of the company. A feedback to everyone who has input an idea must be done on time (immediately when filed and directly after decision with reasons) to keep those creative employees motivated for further ideas. Product ideas above a certain chance value will be further investigated in the research department (feasibility study) or directly in a product centre if the technology is well known.

IdeaPool				Not According Strategy	Low Hanging Fruits		Ansoff-Matrix		Competences		
#	Idea Description	Economic Data (turnover, abs. & rel. gross profit)	Customer Need	Not Military & No Automotive Private Vehicle	Volumen New Potential Turnover >3 Mio. €	Technology or Solution is Known	Product	Market	Technical Competence	Sales and Marketing Competence	Chance Value
1	A	confidential	Heating	No	Yes	Yes	modified	new	high	low	70%
2	B	confidential	Heating	No	No	Yes	existing	new	high	medium	50%
3	C	confidential	Air Quality	No	No	Yes	new	Caravaning	medium	high	50%
4	D	confidential	Heating	No	No	Yes	modified	Caravaning	high	high	30%
5	E	confidential	Electric Energy	No	Yes	Yes	new	new	medium	medium	80%
6	F	confidential	Heating	No	No	Yes	modified	new	high	low	70%
7	G	confidential	Heating	No	No	Yes	existing	new	high	medium	50%
8	H	confidential	Heating	No	Yes	Yes	existing	new	high	low	60%
9	I	confidential	Cooling	No	Yes	Yes	existing	new	high	low	60%
10	J	confidential	Heating	No	Yes	Yes	existing	new	high	low	60%
11	K	confidential	Hygiene	No	No	Yes	modified	Caravaning	high	high	30%
12	L	confidential	Heating	No	No	Yes	modified	new	high	low	70%
13	M	confidential	Simple Use	No	No	Yes	modified	Caravaning	high	high	30%
14	N	confidential	Hygiene	No	No	Yes	new	Caravaning	medium	high	50%
15	O	confidential	Air Quality	No	No	Yes	new	Caravaning	gering	high	60%
16	P	confidential	Simple Use	No	No	Yes	modified	Caravaning	high	high	30%
17	Q	confidential	Simple Use	No	No	Yes	modified	Caravaning	high	high	30%
18	R	confidential	Electric Energy	No	Yes	Yes	new	Caravaning	medium	high	50%
19	S	confidential	Simple Use	No	No	Yes	new	Caravaning	high	high	40%
20	T	confidential	Sleeping Comfort	No	No	Yes	new	Caravaning	medium	high	50%
21	U	confidential	Simple Use	No	No	Yes	modified	Caravaning	high	high	30%
22	V	confidential	Hot Water	No	Yes	Yes	new	neu	medium	low	90%
23	W	confidential	Heating	No	No	Yes	modified	Caravaning	high	high	30%

Fig. 1 Idea pool

Ideas with a chance value slightly below will be set on "further investigation" remaining on the list. Clearly refused ideas will be collected in a "cancel list" including a description of the refuse reasons to avoid Jojo-ideas, coming up periodically after cancellation.

2.3 Roadmap of All Product Development Projects

A planning method is needed for multiproject management enabling the R&D management to keeping track of interdependent milestones, shifting personnel, controlling budgets and resolving bottle neck resources.

The roadmap contains all projects, one project per line, with a short product description, customer group, core economical data, capacity information and important milestones. All projects in one table means all ongoing product developments and all projects generally planned or budgeted for including projects for successor products and bigger improvement projects (e.g. cost reductions, facelifts). All project leaders have to report on a certain date their data to the head of R&D who has to work out an overall proposal. This roadmap draft is then discussed with the heads of development departments resp. product centres, of product management and of sales and marketing directors. A coordinated roadmap is the result.

Experience: The roadmap was actualized every 4–6 weeks avoiding overreactions as well as too late counter steering. Managing a lot of parallel product development projects is managing shortages of people, of technical equipment, of solutions, of time, of money, and other resources. A decisive, well balancing but clearly goal-oriented manager is a must for that job. Every time each project must get one certain priority which no other project has. This priority might change from meeting to meeting, e.g. a product with low profit margin will get a high ranked priority once the customers are informed and preparing to fit or sell the new product already. The R&D director's and sales director's agreement is a must for the actual roadmap. Otherwise, they have to work until white smoke rises! It is economically inefficient to provide overcapacity or prolong unnecessarily milestones. Development teams will spend easily more time in searching for better solutions even if the actual one is fulfilling the goals already. If there were no last minute, nothing would become finished on time! If the R&D manager or project leader do not set and follow consequently the main goals and conditions, they will get bogged down easily. The same attitude was discovered when investigating individual designers (Fricke 1993).

2.3.1 Project Management Level

Project leaders plan tasks, people, resources and approaches for "their" project followed by controlling and updating their planning regularly.

Contradicting specifications and unforeseen complications without too much "planning with reserve" leads to analogue problems compared to the roadmap planning. On single project level, the project leader has to manage different experts, tasks, unforeseen problems and new conditions. Standard project management software is helpful but often too sophisticated.

On a more technical level, the project leader organises the search and fit of optimal technical solutions fulfilling the specifications for the new product.

Experience: A successful project starts with the specification from the market/customer point of view and a feasibility study, even if only a short one. A core team should work together from feasibility study until the start of sales. Undocumented aspects are lost if a project starts with an entire new team after signing the specification documents. Also feasibility studies should be handled officially as projects avoiding inefficient "submarine" project management. A balance is necessary between innovating creatively and developing routinely. It is a must to define officially a few milestones, the main technical and economical goals leads—also for feasibility "projects".

Project leaders must get a clear authority for managing people, technical and economic issues in order to achieving the project's success. The bigger the project, the earlier a person for planning and controlling is advised. Positive top management support for project leaders is necessary especially in complex organisations like in matrix structures.

On a day-to-day basis, the Task-Board-Method is helpful. The team stands together (not sitting!) for 15 min on a fixed time. All tasks for the coming 5 days are quickly summarised by each responsible engineer, written on a card, signed and then fixed on a Task Board. The task is then assigned to "not done yet", "in progress", "waiting for" or "done". This transparency and commitment is helpful especially in critical phases of a project. In addition, a monthly project report is the main controlling tool for the project leader (description see below).

2.4 Product Level—Developing Product Structures

2.4.1 Definition and Concept Phases

In general, a specification list represents the start of a project. Even before that or in parallel, a feasibility study is worked out.

Experience: A market specification profile should describe the main specifications and USPs (unique selling propositions) from the customer point of view. It also contains main economical conditions, technical and market restrictions and stop-loss values for distinct performance, economy, quality and time factors. It should be worked out under sales and marketing responsibility ("customer") supported by R&D ("supplier") and then signed by the management board. A technical requirement table is worked out, translating the customer needs into technical requirements including costs, efforts and milestones.

The main USPs, costs, capacity, planned price and volume as well as milestones are tracked monthly in a project report to control the project and to inform internally about the status—in case of deviation: actions have to be defined and started immediately.

Still designing one function but purchasing already serial parts for another area is typical for Simultaneous Engineering (Bullinger and Warschat 1997). Number and grade of overlapping activities reflect the risk. The better goals are defined without modifications over the time the more efficient a project is executed without too much stepping back and forth. Analogue results were found when investigating individual designers: successful designers noted the essential requirements as concretely as possible and followed flexible the general approach from task clarification, concept development to embodiment design (Fricke 1996).

At the beginning, a feasibility study should be worked out in case of high technical novelty and economic uncertainty. Well-known design methods are available for goal clarification and for finding the best working principles (Pahl et al. 2007). Unfortunately, in industry these methods are assumed as too time consuming and used mostly when the conventional muddling through had led to a dead end because of low confidence or low practical experience.

Nevertheless, combination matrices like the "Morphologischer Kasten" (Zwicky 1966) were used in feasibility studies helping to visualise alternatives and to optimize patent descriptions. But such matrix methods or function structuring were seldom applied in projects under time pressure. Discursive methods were only used after "dead end periods". That helped to restructure the problem and initialized new approaches of finding solutions. The "Galeriemethode" (Hellfritz 1978) is a brainstorming derivation for finding appropriate working principles or embodiment designs especially if those solutions were easy to sketch. Its use was very helpful in early concept phases or if no established solutions where available. But at least one methodically educated engineer had to participate in those workshops to avoid wrong practice. It was disappointing that the "muddling through approach ending with failure" was followed for a long time especially by less experienced designers working alone. Only experienced technicians were able to achieve at least acceptable solutions on time when muddling through in such critical situations. Junior design engineers should be advised to a systematic approach using simple methods in critical situations or collaborate closely with a senior expert. Design teams with different expertise, competence and seniority were more successful than homogeneous groups.

After a creative phase the alternatives have to be evaluated. The most important criteria (8 or less, balanced functional and economical criteria) must be clearly defined before. Solutions should be evaluated as simply as possible (0 pts.: inacceptable—10 pts.: perfect) and reasons for each value have to be visualised and protocolled.

If it is required legally to ensure a product's safety, it has to be proofed that everything has been done according to the state of the art to reach an acceptable safety level. System-, Product- and Process-FMEAs are common methods to minimise safety risks. In case of legal issues, it is also an important document and legal argument if the FMEAs were executed correctly. It helps to use the FMEA documentation as a technical controlling tool making sure that all relevant modifications during the embodiment design are implemented. A lean FMEA was adapted avoiding loss of focus and concentration on the relevant risk areas.

2.4.2 Engineering and Realisation Phases

Design engineers learn basic technical rules (e.g. clarity, simplicity and safety) and principles of embodiment design (Pahl et al. 2007) as well as "how to design cost efficiently" (Ehrlenspiel et al. 2007). This embodiment design knowledge grows with a more subconscious learning on the job in industry.

Experience: Design engineers seem to become specialised after a couple of years because of their personnel experience e.g. in sheet metal or packaging design. Open-minded designers complete university knowledge with practical experience on the job, further training, discussions with senior experts in the company and collaboration with expert suppliers. The product concept has the biggest influence on cost and achievement of the goals. Often underestimated, the embodiment design engineers have the second biggest influence especially on cost and quality. Their motivation and competence is important for the economic success of an industrial company.

Besides general design rules, most product developing companies have their own guidelines for aesthetic design, embodiment design (product structure including all mechanic and electronic interfaces, CAD models and commitments, using existing parts/standardisation, modularisation, part list structuring, modification process, packaging) as well as checklists for software and hardware development. This important practical knowhow is based on experience and the specific environment of the company. It should be recorded for general use and with easy access for the engineers.

3 Remarks for Research and Academic Education

Methods for individual designers or for well-defined product requirements are known and used partly in industry. Findings about success-promising approaches of individual designers investigated in artificial environment are partly transferrable to industrial application.

More investigations of product development in industry on project and on management level are needed for understanding and supporting better the processes how to come from a fuzzy bunch of ideas to a successful product within a complex, dynamic and real-life environment. Reliable research methods are available (Blessing and Chakrabarti 2009). It is necessary for innovative leadership to improve the implementation of product development methods in real-life environment to achieve better products pursuing more efficient development processes.

Teaching those methods in university and professional training accelerates its success-promising application in industry. But we need urgently a more intensive investigation about practical use of those methods, its optimization avoiding the gap between sophisticated method development in universities and dissatisfying assignment of successful methods in industry and about simple implementation of sustainable design methods into active usage. Methodically experienced engineers must participate in much more industrial projects. Companies ought to engage and educate methodical experts for participating in projects as internal project supporters and this infiltration should be supported intensively by universities or consultant firms.

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Design as an Unstructured Problem: New Methods to Help Reduce Uncertainty—A Practitioner Perspective

Bruce Garvey and Peter Childs

Abstract At inception, much design activity is unstructured and as such is faced with an array of uncertainties. If not addressed early enough these uncertainties can gestate into undesirable outcomes which the design team will find difficult to redress at later stages in project—especially, where the project is constrained by resources (time, money, people). In order to militate against such circumstances occurring the design team has to understand both the nature of the problem facing it and the nature of the uncertainties contained within the problem space. These issues impact not just at the creative, early stage of the project but across the design spectrum. The chapter begins by identifying the main elements within this spectrum; creativity, innovation and the oft-neglected execution phase. Two core conditions that designers have to come to terms within this process, are then explored: how can problems be categorized and which of these variants is the most problematical? The second condition addresses the nature of uncertainty when applied to the more intractable end of the problem scale. In response to design situations governed by these two conditions, methods that support decision making and mitigate risk are introduced under the broad category of Problem Structuring Methods (PSMs). Within the gamut of methods available the authors then explore the particular value of two methods which operate best when faced with qualitative judgment rather that observed metrics; morphological analysis to help generate and identify viable possibilities followed by Multi-criteria Decision Analysis which can help position these possibilities in a hierarchy. Finally, an argument is posited that the design process or system has to take into account an understanding of the business model for the designed item as this can impact success or failure at the execution phase when the end product is introduced to the end user. Early consideration of the business model (in all its variety) can redress some of the inherent uncertainties during the overall design process.

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1 Part I—A Design Landscape

1.1 Design and the Design Process

"Design is the ability to imagine that-which-does-not-yet exist, to make it appear in concrete form as a new, purposeful addition to the real world" as stated in Nelson and Stolterman's book "The Design Way" (Nelson and Stolterman 2012). Whilst their book is a commendable addition to the literature of design thought, one can take issue with this interpretation as it could be perceived as being too restrictive—which we do not consider is Nelson and Stolterman's intention.

First of all it seems to imply that design is an activity resident largely in the creative space, as opposed to also being majorly present at the innovation stage (post creativity). Second the expression "in concrete form", may imply that design is restricted to tangible artefacts as opposed to both tangible and intangible manifestations of design. Thirdly it appears to put forward a more holistic approach to design rather than an integrated holistic and reductionist approach. This third observation of the need towards holistic/reductionist integration is of importance if one accepts that design, continues its influence into the execution phase post innovation (Garvey and Childs 2013).

What can be said is that, at the beginning of a new design project, a problem exists for the designer or the design team (avoiding the common euphemism of calling a problem a "challenge") caused by uncertainty of outcome. Indeed the further away a design concept is from realisation as a finished item, the more it is prone to varying conditions of uncertainty. Two crucial conditions relating to design evolution are highlighted here:

1. What is the nature of a problem (they are not all the same)? and
2. How to understand and address uncertainty?

These two conditions are not just present at the initial creative stage of the process—creativity being seen as the first stage across the design spectrum—but in the subsequent stages namely, innovation and execution. Across this design spectrum—the nature of the problem and the uncertainty it brings, abound.

This chapter, thus examines the two core conditions (problem identification and uncertainty), under which the design process operates, the understanding of which is vital, if design research is to support decision making in the practitioner domain.

In its broadest sense design, "…is multi-faceted and multi-dimensional, consisting of both the physical/technical (or functional) areas of design as well as factoring in behavioural and contextual responses to the designed object by users of the end product."

Garvey and Childs identify further areas of specificity by stating, "Physical design methods and the behavioural responses to such design (many of which are not quantifiable), is highly complex, exacerbated by high levels of interconnectivity. This is not just due to the variety of components that have to be considered in the design process (physical complexity), but to intangible factors inherent within the nature of individual and group behaviour in response to designed objects".

In the particular domain of Design Research, Blessing and Chakrabarti (2009) indicate that such research should support the selection and application of methods and methodologies (the approach) in order to assist in turn the development of more effective and efficient design research framework.

1.2 Where Do Design Interventions Occur?

Creativity, Innovation and Execution Creativity is the thinking process that enables the generation of ideas, whereas "Innovation" is the practical application of such ideas towards meeting an organisation's objectives (Majaro 1988). Too often, these two terms have been used interchangeably, leading to confusion. They are distinct entities in their own right yet mutually dependent—one is not much use without the other. In the excitement to create and innovate, the all-important "Execution" element is often neglected. Execution, and an organisation's ability to provide a climate for change, (so that the outcomes of Creativity & Innovation (C&I) processes can be integrated into broader organisational objectives and operations), are often in conflict (Govindarajan and Trimble 2010): alignment of C&I with Execution (CIE) is thus required.

Design, intervenes at all stages in this process. It is vitally important to acknowledge that it is not just a linear process but an asymmetric and symbiotic one. Whereas creativity is usually seen as the starting point for the design process—its efficacy is reduced if innovation is absent: the product remaining in a vacuum if the design has little relevance to functionality or purpose—a case of "style over substance".

Innovation on the other hand can mean that the substance can override style (not always necessarily so) as the design matches the desired purpose as defined by users of the product. In this case, we can state that substance overrides style (for example the low cost Ford Model T opened up the motor vehicle market through innovative manufacturing processes albeit it was not as beautiful as a very expensive Hispano-Suiza). Already the introduction of innovation can come into conflict with that intangible and highly subjective term, "style"; has anybody really defined what "cool" means?

Good design often involves a combination of creativity and innovation where each component mutually re-enforces and stretches their different intellectual, artistic and functional inputs, with innovation seeing the realisation of the ideas. In this instance, the end design should be made up of both substance and style.

Finally, substance and style can be all for nothing if a suitable business model to underpin execution of the designed product into the market place is not integrated into the design process. Both conceptual designers and academics, which tend to reside at the creative end of the spectrum need to engage continuously with practitioners and of course end users, operating at the innovation/execution end (and indeed vice versa) if the design outcome is to be commercially and functionally successful. Hence, the acknowledgement of and the addition of execution to the design process—more so as in many organisations, on-going operations, the here and now, can conflict with longer term intangible activities such as innovation.

2 Part II—Uncertain Problems

2.1 Design as an Unstructured Problem

Design is a discipline that embraces substantive and quantitative methods, and has much in common with the wider discipline formerly known as Operations Research (OR). However, not all problems are the same in structure and have different inputs and outcomes—there is a dichotomy to problems (Rosenhead 1996). Design and OR have had to address similar issues and confront similar orthodoxies.

In the last quarter of the last century traditional OR orthodoxy was challenged as it appeared to concentrate on tackling well-defined problems—and that the standard techniques used assumptions based on relevant factors, constraints being established in advance and consensual.

Many aspects of our highly interconnected and socially complex arrangements, in the absence of analytic inputs, operate, if at all, only ineffectually or with unreasonable waste of effort. It is this concern that encourages and justifies the use of problem structuring methods. There is a notable distinction between tame versus wicked problems (Rittel and Webber 1973), problems versus messes and puzzles (Ackoff 1981) and "moon ghetto problems" (Nelson 1974). All these authors concluded that the methods for problem handling appropriate to pacified conditions do not transfer to more turbulent and problematic situations (Rosenhead 1996).

The best way to understand what Rittel and Webber meant by a "wicked problem" is to understand what a tame problem is. A tame problem can be characterized as follows: (Ritchey 2005).

- It has a relatively well-defined and stable problem statement.
- It has a definite stopping point, i.e. we know when a solution is reached.
- It has a solution which can be objectively evaluated as being right or wrong.
- It belongs to a class of similar problems which can be solved in a similar manner.
- It has solutions which can be tried and abandoned.

Wicked problems are completely different. They are ill-defined, ambiguous and associated with strong moral, political and professional issues. Since they are strongly stakeholder dependent, there is often little consensus about what the problem is, let alone how to deal with it. Above all, wicked problems are not stationary: they are sets of complex, interacting issues evolving in a dynamic social context.

The next level down is what Ackoff calls a *problem*. This is an issue that does have a defined form or structure; it is dimensioned; it has variables and we know something about how these variables interact but it does not have any one, single, clear-cut solution. As long it is a problem—in Ackoff's use of the term—it has many different, alternative solutions "depending on", for example: what resources are available; what type of technology is going to be available; what materials are best suited for the purpose.

Finally, we have what Ackoff calls a *puzzle*. A puzzle is a well-defined and well-structured problem with a specific solution that somebody can work out: the most concise definition being said by Michael Pidd (1996).

> "One of the greatest mistakes that can be made when dealing with a mess is to carve off part of the mess, treat it as a problem and then solve it as a puzzle – ignoring its links with other aspects of the mess."

In the last quarter century Rosenhead (2001) has attempted to bring together a set of "softer" OR methods called Problem Structuring Methods so that decision makers will be more likely to use a method and find it helpful if it;

> " …accommodates multiple alternative perspectives, can facilitate negotiating a joint agenda, functions through interaction and iteration, and generates ownership of the problem formulation and its action implications through transparency of representation."

Rosenhead states that lay people can generally express their judgments more meaningfully by choosing between discrete alternatives rather than across continuous variables and estimating numerical probabilities which in turn gives way to identifying relevant possibilities often in the form of alternative scenarios.

2.2 Uncertainty In Design

The transition from creativity to innovation to execution (CIE), can reflect a movement from uncertainty to risk and from the contextual (external) through to the strategic (internal) response. C&I are inherently characterised by high levels of *uncertainty* both in terms of the inputs into the creative process and the resulting outputs at the innovation stage. Uncertainty, as opposed to risk, significantly reduces the efficacy of quantified methods with their inherent assumption of causality. It cannot be assumed that we know all the characteristics of an idea that will have a high probability of becoming a successful innovative application, as unintended outcomes are forever present.

A brief examination of the semantics involved shows that: *Certainty* occurs when it is assumed that perfect information exists and that all relevant information to a problem is known. *Risk* on the other hand indicates that partial information (usually metrics), is available and in many cases is probabilistic so that when future events or activities occur they do so with some measure of probability.

Uncertainty implies incomplete information where some or all of the relevant information to a problem is unavailable. Uncertainty can also be explained as being a situation where the current state of knowledge is such that:

- The order or nature of things is unknown.
- The consequences, extent or magnitude of circumstances, conditions or events is unpredictable,
- Credible probabilities to possible outcomes cannot be assigned.
- A situation where neither the probability distribution of a variable nor its mode of occurrence is known.

Whilst Risk can be quantified (via probabilities), Uncertainty cannot, as it is not measurable. However, very many people, still confuse the two, which has led to the premature use of quantitative methods and where a more qualitative evaluation would be of great use. This distinction is crucial, since the appearance of precision through quantification can convey a validity that cannot always be justified. The diversity of outcomes that might occur has to be embraced if we are to mitigate the impact of future events whether or not they have emanated as unintended consequences of past actions, or from situations over which we have no means of controlling.

The states of uncertainty and risk are not discrete—represented, as it were, by a sliding scale from Genuine Uncertainty though to Risk based on high levels of probability and on to (near) Certainty. Quantification and measurement in turn should not be treated as existing or not in such discrete domains. As we proceed further to the uncertain end of the spectrum probable outcomes are reduced to being only possible outcomes and where information, especially in its (metric) quantitative form becomes increasingly unavailable and/or not relevant.

Whilst too much uncertainty is undesirable, manageable uncertainty provides the freedom to make creative decisions. In the right hands and with foresight, the ability to address uncertainty can excite the designer and create competitive advantage when the time comes to deliver (or execute) the idea into the market place.

2.3 Understand Uncertainty—Understand Your Design Options

2.3.1 Certainty and Its Limits—Uncertainty and Its Opportunities

Whether we like it or not, people are required to make decisions based on insufficient, incomplete, or minimal data,—not to exclude the impact of “fake” data! This is an extremely uncomfortable place for decision makers (including designers) to be, and organisations and individuals within the organisation will go to great lengths to avoid making a decision under such circumstances. It would appear that the more information we have access to, the more fearful we are when required to make a decision where data is incomplete or absent altogether. The design process largely begins under such conditions. Yet early stage design can exist and thrive in this space and is indeed part of its nature and subsequent evolution.

The following dictum best summarizes how to position uncertainty;

> " ………precision and the future are incompatible terms. In essence it is far better to be approximately right than precisely wrong" (John 2007).

Much of the more contemporary dialogue as to the uses and abuses of the scientific method and its ability to address "uncertainties" stems from ideas postulated by Funtowicz and Ravetz in the early 90s (drawing upon earlier dialogues between schools of thought developed by Popper (1959) and Kuhn (1962). Funtowicz and Ravetz (1994) focused on the quality of the scientific inputs to the policy process as being problematic.

> " The interaction of systems uncertainties and decision stakes can be used to provide guidance for the choice of appropriate problem solving strategies. When either or both are high, then mission-oriented applied science and client-serving professional consultancy are not adequate in themselves, and an issue-driven post-normal science is necessary."

They go on to state that "systems uncertainties" can be interpreted as meaning a problem is less concerned with the "discovery of a particular fact (as in traditional research), but with the comprehension or management of a reality that has irreducible complexities or uncertainties".

2.3.2 Profiling Risk and Uncertainty

An organisation and its stakeholders, including designers, will be confronted with, and be required to address, a wide range of different strategic and operational outcomes or events—some as a result of their own internal actions (including past actions) and some as a result of externally imposed conditions—the contextual environment. As we have seen with the analysis of problems, there are also various forms of uncertainty and risk, often with occluded boundaries. Two axes represent event status:

1. Event Predictability
2. Event Visibility

These two axes generate a 2 × 2 matrix with the following event states:

- predictable & identifiable.
- predictable events not yet identifiable.
- unpredictable & identifiable.
- unpredictable & not identifiable.

For design purposes one can enquire 'how radical a design is one prepared to contemplate'? It is however those outcomes identified above as being largely in the fourth category and partially in the third and second categories that cause organisations real or "practical" uncertainty. Being difficult, if not impossible to quantify—the lack of metrics causes discomfort and dissonance. Aphorisms such as "if you can't measure it you can't manage it", remind decision makers of their own fallibility—an uncomfortable realisation. Dissonance triggered by—"pseudo black swan" events and learning to "think about the unthinkable" forces decision makers to confront the zone of uncomfortable debate. It is also the area where theoreticians and practitioners (including implementers) can offer different perspectives as to desired outcomes.

How can issues of problem definition and uncertainty be tackled and mitigated?

3 Part III—Structuring Problems Under Uncertainty

3.1 Problem Structuring Methods (PSMs)

Design of an object, system or idea, can be seen as being a problem waiting to be structured: in effect *at inception design is an 'unstructured problem'*. Risks in the design process include the designer being overly prescriptive and subjective, at the initial conceptual phase of the process. A problem structuring approach throughout the process but particularly at project inception, can facilitate the design process by reducing the number of "blind alleys" the designer may be induced to follow.

Into this complex arena both Problem Structuring (PSMs) and Decision Support Methods (DSMs) can be used to facilitate the integrated CIE process through to effective execution and mitigate the risk of failure. However, the different phases of transition from creativity through to execution impose constraints on the types of models which best serve decision-making. At the creative, (most uncertain), end of the spectrum, qualitative approaches are more applicable, whereas for execution the introduction of more causal, quantitative methods can be applied as well. The innovation to execution phases is likely to require hybrid (a mix of qualitative and quantitative) methods.

Such complexity is a problem for practitioners, be they inventors, entrepreneurs, knowledge transfer specialists, investors and of course designers of all shades. The problem is that no one method or tool is sufficiently robust to help the decision-making process when faced with uncertainty (and risk). Some of these methods are relatively easy to grasp, leading to wide adoption by numerous practitioners. Unfortunately many of them only address part of the problem. When applied discretely they can appear to be over simplistic and not address the high levels of complexity, interconnectivity and uncertainty inherent in the problem space. The situation is exacerbated exponentially when multiple criteria and parameters have to be addressed. There is a tendency to treat problem structuring and problem resolution in isolation, as puzzles, (Russell 1974) falling into the trap expressed earlier by Michael Pidd.

The inherent complexity of integrating current models and methods should not necessarily act as a deterrent since such complexity, although a challenge for practitioners, outweighs the dangers of using overly discrete methods to solve problems in the areas of uncertainty and risk. It may be that concepts such as "Fuzzy Management", which recognises that we live in an occluded world, can help smooth the route from theory into performance enhancing practice. Grint (1997) As identified earlier it is often better to be approximately right than precisely wrong!

Faced with a plethora of decision support methods and tools,[1] and their intermittent and patchy uptake by even specialist practitioners, design and business academics have an important methodological role in formulating different paradigms, which can be readily applied by the practitioner community. O'Brien (2010) Such frameworks need to encourage practitioners to become both more aware of the availability and relevance of methods and more crucially how their introduction and application can enhance business performance.

3.2 General Morphological Analysis (GMA)

3.2.1 Reducing the Problem Space into a Solution Space

One of the methods which fits our criteria for modelling uncertainty, especially, when dealing with large amounts of intangible data, and that can be updated and modified in real time, is a computer enhanced form of Morphological Analysis (MA) incorporating strong facilitation with "stretched" teams of multi-disciplinary experts—called General Morphological Analysis (GMA) (Ritchey 2011).

The activity of design begins as an unresolved and unstructured problem and goes on to initiate exploratory creativity. General Morphological Analysis (GMA) is a key PSM method that can improve the effectiveness of the idea and concept generation phases within the design process.[2] Generating concepts from a morphological matrix began over 50 years ago, pioneered by the Swiss astrophysics professor Fritz Zwicky (1898–1974), whilst at the California Institute of Technology and is still used today as an important step in the engineering design process.

This form of Morphological Analysis straddles the fence between "hard" and "soft" scientific modelling. It is built upon the basic scientific method of going through cycles of analysis and synthesis and parameterising a problem space. It defines structured variables, and thus creates a real, dynamic model, i.e. a linked

[1]The author's current research has identified in excess of 500 decision support methods and tools …and counting!

[2]Conceptual Design Using a Synergistically Compatible Morphological Matrix Richard G. Weber, BEI School of Engineering, Fairfield University, Fairfield, CT-06430 Sridhar S. Condoor, Department of Aerospace & Mechanical Engineering, Parks College of Saint Louis University Saint Louis, MO-63103.

variable space in which inputs can be given, outputs obtained, and hypotheses ("what-if" assertions) made.

GMA can help us discover new relationships or configurations, which may not be so evident, or that might have been overlooked by other, less structured, methods. Importantly, it encourages the identification and investigation of boundary conditions, i.e. the limits and extremes of different contexts and problem variables. It provides a structured environment within which to handle Uncertainty (and even Genuine Uncertainty).

In a morphological model, there is no automatically designated driver or independent variable. Any parameter—or set of parameters—can be designated as such. Thus anything can be an input and anything an output. For instance, instead of simply letting a scenario stakeholder define a relevant strategy, one can reverse the process and let chosen states within a proposed strategy configuration designate relevant scenarios. This is the basis of an inference model: given a certain set of conditions,—what is inferred with respect to other conditions in the model?

Being able to define any combination of conditions as inputs (and indeed outputs)—even mixing external and internal conditions—gives morphological models great flexibility. The "what if" functionality makes the model an extremely powerful tool, for not only looking at a wide array of possible outcomes, but through computerization, enables management and researchers to examine alternatives in real time.

A central feature of morphological analysis is the flexibility it provides to parameterize a problem complex, acting as scene setter for other decision support methods. In this case, the results of a morphological model can provide input for the development of other (possibly more complex) models such as Bayesian Belief Networks (BBNs) and the Multi-Criteria Decision Analysis (MCDA) where possible outcomes derived via a GMA exercise can be compared according to a hierarchy of goals and goal criteria, providing validated inputs for scenario planning exercises.

When supported by Cross Consistency Assessment, GMA is a method for rigorously structuring and investigating the internal properties of inherently non-quantifiable problem complexes. It encourages the investigation of boundary conditions and empowers practitioners to explore a wide variety of contrasting configurations and policy solutions. As a method for identifying and investigating the total set of possible relationships or "configurations" contained in a given problem complex GMA's primary task is to generate ideas with the aim of generating as many opportunities as possible.

Morphology supports the designer in organising alternative solutions for each function of a system and then combining them to generate a large number of solution variants each of which can potentially satisfy the system-level design need.

Apart from singling out the most important dimensions of specific problems it also allows for the examination all the relationships between them. It is an exploratory approach and attempts to identify opportunities (or possibilities) and allow the user to "structure" a problem rather than solve it and why it can be classified as being a Problem Structuring Method (PSM).

This method does not replace creative thinking but allows for structured means for developing and documenting, design alternatives, without confining them to human short-term memory limitations. It is particularly suitable to input by small groups of experts but who are "managed" by an independent facilitator to overcome overly subjective and single stakeholder points of view. This approach is of particular relevance for practitioners who often have to manage change within their organisations for a diverse array of stakeholders—some of whom may not have a design heritage.

The approach begins by identifying and defining the dimensions (or parameters) of the problem complex to be investigated, and assigning each of these a range of relevant "values" or conditions. Each cell of the parameter space contains one particular value or condition from each of the parameters, and thus marks out a particular state or configuration of the problem complex.

3.2.2 Yes, but…!

Whilst an excellent concept for generating (thousands of) ideas derived from multiple dimensions or parameters it does create a practical problem of how to analyse all the configurations generated by the model.

The solution is to reduce this vast number to examining "… the internal relationships between the field parameters and to reduce the field by identifying, and weeding out, all mutually contradictory conditions" (Ritchey 2011). This is carried out for each matrix by an exercise called Cross Consistency Assessment (CCA), where all of the parameter values in the matrix field are compared with one another on a pair-wise basis—similar to a cross impact matrix. As each pair of conditions is explored a judgement is made to see if the pair can co-exist. Note that it is important to understand there is no reference to causality—only to mutual consistency. Via this process a typical morphological field can be reduced by well over 95 % internally consistent outcome strings.

The outcome is a matrix converted from a problem space into a "solution space" and as highlighted earlier, becomes an interactive inference model where any parameter or state, can be selected as an input and any others as an output.

It is to be noted that the modern manifestation of morphological analysis as developed by Zwicky was used almost exclusively for engineering purposes in the jet engine sector where he sought to use his version (GMA) to explore alternative types of propulsion based on different parameters such as thrust mechanism, oxidizer, and fuel type. Ayres (1969) illustrates the use of GMA when studying electric motor configurations and shows how it can identify opportunities, which had previously been overlooked. He goes on to present numerous other engineering applications such as a morphology of combustion engines, and for a high-speed underground transport system.

Many practitioners, although admiring the concept, have been put off from using the method more extensively due to the potential for producing vast quantities of outputs and the paucity of readily available software to synthesize this data. The use of CCA as a device to reduce the large problem space configurations is not widely known—having been originally developed within the constrained environment of a Defence establishment for policy option purposes, rather than industrial design applications. However, it has been largely from a recent design engineering academic standpoint that the method has been "re-discovered" as being highly applicable within the gamut of methods of value for both design in general and as a valid research tool within design research.[3] More specialist practitioners[4] are engaging with a wider variety of business sectors—including design engineering—to proselytize these methods, whilst working in conjunction with academics to research and develop new methodological variants.

Recent research involving a team of specialists at Imperial College in the area of safety helmet design provides a useful insight how a multi-variable and complex problem can use GMA to provide clarity and direction for downstream research.

3.2.3 Case Study

The research team of three specialists was facilitated in the use of morphological analysis by initially agreeing on a focus question, identified as being:

> "What are the main factors that contribute to better protection of the head during a motorcycle accident?"

During a series of both offline and group facilitated sessions the team established that the problem was broken down into two core components—Impact Conditions and Helmet Design. In turn the main focus question was divided into two supplementary questions, each relating to one of the two core components. Thus for Impact conditions the team agreed that: "Given the impact conditions what type of head injury is likely to occur?' and for Helmet Design: "What are the material design components of the helmet that mitigate/prevent this type of head injury?"

In other words the essence of the focus question was to determine what helmet designs were preferable subject to different types of impact in an accident. It was seen early on that it was unlikely that one discrete solution would suffice to offer protection under all conditions, and thus by breaking down the problem into a series of parameters the scale of the problem was addressed—albeit that subsequent analysis would be required to progress product design for helmets. Crucial to the exercise was identification of those scenario configurations which were internally consistent and which in turn would help the research team in not pursuing unworkable design paths that might manifest themselves further into the design process.

The problem space relating to "Impact Conditions" is shown below as item 1.

[3]The Innovation Design Engineering (IDE) double masters programme, run jointly by the Royal College of Art and Imperial College London.

[4]Such as Strategy Foresight Partnership LLP at www.strategyforesight.org.

Impact conditions					
Relative impact velocity (km/h)	Impact site/type	Body impact angle	Multiple impact	Shape and composition of opponent object	Type of head injury
0–10 km/h	Normal-front	0° upright	2 hits	Flat–soft	Skin damage
11–20 km/h	Normal-side	30°	3 hits	Flat–hard	Skull fracture
21–30 km/h	Normal-rear	60°	4+	Cylindrical-soft	Haemorrhage (rupture of bridging veins)
31–40 km/h	Normal-crown	90°		Cylindrical-hard	Contusion (damage to the surface of the brain)
41–60 km/h	Oblique-front				Concussion (mild TBI)
61+ km/h	Oblique-side				Diffuse axonal injury
	Oblique-rear				
	Oblique-crown				
6	8	4	3	4	6
					13824

The problem space relating to the Helmet Design was determined as item 2.

Helmet design					
Type of head injury	Shell	Liner	Retention	Visor	Overall mass
Skin damage	Polycarbonate	Aluminium Honeycomb	Chinstrap	Full face + hinge	0–2 kg
Skull fracture	ABS	EPS	Jaw padding	Full face visor only	2–4 kg
Haemorrhage (rupture of bridging veins)	FRC	PV	Neck brace	Open Face	4–6 kg
Contusion (damage to the surface of the brain)	Ceramic	Cardboard	Whiplash strap		6+ kg
Concussion (mild TBI)		Nothing			
Diffuse axonal injury					
6	4	5	4	3	4
					5760

This two-tier representation, and based on facilitated input by the team of experts, established that there were five parameters in each of the two matrices with an additional LINKING parameter attached to each matrix and which addressed a specific issue in the focus question: the type of head injury to be mitigated according to both impact and design of the helmet.

Item 1 identified an overall problem space of 13824 unique configurations whilst item 2 identified an additional 5760 configurations. If we had combined all 11 different parameters (5 + 5 + 1) then the combined number of configurations in the model would rise to over 1.37 million configurations.

The question still remains though of 'how are the possible solutions from the GMA exercise, which may still run hundreds of internally consistent outcomes, processed so that a preferred list, or hierarchy, be determined'?

The process the research team was able to adopt, was to reduce initially the Impact Conditions problem space to a much smaller solution space, using proprietary software made available over the web and employing newly developed cross-impact algorithms. The solution space identified a much reduced set of configurations or scenarios where different forms of Head Injury were the output.

A second exercise was run for the Helmet Design problem space which also reduced the problem space to a small number of internally consistent configurations.

As both sequences had a common parameter—Type of Head Injury—the team was then able to match viable outcomes from each of the two components—Impact Condition and Helmet Design—using the software scenario list to establish those configurations which could work.

3.3 Multi-criteria Decision Analysis

Other multi-criteria methods can be introduced clustered under the category of Multi-Criteria Decision Analysis (MCDAs).

MCDAs process subjective and personal preferences of an individual or a group in making a decision. With these methods, hierarchies or feedback networks are constructed, then judgments made on pairs of elements to derive ratio scales (similar to the pair-wise approach in CCA). These judgements are then synthesized throughout the structure to select the best alternative. Small group facilitation is again applicable here and although judgements can be made by any one individual, a consensus driven approach based on a heterogeneous group structure will yield a more rounded and objective response. The keyword here is heterogeneity in that a group made up of individuals within the same function or any other identifiable homogenous subgroup, could be subject to "group think". In this respect, the nature of the participants in the decision process is very similar to GMA and can consist of the same team for continuity purposes. On the other hand it could be that a more policy driven team is better positioned to carry out this stage of the task.

MCDAs such as AHP work by developing priorities for alternatives and the criteria used to judge the alternatives and are particularly suited where only qualitative criteria are suitable. First, priorities are derived for the criteria in terms of their importance to achieve the goal, followed by priorities for the performance of the alternatives on each criterion.

The process of prioritization solves the problem of having to deal with different types of scales, by interpreting their significance to the values of the user or users. Finally, a weighting and adding process is used to obtain overall priorities for the alternatives as to how they contribute to the goal. There is a danger here that certain practitioners of the method will interpret the weighting in purely discrete terms. This is erroneous as the method really aims to identify "relative" differences between criteria rather than absolute differences. With MCDAs a multi-dimensional scaling problem is thus transformed to a single dimensional scaling problem.

3.3.1 Facilitation: A Vital Component in the Process

The introduction and use of decision support models into the process alone will not ensure satisfactory results. All models are subject to constraints imposed by the real world—particularly individual and organisational behaviour. Both GMA and MCDAs are methods suited to collective concept exploration creativity and the development of collective understanding of complex problems (Ritchey 2011).

Groups bring together actors and stakeholders with differing viewpoints, helping to develop new designs for products and services (Schwarz 2002). However, arguments from dominant personalities in the group can distort the group's effectiveness by reflecting overly subjective viewpoints and hence nullify a consensual approach.

It is for this reason that the group be facilitated. The facilitator will help the group increase its effectiveness by acting as a neutral participant particularly where problems are of a complex nature.

The composition and behavioural profile of the group being facilitated is important. Each of the members of the group should be subject matter specialists in their respective area, come from heterogeneous backgrounds and where duplicate competences are kept to a minimum in order to avoid "group think". Ideally, the project group should be brought together physically in one place for as long as possible (body language of participants can provide the facilitator with powerful non-verbal signals as to the group's effectiveness and how it is working).

However, it is acknowledged that time away from formal positions, geographic dispersal of selected participants as well as the potential open-endedness of workshops, are operational constraints and can act as barriers to bringing a group together in a formal setting. Such issues are especially dominant for practitioners who have a diverse range of work pressures to manage.

Other facilitation approaches do exist and allow for dispersed facilitation to take place such as IBIS (Issue-Based Information Systems) and the Delphi (Linstone and Turoff 2002) method (and its real-time variant)—the proviso being that such devices should not degrade the methodological integrity of the particular model being used. Within the design domain "designVUE" (a variant of IBIS) is particularly suitable as a dispersed facilitation dialogue tool as it addresses both individual and collaborative design practice. The application has been enhanced to provide support for a range of design and engineering information processing activities including requirement capture and justification, design rationale capture, functional modelling and decision making.

3.3.2 Applications

In addition to the case study discussed earlier, GMA in the generic form highlighted here has been employed in well over 150 projects—a mixture of Public and Private sector, and more academic projects. There is a greater awareness of MCDAs by practitioners (O'Brien 2010) partially due to a range of commercially available software such as Decision Lens, Expert Choice, and Macbeth.

Interpreting design in its widest sense—this form of the method has been used in a number of specific product design scenarios particularly within the Swedish Armed forces including Army boots, future submersible systems, ground target systems, new styles of infantry soldiering.[5] Security and confidentiality requirements mean that we can only identify the projects and their titles for wider publishing circulation purposes.

A number of exercises have taken place concerning organisation design and re-design and at a more generic level for policy design and evaluation. The authors are currently carrying out further research using such methods in the area of Safety Helmet Design, an earlier position paper already having been published (Garvey and Childs 2013).

However, it is acknowledged that use of each of the main methods discussed in this document, GMA and MCDAs are not widespread in the broader operational research (OR) practitioner sphere, let alone within the sector confines of Design (O'Brien 2010; Stenfors et al. 2007).

The mixing and linking of methods described above, although part of a logical sequence to narrow down decision choices, are even rarer, with most methods and tools being used discretely to tackle what, in effect, are 'puzzles'. Little evidence is available in either the academic or practitioner domains of integration of methods to create a decision path process. This can partly be explained as a reflection of the academic position ensuring that scientific rigour and high levels of empirical research are maintained, whereas such enquiry is deemed too narrow for the "messier" landscape experienced by practitioners (Posner 2009). On the other hand practitioners seek ease of use and visible functionality when addressing complex problematical issues.

It can therefore be argued that the relevance of use and application of such methods, whether individually or linked as part of a process, is less to do with the efficacy of the methods but more to do with awareness and ease of use and operational resource constraints. The danger of course of such behaviour is of starting

[5]The full titles of the defence related research reports can be seen at www.swemorph.com.s

out in the wrong place leading downstream to negative unintended consequences of earlier actions which could have been avoided.

4 Part IV—It's no Good if Nobody Wants It!

4.1 Designing for Success—in Search of the Lost Relative

Govindarajan and Trimble (2010), see that the greatest challenge to innovation is execution—due in part to the latter being seen as a given, which it rarely is, and the other that execution is as much to do with meeting basic performance targets—whether financial or not. In order for there to be an effective transition from innovation to execution they identify a number of areas that challenge innovation myths, if innovation (along with creativity) is to lead to successful market acceptance. These issues include:

- Do not assume that following the innovation process that execution will be simple.
- Innovation initiatives of any significant scale require a formal and intentional commitment of resources—innovation does not occur organically.
- Innovation is incompatible with on-going operations and cannot be embedded within an established organisation as it will come off second best when subject to short-term operational constraints (internal or external).
- Innovation cannot be isolated from on-going operations and requires mutual engagement—maybe an upstream creative function can exist as a "skunk works" but innovation cannot—it is the precursor to execution and has to accept that it is responsible for a certain level of understanding about the execution process.
- Innovation needs to be carefully managed as it is more constrained by end user demands that manifest themselves at the execution stage (c.f. creativity).

However, one key area that is often overlooked and can lay claim to applying the term innovation, whilst supporting earlier design related forms of creativity and innovation, includes adoption of the right 'Business Model'.

4.2 Business Models

Great designs and ideas can come unstuck if a suitable business model is not adopted to exploit innovative design. To stress the importance of an awareness of the business model the examples below highlights how quality products have been impacted by competitors having superior ones, albeit that product design is of poorer technical quality.

Anecdotal examples of acknowledged superior technology failing to capitalise on their technical design superiority due to business model deficiencies (aka Execution) include, amongst others, Betamax versus VHS, the lossless TIFF compression algorithm versus the lossy JPEG, the GUI superiority of the Apple operating system versus Microsoft (both taking powerful elements of Xerox—Palo Alto Research Centre—originated technology—which in turn failed to take advantage of its earlier xerographic business model) (Smith and Alexander 1999). Microsoft's original business model was to offer not hardware but its MS-DOS software to third-party equipment manufacturers (initially the IBM PC). This gave it the volume distribution edge over many of its proprietary combined hard/software rivals.

Conversely, we see that when product design technology excellence is combined with an "innovative" business model the outcome for young organisations can be ground-breaking, as witnessed by the technologically advanced xerographic plain paper printing and copying machines. Advanced most certainly, but it was the decision to sell what had generically been seen as a capital item through a basic rental and click-charge usage scheme that allowed Xerox to dominate the market for so many years as the purchase sign-off for a rental was much lower than for an outright purchase basis thus facilitating astounding market penetration.

The importance of the business model within the execution phase has been highlighted by Chesbrough and Rosenbloom (2002), where they initially contrast how the business model concept differs from that of strategy, namely: " a business model performs two important functions: it creates value, and it captures a portion of that value. It creates value by defining a series of activities from raw materials through to the final consumer that will yield a new product or service with value being added throughout the various activities. The business model captures value by establishing a unique resource, asset, or position within that series of activities, where the firm enjoys a competitive advantage." One can add to the last quoted sentence that one of those activities is design.

Chesbrough and Rosenbloom identify a number of components characterizing the business model including "The Value Proposition"—where the client problem is identified and how the product addresses the problem so that an assessment of the product value can be made from the client's point of view and "Competitive.

Strategy"—how can the company develop and achieve competitive advantage (e.g. price, distribution differentiation, etc.). Both these components contain powerful dependency on good design.

Design can address these issues (amongst others), by introducing modular design principles around a central core to allow the product offering to be altered according to different market segment needs (for example hand electric drills with add-on components for a variety of purposes and the earlier Xerox product range via refurbished upgrades using the same shell).

Creativity and innovative design of products (and indeed services) need to address those implications of design able to embrace these components and in a way allowing for flexibility and adaptability as manufacturing resources allow and market circumstances change and evolve. Failure to do so can lead to major performance and market penetration risks when the time comes to bring the product to market.

5 Concluding Comments

Many disciplines can obtain greater insight (as well as foresight) by engaging with other disciplines, often, at first glance having no apparent points of commonality. The potential benefits of such cross-fertilization have attracted numerous forms of description, such as symbiosis, serendipity—some of the new relationships and combinations come from structured methods other from unstructured ones. The approach in this chapter has been to illustrate a more structured approach when exploring both intangible problems and high levels of uncertainty when applied to the design domain.

Design and in particular its problem facing branch—Design Research, can gain from an examination of methodologies, methods and frameworks used in other disciplines such as Operations Research and indeed vice versa.

The multi-criteria nature inherent across the Design/CIE spectrum is readily suited to the application of Problem Structuring Methods such as General Morphological Analysis and Multi Criteria Decision Analysis. Such method integration allows for the condensing of a great many ideas—generated at the creativity stage to be filtered down into a much smaller list of internally consistent outcomes, and then positioned into a preferred hierarchy (via Multi Criteria Decision Analysis) prior to being assessed according criteria which will enhance execution and end user acceptance.

Such is the prevalence of “complexity” within the broader design process, that organisations and their design teams can be exposed to high levels of unintended consequences, particularly if “all relevant” factors concerning a decision are not addressed with suitable diligence. It is also hoped that the multi-method approach presented in this paper will encourage other academics and practitioners to explore complex decision support issues.

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Executing Distributed Development in Industry and the Influence of Design Research

Jöran Grieb and Christian Quandt

Abstract This chapter looks into distributed development in industry and the question of the influence of design research. The authors describe an example of distributed development in praxis and discuss the connections to design research. Thereafter the communication and transition of insights between industry and academia in general is discussed. Besides already successful cooperation the authors identify room for improvement and propose to deliberately consider the three different roles of "academia," "industry partner," and "industry consumer" when setting up information exchange or joint research projects consisting of members from industry and academia.

1 Distributed Development Over Two Locations—an Example from Praxis

The example from praxis discussed here comprises an enterprise which is developing and producing products for end customers and is practicing distributed development over two locations. The example can be described in the following way (Fig. 1): The headquarter of the company is located in country A, the factory, where technical appliances are build, is located in country B. The central development is located in country A. It is closely linked to the company headquarter. The series/factory development is located in country B. It is closely linked to the factory where the products are built. The development of appliances is distributed over these two countries.

New development projects are developed by the central development with the support of series/factory development. If the new project becomes a series project,

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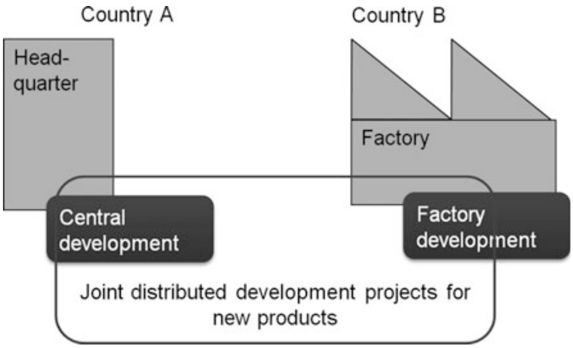

Fig. 1 Set up of the example of distributed development over two locations

the development for this project is completely shifted to the series/factory development. During the phase of new development, there is an intense cooperation between central and series/factory development and the development work is strongly distributed over both locations.

As described in literature, the distributed working leads to significant challenges regarding the coordination of work, the potential of conflicts and problems in communication, e.g., (Larsson et al. 2003). In fact we believe that these challenges of distributed development appear in nearly every development process, which involves more than a handful of people, even if the effects are weaker than in locally distributed teams.

2 Communication Is Supported by Sketching and Organization

There are several aspects which need to be considered for a successful implementation of distributed product development. As already stated in (Kristensen 2004, p. 20) team members are forced to extend the use of computer-based communication media since personal meetings are very time consuming and expensive.

Apart from the generally known communication techniques (email, telephone, etc.) we identified two important aspects for a successful communication in distributed design. These are the communication media (with a focus on computer-based sketching) and the organization and structure of the product data (with a focus on thinking in functions).

If communication and organization are not sufficient, it could happen that designers on the far location work on old data, work on the wrong data, or work on the right data, but misunderstand their task. If the worst comes to the worst this is not realized in time.

Sketching is a very important communication media in design, because sketching is the best communication tool to support the discussion of 3D-models or conceptual solutions in product design.

Another very important aspect is the organization and structure of the product data. It is very important that there is a common understanding of how the data is stored and organized. Everyone needs to understand and respect this organization. A proven approach is to structure the data in one root assembly. This root assembly has to be established as the only valid source and storage of engineering product data, e.g., by always referencing to this data in official meetings. A reasonable structure of this root assembly appears to be important to support the acceptance and facilitate the use of the root assembly. This structure needs to be complete and consistent to prevent misunderstandings and create a standard over different products. The best way to do this is by thinking in functions. The parts change through time and projects, but the functions (generally) stay the same.

In our example we use electronic whiteboards with application sharing for the communication via sketching and one 150 %-Root Assembly for each Project, which is subdivided in functional units for structuring the product data. The functional units are the same in every project and every system that is handling the data. 100 %-Assemblies for certain variants are derived from this master assembly. These measures are improving the distributed development process from our example significantly.

3 Links to Design Research Considering Communication in Distributed Development

We see links between our example from praxis and the area of design research in the fact that our key aspects from praxis are widely known topics in design research and show several connections to research outcomes. Distributed development is an important research and practical area! The key issues communication and organization/structuring that we identified as critical are both covered in the area of design research.

The first link to the area of design research is that distributed development itself, as well as sketching as a communication media in distributed development is seen as a research area and there are several publications. (Luczak and Eversheim 1999, p. 47) state that communication is the basic success factor in distributed development and (Hoffmann 2000, p. 31) emphasizes the importance of powerful communication media. (Abramovici et al. 1998, p. 70) regard computer supported communication as essential in distributed product development. (Ruiz-Dominguez et al. 2004) analyze the effect of communication media on the efficiency of development processes. (Lindemann et al. 2001) describe sketching as a very important communication tool in the area of technical work, (Milne 2005) identifies sketching as one of the critical communication paths in distributed development teams and (Grieb 2007) emphasizes this especially during conceptual design phases.

Moreover our second topic, the functional thinking and structuring, is an important area of design research. (Schlichter et al. 2001, p. 6) state that coordination is a very important aspect of managing group activities. Several authors describe the thinking and structuring of products according to functions as a reasonable approach in product development processes. E.g.: (Pahl and Beitz 1993, Ehrlenspiel 2007, Lindemann 2007), etc. Even if the connection to distributed development is usually not the first focus, the methods and tools developed in the area of functional thinking are particularly helpful here.

Another topic that links design research and praxis is the question how the knowledge about helpful tools and methods was transferred and implemented in praxis. It is not routine that normal designers from product design read scientific publications or participate at conferences to achieve this knowledge.

Referring to our example the aspect of sketching in the development department was strongly supported by a tool. Electronic Whiteboards were purchased and installed in the design environment. Additionally, the use of these tools was supported by a concept to implement them in distributed meetings. This consisted of an experienced person who trained the efficient use and implemented the tool use in the distributed design processes and management attention regarding the use of this tool.

The transfer of the aspect of organizing and structuring according to functional thinking was transferred by people, who had been in contact with design research and implemented these insights out of their knowledge of research findings. Since it was necessary to transfer these insights to more participants within the company, the knowledge was transferred in the form of workshops and presentations, again by people as a route. Therefore it was necessary to change the information. The information needed to be on a more concrete level and fitted to the company and the use case by an expert of design research. This transformation of the information to company level was very important to enable the efficient use and implementation of the design research findings in the company.

Even if the implemented topics led to a significant improvement of the distributed development process there are still a lot of open issues and desires to further improve the process. We could imagine that these kinds of concepts reach an even higher level of quality, lead to better communication and further enrich the support of distributed development in the future.

An important aspect is to develop the communication via sketching to a synchronous 3D-Modeling which could be used in meetings to support especially the design work. The conventional sketch has the disadvantage that it exists only in two dimensions. The discussed product models have three dimensions. Additionally, the sketch is strongly dependent on the sketcher and has to be supplemented with comments. If it is not commented there is a high probability for misunderstandings.

The next step after sketching could be a real-time modeling in 3D during the meeting, which is based on direct modeling (without parameters). The abstinence of parameters would ensure an easier and quicker use. The parameters are not necessary, because all the information is in the geometry. There is no history and the geometry created in the meeting on the fly is easy to separate from the “designed” geometry. The meeting geometry is kind of a 3D-Sketch just for communication and there is of course still the need to redesign the geometry parametrical if the discussed changes are decided.

A further step could be to discuss this real-time modeling in a virtual reality environment/meeting room and increase the immersion. The goal would be to come as close as possible to a face to face meeting on a physical part.

A step far in the future for discussing product development could be real-time 3D-printers on each communication site, who transform the discussed ideas in real parts or products during the meeting.

Apart from the communication media the settings of the meeting situations could be improved. The authors observe in practice distributed meetings, where the setting and the meeting situation should be improved. This includes the setup of such meeting rooms. Specific rooms especially for sketching as communication media in meetings improve the situation for these meetings. These rooms should allow everyone to participate on the sketch during the meeting (everyone is standing in front of the sketch-board). Video is a good possibility to increase the awareness for the participants of the far side.

All in all, the experiences from the practical side show that holistic approaches are needed which integrate design research, psychology, work sciences, etc. Most of these ideas have already been subject of research and there exist a lot of research findings which show solution ideas. Some are available for quite a lot of years. An interesting question is why many of these solutions never experienced a wide distribution in the product development industry.

4 Communication and Transition of Insights Between Industry and Academia

In the following passages the authors discuss the relation between academia and industry on a more general level. The questions are: Which links exist today, what are the problems and what could be done to improve the situation in the future?

4.1 Links and Platforms for Exchange of Insights Between Industry and Academia Which Are Used Today

One of the most common links between academia and industry are people who come from academia to industry and transfer insights by taking these with them. Usually, these people have been involved in research and have acquired deep knowledge about their research topics. This enables them to apply their theoretic knowledge in praxis.

Another common link is students which conduct their academic thesis in the setting of industry and are supervised by academia. Regular meetings with student, academic supervisor, and industry provide opportunities for knowledge exchange. Joint research projects with partners from academia and industry do the same thing on a much more intense and detailed level: They provide a lot of opportunities to exchange knowledge. The common goal and the long and intense cooperation of joint research projects are helpful to intensify the knowledge exchange. At these projects the exchange of knowledge (e.g., detailed requirements) from industry to academia has a strong focus, too.

Another commonly used way of exchanging knowledge between (product developing) industry and academia is by involving spin-offs from academia or other companies who are specialized in supporting the product design process and are founded by people from academia. Generally, this is the exchange by involving external consultants who are in close contact to academia. Especially, when involving external specialists the transition of knowledge is quite often supported by tools (e.g., special software).

All in all there already exist several opportunities where industry and academia can get in contact.

4.2 What Hinders the Successful Transfer and Implementation of Insights in Praxis?

Even if there are many opportunities to exchange knowledge and insights between industry and academia, the actual transfer of knowledge and successful implementation in praxis seems to lag behind the possibilities.

Very big problems are in many cases confidentiality and other legal and organizational issues. The administrations of academic and industry organizations are usually focused on working within their "type" of organization and cooperation is often complicated if it is between different (academia/industry) "types" of organizations.

In some cases the research findings might not be relevant for praxis. There are lots of different research areas and sure enough a lot of topics could be very interesting for praxis. We believe that this is not one of the main problems. Nevertheless from an industry view, the research community should always take into account what is needed in praxis.

Sometimes the existence of the research results is not known in praxis. A lot of people from praxis do not have the time and possibility to participate in the academic community, visit conferences, and read scientific papers.

Another reason that surely hinders the transfer of knowledge is that research results (if they are known and relevant for industry) are often quite abstract and generic, so that people from praxis do not understand the relevance of the findings for their area.

A general problem that we want to address is the misunderstanding of roles. In a lot of contacts between industry and academia, industry is called "partner" of academia. But this is not always the truth. A lot of times industry sees itself as "consumer" not as a "partner" of academia. If there is a company who is developing technical appliances, then the core competencies are linked directly to these products and not to the development process. Even if there are some specialists who think about development processes, most of the people of the development think about the products. This constellation can lead to the situation that academia offers insights, but the industry company wants to get consumable outcomes that help in the development of products. The company does not have the possibility to make consumable products to support design out of these insights itself. This will normally lead to the situation where the insights are not implemented in praxis.

4.3 What Could Be Done to Improve the Transfer of Design Knowledge to Industry?

The authors believe that the exchange of knowledge and insights between industry and academia is valuable for all involved parties and propose the following approaches to improve the situation.

The above-mentioned legal and administrative issues need to be solved by the administrations of the organizations. Since this is not part of design research this is not discussed in detail here.

An important point is to make sure that a large amount of research topics and findings are relevant for praxis. Up to some level the funding organizations of research are taking care of this. Additionally an intense and permanent exchange between industry and praxis helps to get the knowledge about relevant problems to academia.

The next point is that important research results are known in praxis. Again this can be achieved by an intense and permanent exchange and contact between industry and praxis. Since this exchange is important for all parties, it should be strongly supported from all sites.

Looking for successful implementations from design findings into industrial praxis we come to the conclusion, that there is a transition needed. Research results are usually too generic and not specific enough to be used in praxis. Most of the industry companies are looking for consumable outcomes from design research, not for insights, which they need to transform in a useful product. This transition could be done by someone from research or someone who is familiar with these research topics. This industry "partner" could be a small company or spin-off who transfers the research results in specific methods or tools, which can be used in product design and "consumed" in the development.

Also the implementation of research results into a tool can be helpful. If a company wants to implement a new method or tool, it is important, that the benefit is considerably greater than the effort and that this is clearly recognizable in advance! But this is usually not possible if one is looking at a research insight. In

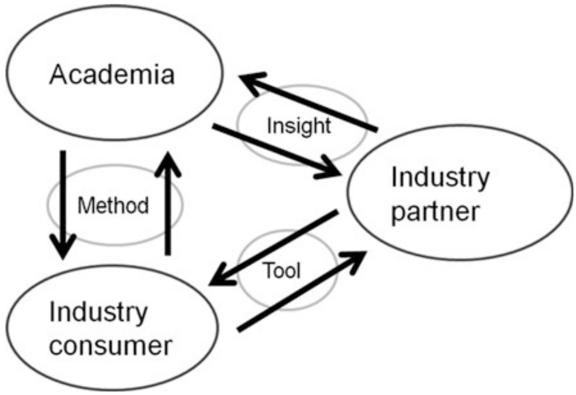

Fig. 2 Role model for the cooperation of academia and industry

most cases it is necessary to transfer the insight into a tool. This tool can then be evaluated by the industry and if positive, implemented.

The research society in product design is communicating its research results and insights to the manufacturers of products. This communication needs to be shifted more to companies who support the development processes (consultants, software manufacturers, companies who provide utilities to support the development process). These companies are the industry "partners" of academia. The companies who manufacture and develop products for the end customer should be treated as industry "consumers".

A platform to support the exchange between industry and academia would be appreciated. Such a platform should consider the three described roles (Fig. 2). It is not sufficient to think in the two categories academia and industry. This platform needs to consider the three roles of "academia," "industry partner," (who support the development process) and "industry consumer" (who develop products) and take into account the very different possibilities, natures, and desires of these three roles. Academia is developing insights and methods which are discussed with industry consumers and industry partners. Industry partners develop tools out of academic insights and transfer generic research models in useful and specific tools. They provide the tools along with the knowledge of usage and implementation to industry consumers. Industry consumers use methods and tools provided by academia and industry partners. But they focus on their core competencies (their products). They provide feedback about the requirements in product development to academia and industry partners.

This model does not mean that there is always a need for three partners. One partner can fulfill more than one role. But it should be always clarified in advance which partner will fulfill which role. The usual misunderstanding is that academia is providing insights, because they think they are cooperating with an industry partner which sees itself in the role of an industry consumer and is expecting ready to use tools.

5 Conclusion for the Transfer of Research into Practice

There is already a lot of successful cooperation regarding communication and transition of insights between industry and academia. But there is still room for improvement. The most important point is an intense and permanent exchange and contact between industry and praxis. Since this is important for all parties, it should be supported from all sides.

If industry and academia are to work together, the authors propose that they deliberately consider the three different roles of "academia," "industry partner," and "industry consumer" and take into account the different possibilities, natures, and desires of these roles.

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A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View

Ola Isaksson

Abstract Bringing new technologies into products and out to a market require continuously improved methods, tools, and skills in engineering design. Following, a brief introduction into challenges for an engine component manufacturer and how engineering design research play an integral role, the aim of this chapter is to discuss experiences from university and industry collaborative research. The university and industry collaborative research is a necessary means to improve practice in industry, and the experience narrated through the cases presented will give some basis as to why this has been, and continues to be the case. Four collaborative research modes are introduced where after three cases from GKN Aerospace Engine Systems as are presented where design research have made impact in several ways. Common to all cases is the long term and deep relation between the academic research team and the company's key stakeholders, who have been decisive to efficiently transit research results into practice. A common understanding of the challenges while ensuring mutual benefit in research initiatives is considered a key pre-requisite for successful introduction of Engineering Design research results. A main argument is that for adoption of research results that impacts the mindset of people—which is often the case of engineering design research—the research must be seen from a change management perspective. The success factors and learning's are summarized into key factors for enabling an effective and efficient collaborative design research.

1 Introduction

Engineering design has, as we shall see, a significant impact on the ability to realize innovative and competitive products and technologies onto a market. Following a light introduction to the aerospace-, and aero engine-, business the role of engi-

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neering design in general and research in engineering design seen from an aerospace manufacturer is presented. The main focus in this chapter regards how to make use of industry-university collaboration to enable improvements in competitiveness through adopting research results.

1.1 The Aero Engine Context

Competing successfully on a market is highly valued by any company, and this typically is measured by the performance of the end product on the market. Companies continuously deliver new products that in most aspects outperform the existing products.

It is compelling to see how the aerospace business continue to innovate, close to 100 years from the introduction of commercial flight, and some 65 years after the introduction of jet engines for commercial flight with the COMET aircraft from De Havilland in 1949.

Advancements in flight performance have been significant and measured in terms of fuel efficiency the improvement rate has been in the order of 1 % improvement per year. One typical metric relevant for aircraft engines is the specific fuel consumption; see Fig. 1 (Avellán 2011). Such improvements allow airlines to make a leap in efficiency when replacing their fleet since aircrafts are in operation for 20 or 30 years or even longer.

The targets for 2020 and 2050 as stated by ACARE (ACARE 2014) are indicated in the same figure, and such targets currently drive research and development initiatives within Europe.

Parallel with the advancements in flight performance, flying is safer than ever where ICAO (ICAO 2014) in 2013 reported 2.8 accidents per million departures, which is the lowest recorded since ICAO began tracking the global accident rate.

The advancements made realized by advancements on aircraft and engines together with advancements in maintenance, operations, air traffic management and

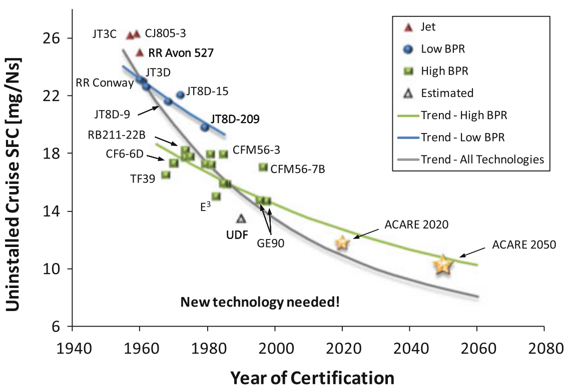

Fig. 1 Improvements in fuel consumption for jet engines (from Avellán 2011)

more. We limit the discussion to jet engines, their components and subsystems and recognize that weight reduction combined with increased temperatures and pressure within the engines have been driving innovation for decades and continue to do so.

Innovations have been made in all areas of the jet engine, among them the introduction of more advanced and capable materials that are tightly coupled to new production methods, innovations within the design and architecture of the engines resulting in higher by-pass ratios, aerodynamic performance on blades and vanes and not to mention the ongoing electrification of engines where pneumatic and hydraulic systems are being substituted by electrically powered solutions.

Since advancements are made on component level, and on architectural and system level simultaneously, it is evident that a modern aircraft, and aircraft engine display a high degree of technical complexity. The aircraft engine is a good example of a technically complex and integrated machine where system performance may directly depend on the performance of its constituent components. The other way is also true, that the conditions and design requirements for components is tightly dependant on the overall aircraft and engine behavior.

Another evolution has been seen in the business models. In the aero engine business it is now common that airliners pay for the availability of the engine function rather than buying the engines and paying for repair. One consequence is the increased engagement in operations of engines by the manufacturer, and a clear link to the design of the product for optimal life.

In summary, the advancements made in jet engines have been significant and been made possible though a range of innovations in a wide range of engineering disciplines.

Companies that have a better ability to develop and integrate more competitive technologies into products operating on the market are in a good position, especially since the business is expected to grow at a rate of 4 % annually at least for the nearest 20 years.

1.2 The Relevance of Engineering Design in the Aero Engine Industry

From the introduction it should be evident that there exists a significant amount of challenges for the aerospace business that require technological advancements to enable the next generation products to succeed. It is not sufficient to “merely” develop a new ultra high temperature resistant material (example), but the new material needs also to be able to fit into a product, pass certification requirements, and perform in-service and maintenance situations. The use of highly optimized technologies risks bringing in a chain of dependencies and conditions that need to be accounted for during design. It may be argued that advancements in technology increase structural complexity, which also drive the effort to successfully develop and integrated technologies. De Weck et al. (2013) found in a preliminary study that

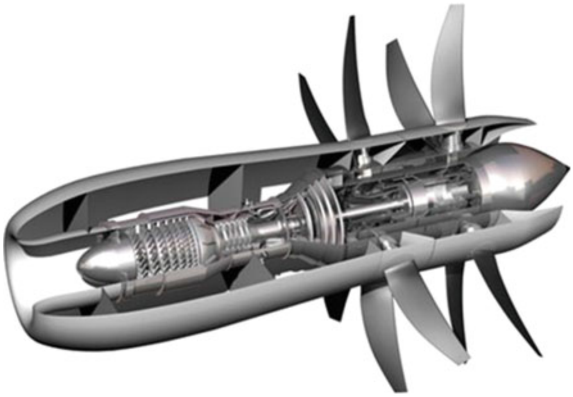

Fig. 2 Outline of an "Open Rotor" demonstrator jet engine

the development effort to realize structural complexity effort increased super-linearly (exponent = 1.69) with increasing structural complexity. Novel technologies need to be demonstrated in a relevant system context in advance of its realization. Several such demonstration and technology validation programs are underway within SAGE (Sustainable and Green Engine) initiatives within the Clean Sky programme (Clean Sky 2014), such as the Open Rotor engine demonstrator seen in Fig. 2.

If a new technology outperforms a previous technology, it is quite common that the area of applicability is altered. Taking materials as a simple example, where there are clear drivers toward raising the operative temperature in an engine.

A more high performing material typically has a more advanced alloy structure, relies on a more elaborate heat treating scheme or may need to be combined with a new cooling technique. The weldability and repairability of the same material or alloy may be changed, which has a direct impact on the production process and on the maintenance procedures. The improvement in thermal durability may come to the cost of less advantageous properties in manufacturability or repairability. The material, manufacturing, and maintenance concepts for infusing such advanced material into a new product require a great deal of engineering design techniques. Simultaneously, parallel advancements in aerodynamic design may have led to aerodynamic shapes that cannot easily be defined unless a complete computer-based three-dimensional representation is adopted. To complicate the situation further, the operative use of the engine as a source for propulsion as well as a power plant for all electrical aircraft systems alters the load situations for the engine and its subsystems.

Engineering design methods, tools, and techniques are needed to

(1) Understand the forthcoming needs and expectations of the products.
(2) Explore and identify the allowable and most valuable design space.
(3) Define and represent forthcoming design alternatives.
(4) Assess and evaluate the alternative designs and design strategies.

(5) Verify and ensure compliance with needs, expectations, and requirements.
(6) Allow even better ways of working within dispersed and multi-functional development teams.

Successful engineering design tools should not only support the design of new products, but also enable a more efficient way of working. Product Development cost is a key competitive factor as product complexity increases while global competition expects continuous advancements in efficiency.

Today's aircrafts and aircraft engines could not have been made without taking advantage of the new techniques that have been brought forward from engineering design research. Looking forward, the trend is clear that next generation aerospace products will require even better ways of understanding and mastering complexity and integration in a robust and efficient way.

1.3 Why Collaborative Design Research?

From a manufacturing company's point of view it may be tempting to argue that universities can develop new engineering design capabilities, to teach students, and let software vendors implement the results in the next generation of various engineering design systems. Companies can then simply expect next version of their engineering software to be more capable and more suitable to allow the design, integration, and evaluation of next generation engine-related technologies.

Such view is too idealistic. There are some core arguments why manufacturing companies and academics need to collaborate in engineering design research, namely;

1. *The time to develop new design capabilities* Bringing new technologies from a discovery state to a mature use in practice typically span a period of at least 10, typically 15 or 20 year period. Radically new design methods follow a similar pattern, and despite the fact that there are short-term benefits—gaining major effect typically spans over a longer time making such problems suitable for academic research. A main factor for adopting engineering design practices is that these often require a new way of working and even a new way of thinking.
2. *Expertise needed to interpret and use findings* There is a certain amount of expertise needed to make best use of research and research findings. It is seldom the case that insight and skill of understanding research results can be directly transferred to practice without investing time to understand the research results. Industrialists need to have a certain degree of involvement in the research to be able to make correct use of knowledge built, and there needs to be a way to explain the effect and level of maturity of the research results also to non-specialists.
3. *Engineering Design research requires deep contextual understanding* When the context is an industrial situation, there is a need to have a broad and deep understanding for the applied context for researchers. Researchers need to have

good access to industrial data and situations, which can be achieved through collaborative work. The necessity to idealize and bound the research problem may lead to highly optimized and capable design tools, but risk to miss out important factors for its deployment in practice. The other way around is equally true, the industrialists need a good understanding of engineering design principles and at least some insight in the specific research domain.

4. *Timing of results and deployment* Industry needs for deployment cannot generally be considered to be stable, linear, and predictable. Needs change and evolve, and the most apparent needs are within short-term problem-solving situations and the current business situation for the company (availability of resource, cases, and resources). Roadmaps and planning are helpful, yet not sufficient, so the adoption of research results is often difficult to schedule.

In short, changing design practices in industry require time, effort, competence, and deliberate ways to overcome contextual barriers between industry and academia. Misalignment in expectations between different stakeholders are common obstacles as industry and academia collaborate, and it is worth the effort to overcome these barriers. Wallin et al. (2015) emphasized three key mechanisms for overcoming contextual barriers in industry and academia networked innovation.

2 Collaborative Design Research

After introducing a simple model to classify research modes, three areas wherein the company has engaged in engineering design research are revisited in order to highlight some key learning's for collaborative research.

As a means to organize the "design research" into a set of complementary research mode's, a simple model is presented to organize the presentation and classify research initiatives into different categories. The model is the used to reflect and analyze findings from three collaborative research initiatives between the company and university.

2.1 A Collaborative Research Portfolio Model

As a way to organize and clarify how to make use of research in engineering design into practice, a simple 4-mode model is proposed. The underlying idea is that by using a model to clarify the expectations of research work and research results in a good way. The portfolio model is inspired by the DRM model by Blessing and Chakrabarti (2009). Here, the intent is not addressing the research methodology, but rather to display complementary design research studies, and as a means to quickly allow industrialists and researchers to set up and manage collaborative research initiatives. The ambition is that this way of presenting collaborative research is to

Fig. 3 Four modes of collaborative research

enable communication between stakeholders and more readily align expectation on the usefulness of research studies. Usefulness should be bi-directional, that is, usefulness both for industrialists and for academic participants.

The portfolio (Fig. 3) organizes research into four complementary modes, each introduced below.

2.1.1 Exploratory Research

Exploratory research in engineering design means that the researchers get the challenge to explore and identify novel and valuable methods, tools, techniques, etc. that (for the company) may serve as inspiration for new thoughts and ideas, or even provide solutions and radically new practices. For researchers, such work may be either quite straight forward if the researcher is experienced in the field already. Conducting an explorative survey, may be an efficient way of start interacting with a company, or require the active search and exploration of what techniques that may be available for a certain problem.

A prerequisite for such research work is that sufficient understanding of the underlying problem and situation can be shared between the researcher and the industrialist.

Benefit to the research community is to find applications and match novel design approaches with strategic and challenging needs. It is further a way to map research findings from different disciplines and aspects, and identify promising new solutions or ideas.

Benefit to the industrial partner is non-biased input to difficult and important problems where “incremental” improvement attempts have not been successful. It is a quick way to get going and often suitable for shorter studies together with experienced researchers.

2.1.2 Descriptive Research

Descriptive research in engineering design means that the research focus is set on understanding and explaining engineering design phenomena's. To some extent this is a necessary step in any research initiative. The results from descriptive studies are typically deep understanding of phenomena's, clarification of research tasks, and evaluation of the effect of new methods and tools. An industrially interesting aspect is the unbiased views and analyses made on the industrial problem. Descriptive studies may be both "in-depth" studies in the organization or design teams and wider studies involving several companies in bench-mark like studies.

A prerequisite for doing descriptive research is a mutual understanding of the expected result from these studies and that sufficient access can be granted for the researchers to access the industrial situation. Equally important is the willingness and ability to invest sufficient effort to reach the necessary understanding of the situation.

Benefits to the research community are typically empirical evidence of needs and problems, statistics, and organization of new and complex applications. It is useful to compare known (research literature) knowledge with practices and empirical findings within one, or several, companies.

Benefits to industrial partners are comparative metrics and surveys of what problem actually exist and how to approach this. Another advantage is to have domain experts to take a close look into various design problems. Often, such studies result in the finding of underlying root causes to problems and ideas about what may be a way forward. Results from surveys involving other organizations are also helpful in overcoming the "not invented here" problem and a more stable validation base in advance of further investments in the research and/or implementation and change initiatives.

2.1.3 Prescriptive Research

Prescriptive research are the studies that result in solutions, methods, and tools that prescribe how a certain design problem or situation can be met. Quite often, companies are eager to come to the point where the implementable results in forms of tools and methods can be deployed and exploited. The dual benefit from undertaking prescriptive research together with researchers and industrialists is that it provides researchers a way to validate new approaches while the industrialists need to prepare implementation by increasing maturity be demonstrating and validating the methods and tools in for them relevant contexts. Collaboration in this phase is typically necessary to transfer knowledge about the methods and tools in order to enable the transition from research to application.

A prerequisite for doing descriptive research presumes that the governing research problem has been well established in advance of the study. Another is a clear and common understanding of to what level of maturity the method and tool aim to be at for the specific research initiative.

Benefit to the academic research community—development and validation of new approaches to design challenges.

Benefit to the industrial partners—a necessary step to bring interesting theories and findings into forms that can be deployed industrially. New methods and theories need to be validated to some extend before more advanced investments or change management actions are taken.

2.1.4 Exploitation Research

Exploitation research studies address primarily the ability to transfer and make use of research results. This is an important phase—decisive for the successful transition of research findings in engineering designs to actually exploiting the benefit of the results. In this phase, it is common that commercialization discussions are intense, that people change positions and that forms for collaboration changes, e.g., that the research project ends and students graduates. It is easy to argue that from an implementation and adoption perspective, this is the most critical phase of research. It is important for researchers in engineering design, simply for the amount of "true" feedback of the candidate benefits foreseen in earlier phases of research (although it may be argued to be another turn on the descriptive studies). In addition, the exploitation phases is also important for financing bodies and industry since the research in engineering design is seen as an investment in learning. Finally, although the research methods, tools, and insights have been reported and demonstrated, the real knowledge in the research findings typically reside among the researchers that have engaged in the research. This is the phase where too many good research findings struggle to lift off.

Benefit to the academic research community through in depth validation and insight in what is needed to introduce and change practices industrially. Such cases may be highly valuable to further validate research and develop courses for undergraduate programs.

Benefit to the industrial partners—to facilitate the transition from academic to industrial application. The "business case" for industry simply relies on that the exploitation phase can be completed.

2.2 Case A—Generative Design Using KBE

The first example of engineering design collaborative research is taken from the research and introduction of automated and generative modeling design tools necessary to explore the design space and further optimize products without introducing unnecessary risk.

Case Description During the late 1990s, the company engaged in a bid effort to be a design and manufacturing partner of a new aerospace engine program, which included product development and production of new jet engine structural components for a new jet engine. The conceptual engineering work was terminated prematurely this time since no business agreement with the engine OEM was reached.

Since the strategy was to increase effort as a development partner, a follow up audit with external resources was made to identify improvement areas for the organization. The audit revealed that despite the company's engineering and manufacturing skills, the conceptual design capabilities were not competitive. Product and production costs could not readily be committed in due time. Practice at the time included a structured analysis of requirements and preconditions, followed by idea generation and sketches that were ranked against the requirements. A few concepts were selected for geometric modeling and refined evaluation of, e.g., structural integrity using Finite Element Analysis.

The company has significant experience from manufacturing similar components and from engineering analysis, yet at the time less experience in engineering design of the same components.

The first Research Approach The Company engaged with researchers at Luleå University of Technology where a research student in a nearby area engaged in the challenge. The researchers were asked to first meet and discuss the outcome of the study and an explorative research study was formed. Taking the company's situation into account, what conceptual design methods are available that could better be used in conceptual design situations?

The researchers' first task were to clarify the root causes to the problem together with leading engineers at the company. The explorative study that followed, included literature search and search for state-of-the-art applications within other companies and organizations. After just a couple of months the explorative study was reported, suggesting that Knowledge-Based Engineering (KBE) technologies had been successfully adopted and used in other aerospace companies already. Advantages with KBE are—in short—the ability to generate and evaluate alternative design configurations by mixing design automation techniques with rule-based configuration and parametric modeling. Moreover, the report also pointed out not only the suggested advantages of a knowledge-based engineering approach, but also some potential pitfalls and limitations with the technique. The suggestion to the company was to learn and invest in learning the KBE technique, while ensuring short-term implementation benefits along the way. A road map was created, where the company invested in developing KBE engineering technologies in parallel with a research initiative where doctoral students started to learn the underlying technologies and aspects of KBE.

In 2002 the lead time for defining and evaluating a conceptual design was about 80 h for a single concept variant. The lead time was essentially consumed by a significant amount of modeling and simulation efforts needed to evaluate quantitatively the behavior of the concept.

Over a 5 year period the readiness (Technology Readiness Level—TRL) of KBE at the company was raised from TRL 1 to 6, and once the technology was

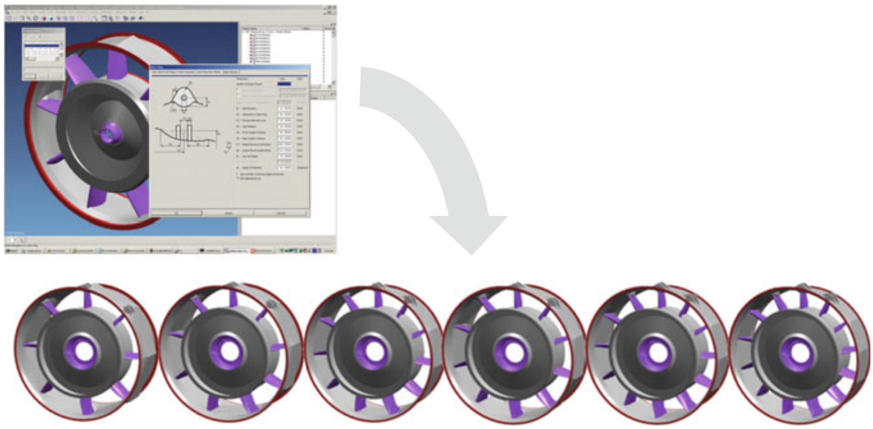

Fig. 4 Generation of design alternatives of an aircraft component

introduced in a subsequent business project it became a success. The ability to define and evaluate many alternatives enabled the definition of a robust product design, something that would have been nearly impossible without the ability of an automated, generative modeling approach. The product design using KBE techniques proved to be efficient and had a significant impact on the design process. Since then the KBE tools have been matured and integrated into the engineering operations. Along the process, research studies have been undertaken both to understand the underlying process and to mature the methods and tools following a TRL scale. The engineering design techniques did not only contain the geometrical generative technology as seen in Fig. 4, but also a framework to develop and apply generative technologies onto a wide range of applications (Isaksson 2003).

Once the core techniques of KBE technologies were “mastered” the same techniques could be used to bring in advanced and competitive analysis techniques into the design process.

To bring out one of several examples of cross-fertilization of research domains enabled using KBE techniques was the introduction of advanced welding simulations into product development. The company was an early adopter of nonlinear welding simulation techniques (Lindgren 2007) and a prescriptive research effort between researchers on welding simulation with researchers and practitioners on engineering design and design automation with KBE. In this work, researchers from different disciplines at the university (engineering design and computational weld mechanics) collaborated with the industry team to combine tools and techniques (Runnemalm et al. 2009) (Fig. 5).

The objective was to enable advanced weld simulation as to evaluate alternative manufacturing design alternatives already in the design phase. Through automation and inclusion of the weld simulation technologies, alternative weld arrangements could be evaluated and validated virtually for several different designs. Previously,

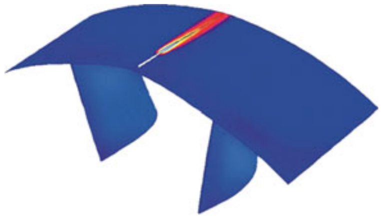

Fig. 5 Nonlinear analysis of welding process to predict distortions induced

this had not been possible during the design phases due to the long lead time to prepare and analyze welding.

Observations and Learning's Case A Several observations and learning's can be extracted from the above case.

- *The investment and strategic collaboration with universities* The company had a strategic engagement with Luleå University of Technology where a series of PhD students and researchers could work together with the company. In this case, such collaborative environment existed at the time where the KBE journey started which made it easy to initiate work with an explorative study. Furthermore, several different researchers could be engaged to a different degree over time, collaborating internally and creating new applications along the way.
- *The demonstration of novel methods onto real-world problems* The researchers worked tightly together with the engineering development team at the company. As the technology matured, the number of engineers who had been exposed to the KBE technologies grew, to a state where participants within the operative design teams had themselves some experience in KBE modeling. The KBE expert team could then easily work together with the operative teams—a quite successful situation for introduction of novel practices in engineering design.
- *Timing with business* Several times as the technology had reached a degree of maturity sufficient for introduction in the intense design situations in operations, there were mistiming with the company's business situation. KBE technology required—at least at the time—a bit of up-front planning since general design models needed to be prepared and validated. As it turned out the business occurred on other applications—not prepared for KBE design at the time. Timing between business and technology and methods development is not always straight forward—especially for demonstration and demonstration on higher TRL levels requiring real and realistic application environments.
- *Critical mass of core competence* The generative modeling support for engineering design required a change in mindset in the organization. From create a model and analyze it, create another and analyze that, to preparing a flexible "parametric" model that through automation can be used to explore variants. The necessary skills were developed within the research and technology team that worked with university, yet to introduce into practice in a wider aspect required a change process in the organization. Keeping a core team centered, as

a support for expert support as the organization undergoes a mind shifting change process is a necessity. Using student projects and trainees as a means to train new recruits in the new skills is a way to develop necessary critical understanding.

In summary, the research initiated in the late 1990s with a generative modeling approach revealed that the new engineering design tools that require a new mindset in thinking can prove to be effective in a small team of experts, yet it need to be seen as a part of a more widely defined change management initiative to adopt improved ways of working. The long-term relation with Luleå University where a series of PhD students and research projects could generate enough critical mass of competence and endurance in research was identified as a key success factor in this case.

2.3 Case B—Developing Product-Service Systems

The second example case concerns another aspect of engineering design. How to design for solutions where the artifact merely is a part of the solution?

Case Description Toward the end the last century, service models had become common within the jet engine marketplace, and Rolls Royce launched their TotalCare® services where airlines effectively pay for a service package rather than buying the engine in the traditional sense. Such transition in business model alters the conditions also for the manufacturing company, its development-, production-, and maintenance-businesses. Merely the fact that the responsibility for the product being available for services is transferred from the user to the manufacturer causes some shift in thinking. The importance of ensuring correct and relevant information from in-service situations becomes a business responsibility and a design opportunity. How can I as a manufacturer make use of the increased responsibility and control over the product through life?

For GKN Aerospace (Volvo Aero at the time) this also had implications as a partner and supplier to the OEM. How did the new business logics impact the established operations and businesses? There were at the time more questions than answers, and from the very beginning it was recognized as a strategic challenge and opportunity. Understanding the new logics and how this impacted engineering and innovation in the company was necessary.

Research Approach Together with national funding bodies and a selection of universities several research projects were launched, taking on the challenge from many different angles. Here we concentrated on the engineering design-related topics, where already after a few years a new research area was formed at Luleå University of Technology, in "Functional Product Development". See Alonso-Rasgado et al. (2004) for reference. The width of the challenge further led to the establishment of a 10 year government supported center at Luleå University (Faste laboratory) for Functional Product Innovation with the aim to gain sufficient critical focus on the trendy area together with other industries. Functional Product Development was a way to open the product centric paradigm and introduce the focus on what the products do (e.g., services and functionalities), rather than how they are defined, and how this challenged the manufacturing industry (Isaksson et al. 2009).

In this example, we highlight one example on how the introduction of a service integrated approach in engineering design environments was made possible. A research question was formulated as *How to enable design of Functional Products?* An Industrial PhD student worked closely with the university-based research team of senior researchers and PhD students collaborated to explore aspects of integrating service and life cycle aspects into engineering design environments, see ,e.g., Sandberg et al. (2005) and Boart (2007).

In short, the emerging results from case 1—where generative modeling engineering design techniques were developed were combined with novel techniques to include service and life cycle design capabilities into the same system, see Fig. 6.

The result of the research was the successful integration and demonstration of a design system capable of supporting a product service system approach. The research picked up upon the importance of allowing users to make use of existing views in their work context, and facilitated the integration of life cycle information in early phase engineering design systems and information sharing. Users both among concept-oriented designers and manufacturing and maintenance-oriented engineers were all positive.

Observations and Learning's Case B Also from this case we identified interesting observations and learning's;

– *Exploitation of design methods* The techniques positively contributed to the exploitation and adoption of generative modeling in general, and successfully

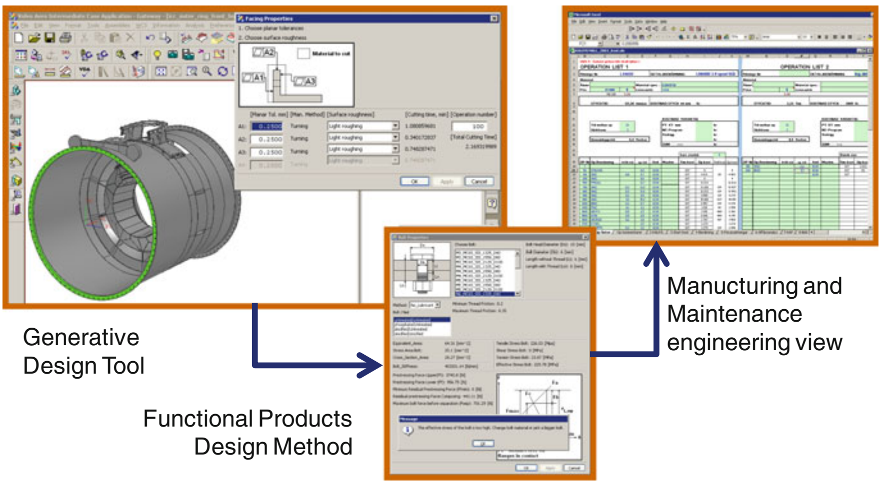

Fig. 6 Functional product design environment

showed how to scale the range of applicability of the recently developed generative design systems.

- *Difficulties in PSS design remained* One of the main objectives was to support functional product design, something which remained difficult to exploit within the organization after successful demonstrations. The learning was that development of product service systems in manufacturing-oriented organizations require a fundamental change initiative on all levels in the organization. This was actually a starting point for taking a wider turn on the problem of what capabilities for a manufacturing organization to adopt Product Service Systems innovation. (see Wallin et al. 2014, 2015).

In summary, this research example demonstrates that engineering design tools must be seen within a wider context, and without all pieces in the puzzle, even successful design methods and tools may experience real issues in implementation and exploitation. It also demonstrates the strength in combining related research initiatives in achieving interesting results.

2.4 Case C—Virtual Geometry Assurance

A third example is provided that is driven by the increased complexity and dependencies between product design and manufacturing.

The Case Description Design and analysis tools are now quite capable of optimizing product function and utilize ever reduced margins in geometrical design. Also, the introduction of new design solutions and materials require an integral approach to product and process design using virtual modeling and simulation techniques. The company adopted a "fabrication strategy" to enable light weight design solutions. Previous design solutions had predominately been based on large and complex castings. As even "tougher" materials are introduced the cost and resilience of a casting approach can be challenged if smaller castings, forgings, and sheet metal parts can be assembled into a fabricated design. Establishing a robust geometry assurance process is crucial to realize manufacturing process stability, and the conditions are set already in the engineering design phases. There is a need to enable design for geometrical variation and stability.

Research Approach The Company participates in the Wingquist VINNEX excellence center at Chalmers together with other industries. Initiated by the dialog with automotive manufactures—where assembly design and manufacturing is commonplace—an explorative research study quickly revealed the opportunity to adopt engineering design tools for geometric variant design available in the center.

Researchers and research students formulated a use case based on GKN's specific conditions prevailing in the aerospace engine business and not in automotive, see Vallhagen et al. (2011). Similar to case A and B, senior researchers worked together with the industry team and PhD students, and soon technology validation studies could be performed together with realistic industrial application cases, see Fig. 7.

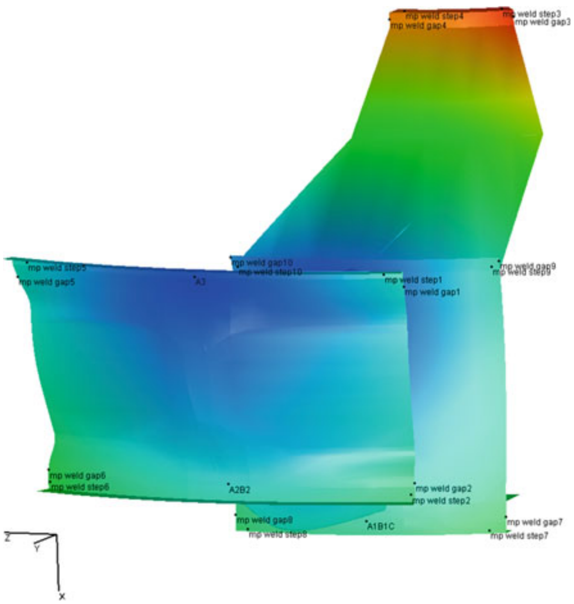

Fig. 7 Locating manufacturing critical points in design (RD&T)

In this case, the last validation case proved successful, and the PhD student could be hired to continue exploiting the results into the company, see Lööf et al. (2013). At present the tool is being established at the company, whereas research collaboration continues with the university in related areas.

The specific research challenges may still take years to introduce into practice, yet the main principles from Virtual Geometrical Assurance could be readily deployed in a shorter timeframe.

Observations and Learning's Case C Observations and learning's from this case;

– *Exploitation of design methods* The research results were readily implementable in a design tool, and the skills (former PhD student) could continue into the company exploiting the results.
– *Collaborative network* The successful learning from other industries via a center collaboration. Researchers had experience from other industries and could easily identify strategies to reapply research findings from one area to another.
– *Timing with business need* At the company there was immediately situations where the research results could be adopted, which enabled recruitment and facilitated exploitation.
– *Short-and long-term balance* The establishment of relevant use cases was delicate. Relevant enough to address industrial problems and specific enough to address research questions. Ability to pursue research with a long-term vision, still finding mutual short-term gains was successful.

In summary, case three illustrated clearly the fact that research results follow people into exploitation to a large degree.

3 Experiences from Collaborative Research Initiatives

Linking back to the portfolio, we can identify several types of research modes. The exploratory mode of research was used in all three cases. The company provided an open question for researchers, which could either by literature studies or research experience conduct short studies as a means to initialize the dialog. Once established research relations, exploratory studies are useful also for students assignments. Researchers, research students, and industrialists can within the frame of ongoing research initiatives support students to explore interesting concepts and design techniques as opportunities. If successful, these can be adopted into the research and exploitation mechanisms.

The iterative pattern between descriptive and prescriptive modes of research can sometimes be difficult to see. Yet in case B it was evident that magnitude of the industrial challenge required a more deep understanding of the underlying phenomena's. Aligning research initiatives with the industrial strategy is needed and research in engineering design should from industry be seen as a part of a change management initiatives.

Another important learning is to align expectations on what research can contribute with. In the cases where there exist similar competences at the university and at the company, e.g., where the company hire researchers and PhD's, the likeliness of understanding each other increases. Still, it need to be emphasized that "researchers" have a wide range of skills and competences and mixing different research domains may be difficult, yet rewarding.

This chapter has presented a way to organize collaborative research initiatives into a "portfolio" of design modes. It is a simple way to clarify that "research" can be undertaken with different objectives and with different means.

At present, several of the engineering techniques highlighted have been introduced into the company practice. Already, many results have been introduced over the years, and a range of skilled people that have developed, and being trained, in the new engineering design techniques are active in continuously developing competitive practices. Collaboration with university is a way to build competence as well as building new engineering design insights and tools.

4 Summary and Conclusion

Three cases have been described where universities and the company have been collaborating to find answers to industrial challenges using engineering design research methods as a means. In each of the cases, there were several learning's and not always a straightforward, linear process. Three main messages can be synthesized;

Exploitation Through People Transferring and implementing design research results in engineering design follow the competence and dedication of skilled people. Research is a way to develop people. Researchers progress in their expertise, PhD students learn and develop new ways of working, and industrialists can be stimulated by new thoughts steaming from research. Dedicated and skilled people are needed at both the university and the company. In all the above cases people are important. Allowing people to develop experience from both the university-based side and the industrial side is important, ranging from student projects to researchers and professors.

Continuation and Change Management None of the cases mentioned above starts from scratch and deliver results through a single research study. Establishing long-term relations between universities and companies are powerful and needed to act quickly once the timing is right, and achieve a relevant understanding of opportunities and needs. The engineering design research must therefore be seen as an integral part of a strategic and tactic change management process within companies.

Align Expectations University-based research and running industrial operations have by definition different objectives. To use this difference there need to be a mutual understanding of these differences in objectives. What is evident within one organization may be unaware of at the other, and there is no single solution to overcome this. Be interactive and engaged, be visual and expressive in explain effects and implications of research or needs in as many ways as possible. The use of demonstrators and prototypes, the use of TRL scales and the use of dedicated collaborative workshops and events are all examples of mechanisms that enable alignment of expectations and innovation.

Finally, returning to the initial challenges, driven by the companies need to deliver products that outperform previous and existing solutions: Enabling such competitiveness is based on building competence on how to do engineering and engineering design. Engineering is performed by skilled people, using appropriate methods and tools. Both people and methods and tools are developed through collaborative research.

Acknowledgements The research in the cases presented deserves recognition to the funding organization, which in these cases has been Vinnova through the NFFP and VINNEX center programs. Support from GKN Aerospace is acknowledged.

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Implementing Product Architecture in Industry: Impact of Engineering Design Research

Matthias Kreimeyer

1 Introduction

This chapter details the setup of how a new engineering design approach, namely the systematic design of "product architecture" in the early phases of the engineering design process at the commercial vehicle manufacturer MAN Truck & Bus AG, was integrated into an existing process landscape. As part of this implementation, models, methods, and tools from engineering design research were drawn upon, and their impact as part of the implementation is discussed.

1.1 Context: MAN Truck & Bus AG

MAN Truck & Bus AG (in short "MAN") is a major producer of commercial vehicles with a product portfolio consisting of light- and heavy-duty trucks, city and long distance buses, and components thereof, e.g., engines and axles. The primary niche MAN occupies is that of mass customization for specialized markets, such as construction vehicles. As such, MAN vehicles are built on a highly modular architecture that supports a wide range of applications, e.g., trucks for different uses (e.g., wood transport, military, etc.) and market segments (such as long haul, distribution, or traction). While trucks cater to variants necessary for these different vehicles from a mostly predocumented (i.e., predeveloped) set of components, buses are developed to order to a certain degree, especially for customers from the public sector.

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1.2 Problem and Scope

Over the past 3 years, the organizational function "product architecture" was systematically integrated as an independent central organizational unit, taking active part in the concept phase of the engineering design process. This was, in particular, done to address the following issues as an operational department within the design organization:

- Establishment of a consistent generic product structure for the whole organization as a basis for standardization throughout the design process (i.e., to structure projects and their work decomposition, to facilitate target management, to reuse components, to consistently describe responsibilities within the organization, etc.)
- Management of product-related documentation standards, i.e., ensuring a similar manner of documentation (drawings, bill of material, variant description, release process, etc.) in all design departments
- Systematic planning of the necessary technical solutions based on a detailed functional product specification, i.e., ensuring that the input of the concept phase is a functional specification and the output is a technical specification that—later, during the preparation for series production—is refined, validated, and readied for production
- Transparency through similar reporting of the technical progress (degree to which the functional specifications are fulfilled and to which the targets are met) to ensure a well-focused concept design phase (i.e., to develop those variants needed by the market)

Initially, however, these goals were not as clear as in retrospective, and, therefore, the organizational unit was first installed to enable a better management of complexity and a more targeted generation of product variants. Only during the installation of the organizational unit its actual goals were refined based on the original intention.

As contextual information, it is important to understand that variants play a very important role in commercial vehicle design. Commercial vehicles, and thus a common vehicle range at MAN, typically have about 10^{45} different vehicle configurations available (in this case, the heavy range TGS/TGX, excluding tires and colors), which, to a large part, impact the actual vehicle topology through different wheel bases, different equipment, or different functionality (e.g., wheel bases are available from 4×2 trucks to 8×8 trucks in steps of 50 mm from 3600 mm to 5900 mm commonly, available as tractors, dumpers, crane chassis, etc.). For a passenger car, a common pool of variant options to choose from (such as with/without sunroof) will be around 100 options (i.e., functional properties driving the technical variants), whereas a common truck has 200–400 options to select to complete a full vehicle specification. On the other hand, production numbers are comparatively low: MAN, for example, produces approximately 100,000 vehicles per year (Stauske 2012).

2 Introduction of "Product Architecture" at MAN

To reflect upon the impact of science, first, the actual story is detailed of how the new concept of "product architecture" was integrated into the company, what means were used to do so, and how it was received. To that end, the basic philosophy of design and design documentation is explained, as it sets the boundary conditions for product architecture as well; based on that, the concept for product architecture and its introduction is described.

2.1 Basic Documentation Philosophy at MAN

As the term "documentation" is central to the industrialization of product architecture, it is defined as follows: "Documentation" regards how the overall vehicle and the design artifacts that describe it are structured. In a way, the product structure is implicitly given, e.g., as the set of all drawings and the sectors of the vehicle in each regard show how the product is decomposed. Thus, when setting up a product architecture, the product is structured, and this impacts directly how each engineer documents the parts of the product he or she is responsible for.

MAN's basic documentation philosophy consists of a "Modular Kit", illustrated in Fig. 1. On the left on a yellow background, the vehicle properties (also referred to as "options" or "codes") are shown; on the right, the product decomposition (symbolized by a hierarchical structure) and the available variants (referred to as "component variants", represented as little U-shaped "bathtubs") are listed. Basically, any vehicle can completely be decomposed into these component variants, and a vehicle is complete if it has one component variant per node of the product decomposition (referred to as "generic components"). The decomposition of these generic components is represented by MAN's product structure, shown as a hierarchical structure with green nodes in the figure.

Hence, when configuring a vehicle, it is necessary to collect the correct "component variants". To do so, each of them is related to the codes (i.e., the properties shown on the left-hand side of the figure; in MAN's sales configurators, these are referred to as "codes"). This means that, if a first property is selected, those component variants available for that choice remain active, while all others are dropped. The more codes are selected (wheel base, total weight, engine power, type of cabin, etc.), the fewer component variants remain valid until only one (or none, if, e.g., no sunroof is selected) per generic component is left. This is shown in the figure: nine out of the available ten generic components are made available, and the combination generates the tractor shown at the bottom.

The properties on the left-hand side, again, can also be related among each other to represent basic constraints, e.g., certain cabins that only allow for certain seats or certain engines that cannot be combined with manual gearshift.

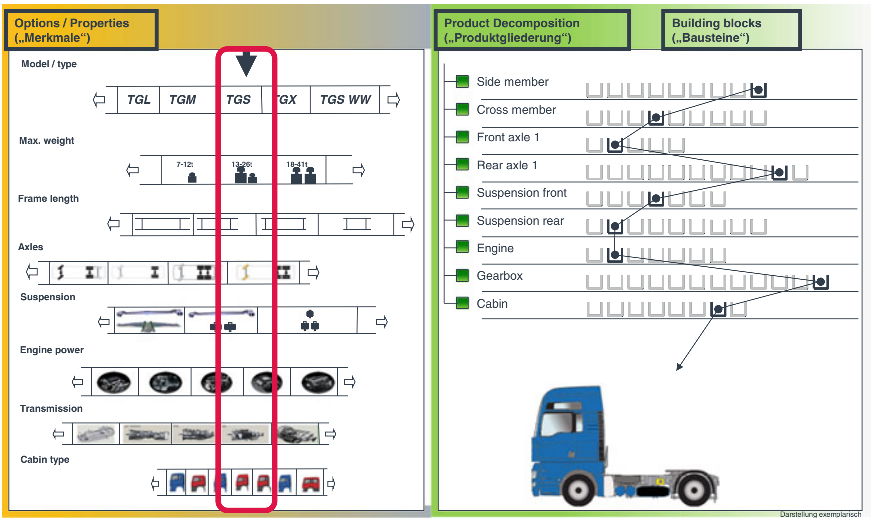

Fig. 1 Modular Kit philosophy of vehicle documentation (Kreimeyer et al. 2013)

2.2 *Initial Situation and Boundary Conditions*

Initially, the documentation described above was only used in the company's bill of material and master data management systems. Hence, the conceptual boundary conditions were set by what these systems could work with. Yet, the existing methodology was far from ideal or "clean", as it had been gone through an organic growth over the previous two decades:

- Almost all departments documented the technical solutions first without focusing much on the needs of the market and on the necessity of technical variants, resulting in a mostly technology-driven approach and not a market-driven one; this, in turn, produced many variants (i.e., "component variants") that, in fact, were not needed and just produced costs but no turnover or benefit
- For the different plants of MAN (the company has, among others, production sites in Germany, Poland, Austria, and Turkey), the product structure had grown apart, i.e., there was no common standard; this resulted in difficulties of transferring or reusing components
- As there was no formal and centrally available product description, a certain mumbo jumbo could be observed when engineers of different plants or projects were speaking of seemingly the same component
- Different organizational units used different ways of structuring their design activities that were, at large, not aligned with the methodology of the bill of material and that caused (and still cause) additional efforts in generating formal variant descriptions for production

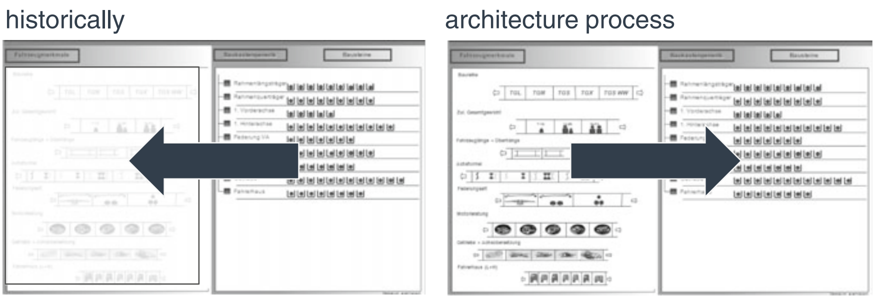

Fig. 2 Change in process paradigm

- As there was no systematic requirements management, the description of "codes", i.e., properties available to the customer was driven by technology, and there was no systematic input to the design process (i.e., what properties the markets need, and what needs to be in a car in a combination) to embody the requirements of the market

In summary, the organization was mostly driven by historically grown structures that were quite fragmented, and the overall process was mostly driven by technology instead of the market needs, as Fig. 2 summarizes: The major intended change of the process paradigm was to go "left to right" in the way of documentation to come to a well-planned modular kit instead of letting the technical design alone drive what vehicles and equipment were available in the markets.

As a boundary condition to do so, two major constraints had to be regarded: the overall design process (referred to as "PEP", i.e., "Produktentstehungsprozess") and existing forms of documentation; for the latter, however, there was a slight degree of liberty, as those could of course, be adapted or modified.

2.3 *Concept for Architecture*

As context information, this section is intended to give a short overview of the resulting concept for product architecture, i.e., the basis for the process. It is based on the "information model" (Kreimeyer 2012), which is the conceptual framework that was developed for MAN. The basic principle of architecture design is shown in Fig. 3: On the left-hand side, the description of product requirements is illustrated; the right-hand side shows the product decomposition. The product decomposition is finalized during the concept design phase to answer two questions: (a) What components and variants do I need and what solution principle is used? (b) How are the requirements met and is the specbook fulfilled completely by the solution?

The specbook (abbreviation used here to represent the "Gesamtlastenheft", the complete collection of all requirements as an input to the project) uses two kinds of requirements—direct and indirect. The former can be associated directly to

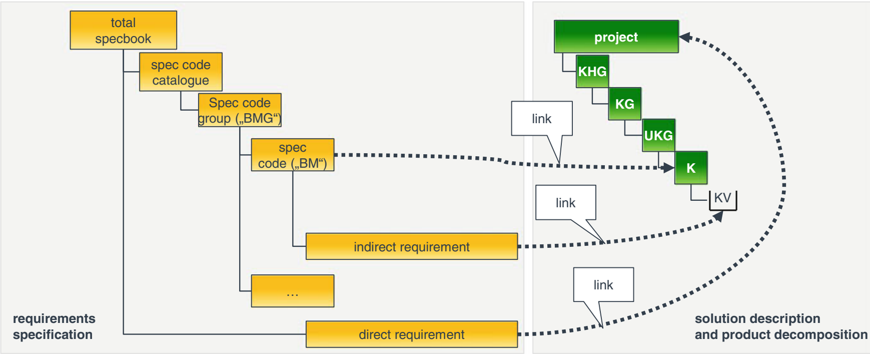

Fig. 3 Basic principle of product architecture at MAN

components (e.g., "maximum of three bolts used to fix radiator"), while the latter are associated via a "spec code" (in German also called "Bestellmöglichkeit", abbreviated as "BM"), which are grouped as "spec code groups" ("Bestellmöglichkeits gruppe"/"BMG"). Spec codes are used to describe the portfolio of variants offered to the markets, i.e., the equipment that is made available to the customer. As each variant is only available in combination with certain other equipment (e.g., "V8 engine only with heavy tractors"), the specification codes bundle requirements for each equipment and serve as a basis to describe, how one equipment can or cannot be combined with another equipment. In turn, these bundles are then associated as one pack of information to a component. These associations are shown as links in the figure: The upper link represents how a spec code (including the associated indirect requirement) is linked to a component K. The indirect requirement at the bottom is linked to the project, i.e., it is valid for the whole product composition (e.g., "no use of non-recyclable materials").

The MAN product decomposition ("Produktgliederung") consists of a four-tier hierarchy of components at the lowest level ("K"—"Komponenten"). These are grouped into "KGs" and "KHGs", and they meet the root node ("project") at the top. The basic idea is that early in a project, not all components are known yet, as not all solutions are developed. Therefore, the lower levels of the product decomposition are not always known yet, and requirements are associated higher up to ensure they are not forgotten.

The further the progress, the lower the requirements move. At the lowest level of the product decomposition, the component variants ("KV", symbolized by U-shaped icons) are the instantiations of small technical systems (invariant building blocks, i.e., they have a static bill of material and a fixed geometry). The goal of the product architecture process is to identify and conceptualize all component variants during the concept phase by, on the one hand, associating all requirements and, on the other hand, identifying and describing the generic components and component variants. This is shown in Fig. 4 (simplified for nondisclosure reasons): Until the start of the project, the product is described only at a high level, while during

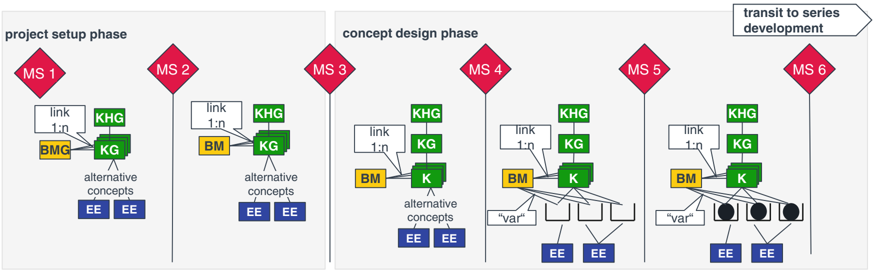

Fig. 4 Detailing of the product along the milestones of the design process

concept design, the information becomes more and more detailed along the process (the process is symbolized my milestones "MS"). It should be noted that actual parts (and part ID numbers) may exist from the start onwards (e.g., as carryover parts), which are represented in blue. At the end of the concept phase, all component variants are identified, the requirements are associated, the variant drivers and the configuration description are completed, and the first parts ("EE", short for "Engineering Element") are designated.

2.4 General Procedure of Introduction

Overall, a basic scientific approach was used to implement product architecture (processes, methods, tools) and its management: After an initial analysis, a concept was designed and refined and implemented step-by-step. Due to changing boundary conditions within the company, however, this was not a straightforward process; similarly, many boundary conditions were initially not as clear as they appear in retrospect, and a large part of the implementation was done in a firefighting mode or it worked out simply through "luck".

In addition, a broad implementation of product architecture at MAN needs to consider that staff has to accept important changes in their work environment, as their own work procedures, processes in general, and tools are adapted. Therefore, organizational change management and training activities beside the technical activities are a substantial part of the implementation.

At a more detailed level, a basic procedure was followed that, to the author's understanding, might be rather MAN-specific: At first, the concept for product structure was fixed to obtain some stability in the discussions; based on that, the flow of the engineering design process in the early phases was aligned with the suspected "growth" of structures (or, documentation in general). This process was then implemented along a first design project using prototypical software tools (mostly data bases) to refine and validate the new process, and only then they were transferred to a PLM environment. Currently, the process is being stabilized through risk management and through further vehicle design projects that make use of the approach.

2.5 Success Factors and Shortcomings

As a closer view on why the implementation of product architecture was successful so far, reviews were carried out with different MAN staff functions (management, architects, project staff in different functions) to identify the key drivers and shortcomings during the implantation up to now as a basis for this publication. Many of these relate more to organizational psychology and organizational change management, which is why in particular those regarding the relationship with engineering design research are focused here. These factors can be classified as shown in Table 1:

An important success factor for the **concept** was the information model (published in an early version as (Kreimeyer 2012), which served as a framework for all discussions and refinements and as a concrete vision. The information model was developed in a scientific manner, i.e., based on a detailed analysis and synthesis process during one year. It made use of a series of published results from academia (mostly common approaches for product architecture and modularization, e.g., Ulrich and Eppinger 2012; Blees 2011; or Göpfert 2009). While at times it was perceived as "too ivory tower" by some staff in the company, overall it was well received and the early integration in aligning the concept provided the first step into a "buy-in" by the involved stakeholders. Particularly helpful were the reasoning for the different elements of the product structure, the setup of how they serve a

Table 1 Types of success factors

Type of factor	Description
Concept	Details of how product architecture was set to work, especially its parallels to accepted standards and best practices in industry and academia (including coordination and alignment within MAN)
Added value/interface management	Projected benefits for the organization, both in collaboration within the organization and in the overall value for the company
Team	Background, setup, and team spirit of the team responsible for implementing and running the department
Outside resources and input	Non-MAN resources that were drawn upon during the implementation process
Introduction strategy	Overall procedure of the implementation, the basic procedural model, and individual tactical moves
Communication	Approach to convincing the organization and to introduce the new approaches sustainably
Training	Step-by-step and top-down education concept to enable the organization for new processes and tools
Operational support	On-site and active support (by doing) for the staff involved with product architecture and its processes
Organizational Change	Activation of change capabilities of the organization and motivation to change mind settings, mitigation of conflicts and resistances
Stakeholder	Sustainable winning support in the Top Management

purpose in the design process and the alignment were scientifically arguable ("this is taught at lectures at university XX and YY").

In addition, documentation from other companies served as an important and helpful input, especially case studies from industrial conferences, which typically do not have a scientific context, and from academically documented case studies. Particularly, the exchange of experience at the level of tools, templates, and basic documents that were made available through cross-company networks were very useful (showing, e.g., what a product structure in a company producing agricultural machines looks like in detail and how, e.g., hydraulics or electric systems are decomposed and described).

A desirable input at the conceptual level would have been a better and neutral documentation of available models, methods, and tools; here, industrial exchange is somewhat limited because of nondisclosure rules. Additionally, those documents that provide information on well-industrialized approaches often come only through software vendors, which cannot be considered neutral and independent. Scientific working papers, on the other hand, often have too narrow a scope (e.g., comparing only aspects of variant tree tools or similar extracts) to help with identifying a greater picture.

An important step for making the concepts understood was—besides being based on credible data from outside the company—to make it understood through examples and easy recognition. The latter was implemented by a color scheme, and today, the "yellow structure" (requirements management), the "green structure" (product decomposition), and the "blue structure" (parts, assemblies and CAD) are common language at the company. This simple approach helped staff in general, who—due to a certain overload of work in daily business—often do not have the time and mental capacity to engage in abstract (and, therefore, seemingly scientific) discussions. Often, only things that appear concrete make people feel like something actually is concrete.

A final driver was an intentionally complex naming scheme for the concept. An example would be the "Generic Component" at the lowest level of the product decomposition. This was done to have a precise name that was not yet taken by any organizational unit. Yet, the idea was that a complex name would grind-in through everyday use into an acronym or a simple term, in this case "Component". This does, in fact, happen. However, the general term component was used colloquially before and could not have been designated right away.

With regard to the **team**, the strong social bond and team spirit certainly were the most important drivers. A clear picture of who the team is and what it stands for generated such a common and shared identity. A helpful starting point was that many members of staff have graduated (M.Sc. degree or Ph.D.) from the same institute, and many have worked on methodology before. The common mindset through this education provided an important ingredient to bypass the otherwise needed orientational discussions, and it allowed having a deep understanding right away throughout the group. At the same time, this background just helped as a common starting point that needed a strong leadership to sustain and foster this mindset and understanding. Therefore the department was, from the outside of the organizational unit, often perceived as a "proactive" team that would accept challenges more than defend against new ideas, driven by a quick and common understanding. The continuity of external partners, some of whom had a similar background as the team in engineering design research, provided more stability here too.

Aside from the continued support by a few selected consultants to provide stability in the concepts, **outside resources and inputs** were used for a number of reasons; in particular the review for conceptual gaps and the help with a certain tunnel vision that comes in over time was helpful, both through consulting and academic discussions. This was especially true with regard to aligning the concept of product architecture with neighboring concepts for, e.g., the bill of material, project management, configuration logics, etc.

In parallel, a number of projects were run with academia to continuously have input and reflection on the progress of the implementation. This was, to a large extent, done through student theses on the context of different research projects: One externally funded project (AMISA, funded as part of the EU FP-7 framework) and one internally funded doctoral student were doing their research on modularization as part of MAN. Specifically, theses were done on, e.g., an architecture framework (what is architecture about), handbooks for the process and for the product decomposition, the database concepts for process support, different examples and their value for MAN, and the alignment with scientific concepts for modularization (e.g., the approach of Erixon (1998) and how it aligns with the needs of MAN). The key in using these concepts, however, was not the theses as such but their stepwise integration into the concept for architecture, i.e., making sure that the initially abstract information model became more and more adapted to MAN over time with the help of these inputs. This mixture of theory and practice takes time, and it could often only be done through students who would serve as a bridge between both perspectives.

The **introduction strategy** was mostly driven by common approaches from organizational change management:

- Stakeholder management, in particular with upper management; unfortunately, lower management and the white-collar workforce were not reached intensively enough
- The establishment of early "champions", such as a new design project that served as a first implementation while the complete concept for the architecture process was not yet finished
- The early integration of captious critics who were closely integrated to identify weak points early

From a scientific perspective, two aspects were adopted, which might seem unusual. On one hand, a steering committee (consisting of line executives and project managers) was established to oversee the implementation of the organizational unit for product architecture, much like it is often done in research projects and, at a smaller level, the supervision of theses. This helped to obtain a shared concept and multipliers within the company early in the process.

On the other hand, a demonstrator for the process (based on a simple database tool, comparable to what often is generated in research projects and doctoral theses) was built to validate and to illustrate the approach. This helped to obtain concrete feedback (e.g., “you missed the attributes for weight management”).

In addition, the related **communication** mostly integrated classic organizational change management aspects. In addition to top management support, the documentation related to the introduction was adopted from university lectures to foster communication through different means of the company and the establishment of different learning approaches for involved engineers: All methods and tools were documented in a way that the individual engineer would either have a click-by-click manual for the tools or an instruction leaflet that would be similar to a lecture note, usually done with Microsoft PowerPoint using the notes function.

Paralleling learning approaches in academia (e.g., case study-based), large-scale workshops were run with project staff involved to assure that the approaches were not just listened to but tried out. This, again, helped to solidify the concept and its acceptance in the organization. Having academic keynote speakers (mostly full professors) on such workshops as facilitators (at times, not continuously) helped further to reflect on the progress and the added value by bringing in an accepted outside opinion.

The **operational support** helped to introduce the concept of product architecture; the remaining two aspects of Table 1 (training and top management support) are not further regarded here, as they do not have any specific linkup to academia. In fact, the concept of operational support is a core principle for all staffs working in the product architecture group, as they design their methods and then run them in real-life design projects. Through this, a bridge was built from the rather abstract concepts to the application thereof within the company. This allowed to identify gaps, to integrate criticism, to train staff, to build experience, and to better understand the problems associated in practice. Summarizing the experience of the past three years, to the author’s understanding this “mixture of theory and practice” was the strongest success factor.

3 Reflection

As part of the reflection, the input from academia and industry is discussed to draw conclusions on what aspects were helpful and what aspects could serve as recommendations for similar future projects.

3.1 Scientific Concepts and Their Influence

The impact from academia and science has had different facets, all of which were rather indirect and did not directly lead to the implementation of product architecture at MAN. The following aspects are considered more closely (Table 2).

Table 2 Types of impact from academia and science

Type of factor	Description
Input and results from research	The actual contents and results obtained at research institutions, mostly as published works
Education in research	The training background of staff involved and the skills obtained through work in research and academia
Cooperation of industry and academia	The working mode with different research institutes and the input generated thereby

The concept, as discussed above, mostly draws upon **input and results from research** published through academia. Essentially, the concept implements the ideas discussed by Ulrich and Eppinger (2012) and similar approaches (especially systems engineering), which were reviewed and collected as a starting point for the concept. However, all reviewed scientific concepts prove to be too high level to be applied directly, or they were too generic to be adapted without larger changes; basically, they provide a basic idea that can serve as a starting point. Despite much research being done initially, little was found on practical implementations of product architecture, although many companies practice such an approach.

Specifically, the lack of variant planning in product architecture processes proves to be a shortcoming that had to be added. Here, a mixture of different scientific methodologies found their input into the concept, such as Erixon (1998), Zagel (2007), Blees (2011), or Göpfert (2009).

Orientation on how such abstract concepts were implemented was mostly obtained through external consultants with a scientific background, namely a few professors from PDM/PLM to engineering design research, who served as reviewers and workshop facilitators at different points in time. In fact, their knowledge, having seen many companies with similar issues, served as a valuable way to gauge the maturity and completeness of the concept for product architecture. It should be pointed out that all selected professors had an extensive background in industry before they (re-)joined their current academic positions.

However, it must be stated that research publications largely fell short of expectations, especially with regard to the following points:

- Many papers only showed ideas and very few examples of implementation; often, just one example is given that rather illustrates the idea than the success factors for a sustainable implementation
- Many approaches remained abstract and too far from industrial implementation, i.e. formats, tools, or templates could not be generated from the publications
- Almost all publications show only parts of a problem and are hard to embed in a bigger picture; often, therefore, research regards only fragments and cannot be applied or transferred, and there are almost no works that build a more complete vision
- The often pragmatic approaches that still need to be implemented in industry (e.g., MAN still has a paper-based release process and a change management

process that does not incorporate VDA standards, yet) are little regarded in research, and there is a wide gap from the common problems to the solutions published

- Industry is quite open to more input in the form of frameworks, white papers, and well-structured collections of material; often, accessing the right results from research proves to be too difficult to be undertaken

On the other hand, the background in academia and the **education in research** of several members of the greater team (three former doctoral students of the same research institute were involved, and five former M.Sc. students who had worked with the doctoral students at that time) provided a common input into the implementation. Here, it was mostly the common mindset formed through having done research together, but also the common understanding of research methodology and the commonly discussed concepts from research that were of use:

- The ability for scientific reasoning, above all, was needed for a concept of such large impact as product architecture. In fact, much of the documentation philosophy at MAN was adapted and refined in the end, reaching from the early phases and the documentation structure in CAD all the way down to the vehicle configuration methodology in sales; therefore, the concept had to be well considered
- The ability to document and teach, as is done with academic lectures and seminars, helped to make the new process available to more and more staff; in particular the simple lecture notes used, such as presentation slides with a short descriptive text, were well received
- The scientific network, gained through conferences and comparable events, proved helpful to obtain closer insights into companies with similar issues; the basic trust gained through a common work focus in the past and the common language about design methodology was the basic enabler for such exchanges (these could be considered informal benchmarks)

Last, the **cooperation of industry and academia** should be regarded; in the regarded implementation, a number of cooperative projects were run (see above for details). Such cooperation projects, above all, provide a context to embed students in the industrial work, mostly through theses that are supervised from both ends as part of a common research project. These theses provide documentation of adapted ideas, and they typically provide enough time and resources to adapt a scientific concept to an industrial context; in a way, the students (at B.Sc., M.Sc., and Ph.D. levels) bridge both worlds thereby.

Another input is academic staff taking part in larger scale industrial events, particularly workshops and presentations. Both the role as academic keynote speaker and the role as a facilitator were used several times with different professors, mostly providing an outside opinion and a certain basic credibility to scientific concepts by making the persons behind the concepts "tangible". Also, the facilitation, at times, helped to simplify concepts that, in the company internal discussions had gone "too far" (i.e., "do you really need that?").

3.2 Industrial Concepts and Their Influence

A few aspects from a more industrial context should be noted, as they are closely related to science; in fact, they extend the ideas previously discussed.

- The availability of industrial standards, such as VDA standard 4965 for engineering change management, to use commonly accepted procedures, commonly accepted nomenclature and validated processes. VDA 4965 was, in fact, a result of a cooperative project of academia and industry itself, and it is, as such, a good example of how such collaborations can be successful and generate value
- The exchange of examples, templates, and handbooks, either through direct contact with other companies or through consulting agencies
- The availability of industrialized methodology through software vendors—however, it must be stated that such companies are driven by an interest to sell their product and therefore regarded carefully.

3.3 Recommendations

How can research better adapt to industry? A few conclusions can be drawn to aid a better alignment of the needs:

- Researchers should understand the need for pragmatism in industry. While many researchers are, of course, aware of this, many also are not. Especially the large number of young doctoral students doing the actual research work have very little or no background in industrial practice, and their ideas from how things should be done are often very unrelated to what can be done. Therefore, basic training in what industrial practice is about, and close discussion of research with industry to ensure its relevance, are advisable.
- The availability of tools, templates, and demonstrators from research projects would be a good step to illustrate research results and make them more accessible for staff in industry. In fact, such simple tools are often the result of a research project, yet normally only published material is available. Having a tool to play with helps to lower the initial hesitation to try out a method, and often it helps convince management that it actually works. To the author's observation, however, it is nearly impossible to obtain such demonstrator tools.
- Results from academia are often not structured for an industrial mindset—most staff in industry think in organizational structures and industrial software tools, and other descriptions are hard to accept. On the other hand, few researchers have close insight into how companies are set up, and therefore find it hard to adapt to this.
- Staff in industry is typically very absorbed in day-to-day problems, which often are quite practical issues; therefore, it takes time and effort to engage in scientific and abstract descriptions. Language and modeling, as often seen in scientific

papers, are quite hard to understand, therefore, and thus of little use. Publishing, e.g., in industrial magazines could help reaching such a level of descriptions.

- Lecture material should be made available to companies on request, or ideally even freely through the Internet. Often, lecture slides and lecture notes contain a good overview of an issue, and outline both industrial and scientific issues and solutions.
- Academia should provide and facilitate more exchange of experience among companies; only academic institutions can do so on a neutral ground without direct commercial interests, which often colors such events if run by consulting agencies or software vendors.
- Topic maps on research solutions and industrial problems would be a positive way to help the dialog and mutual understanding. They could be countered by scientific frameworks to provide orientation and help with a bigger picture on individual topics. They could also be completed with available definitions and examples. In fact, such a framework was generated for MAN as a starting point, and in collaboration with academia.

3.4 Conclusion

In conclusion, it must be said that the implementation of product architecture design at MAN would not have come this far without the input from and support by academia. At all stages, the adaptation to the company needs was necessary, and it cannot be expected that research results be ready for industry right away.

At the same time, not all researches (even in engineering design methodology, which is a very narrow field of research) have to be relevant to industry. The influx of novel ideas only is possible when there is room to think outside the box.

Yet, it needs a balance of both to ensure progress. Here, industry needs to open up to the fact that "ivory tower" is not bad per se. The comments from colleagues at MAN confirm this more than once. At the same time, researchers need to ensure that they understand industry to be able to discuss their results in a multifaceted manner and regard the relevance of their results.

An ongoing dialog between industry and research is needed to ensure mutual understanding, e.g., through conferences, workshops, seminars. This needs effort, especially to overcome the mismatch of abstraction that is needed on the academic side but that makes immediate implementation in a company difficult.

The role of consultants needs more consideration. From an industrial point of view, consultants—especially their experience across companies—are the typical means of implementing new procedures and tools; therefore, their access to the state-of-the-art methodology helps transferring this knowledge into industry.

Developing new methodologies and tools without regard for how existing approaches or established processes in a company can transit into a better methodology makes it hard to adopt new methodologies. Therefore, the dialog in science needs to put focus how industry works today in much detail to be able to provide acceptable new methodologies.

An important enabler in this research was the prototypical introduction of the new architecture process to gain feedback on its viability. The use of interim tools went much beyond the typical scientific validation and—due to the industrial environment—was carried out with less scientific rigor. At the same time, it provided the necessary details needed for a fully industrialized solution. Academia could adapt this idea through, e.g., process labs in cooperation with industrial partners or through larger scale simulated design projects.

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Verification Upstream Process, a Quality Assurance Method for Product Development in ODM Mode

Antti Perttula

Abstract Product development of many high-volume consumer products has moved to original design manufacturers (ODM) during last few years. The ODM market has grown steadily and has been estimated to reach several hundreds of billions euro currently. In ODM business mode, ODM customer sets requirements for product, carries out quality assurance activities, and approves the product finally. ODM's role is to manufacture the product and to participate in product development activities with ODM customer or to do the research and development completely by itself. Naturally, there are remarkable differences between the ODM and ODM customer in order to make this working mode meaningful. ODM's development and manufacturing may be closer to market, resourcing can be more flexible and thus shortening time to market, labor costs can be lower or ODM may simple have specific knowledge on new technology like electronics chipset needed in the product. In this article, we describe the benefits and challenges of ODM mode. The main focus is on quality assurance activities. We describe how one quality assurance method verification upstream process (VUP) can be used in ODM business mode. With VUP, we can improve verification and validation (V&V) requirements setting, harmonize V&V tools and methods as well as to improve results reporting. VUP focuses on early risk management, where ODM takes care of part of quality assurance by itself.

1 ODM Mode

1.1 What Is ODM?

Original design manufacturers (ODMs) are being used widely in electronics product development and manufacturing recently. Typically, products are consumer devices with large manufacturing volumes. The products are not necessarily meant to meet

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extremely high quality or reliability requirements like what is required in aviation, medicine, or military industry. Normally, ODM takes care of manufacturing and participates in R&D as well. Similarly, component sourcing can be done by either ODM, by ODM customer, or by both parties.

ODM has not a brand of its own but the products are sold under ODM customer's brand. The largest ODMs include Quanta Computer, Pagatron, Compal Electronics, Wistron, and Lyell (2012). Main ODM customers are well-known brands like Apple, Hewlett-Packard, Dell Computer, Asustek, and Nokia. Many ODMs are very large companies; the two largest ones together have over 46 billion euro turnover Quanta (2012), Pegatron (2012). Interesting is that in practice all main ODMs in electronics industry are Taiwanese firms who have manufacturing sites in Mainland China. R&D is in Taiwan or in some cases both in Taiwan and in China. It has been estimated that Taiwanese ODMs manufacture over 90 % of world's notebooks and most of the tablets as well. Compal Electronics alone is expected to produce up to 10 million tablets in 2013 The China Post (2013, Jan 20).

1.2 Benefits of ODM

ODM business mode has many benefits and so it is widely used model in product development and manufacturing. For ODM customer, it increases flexibility in terms of resources and thus time to market. For ODM this is a good way to focus on cost-efficient mass production without needing to invest in marketing of the end products. In addition having for example smartphone manufacturing in China, which is also the largest market for those devices currently, brings many benefits like savings in logistics costs, faster time to market, and also savings in customs duties Savitz (2012). Similarly, if also R&D is close to the main market then it should be easy to make products to meet customer wants and needs.

ODM customers and ODM manufactures are different in many ways. Only by taking in use the best from both parties, the optimum outcome can get out of this relationship. ODM customer must not control ODM's internal practices if they are not related with product development or product quality itself even if activities look a bit strange. One example could be the normal habit in China to shut down lights in the office and take 1 hour nap at desk during lunch hour. If ODM mode is properly understood and managed, it is possible to bring high quality products to market very fast.

1.3 Challenges of ODM

ODM and ODM customer have many differences, which on one hand make this kind of working mode meaningful, while on the another hand introduce challenges as well. Challenges include differences in company cultures—in language and organizational structures. Partners are physically in different locations, may be 15,000 km and 10 time zones away which makes communication and face-to-face meetings very difficult. ODM may have lower labor costs which lead to differences in manufacturing processes. More manual work and less automation are in use. To prevent assembly mistakes, different kinds of jigs must be implemented. Also proper operator training plays a key role.

The author has noticed that language differences introduce many problems. Greatest challenges seem to be misunderstanding at both sides. Communication by e-mails is far from enough in most cases because nonverbal communication is extremely important in Chinese culture. In Mandarin language, a sentence may have completely opposite meaning if words are pronounced in different way. If you see the person’s body language and faces, you have better probability to understand the message right. One example in Mandarin is a word “mai,” which means both selling (卖/mài) and buying (买/mǎi) depending on which tone is used in pronouncing. Even for native Chinese speaking persons, it is often difficult to understand what one individual world or sentence could mean without having the full context with more dialog. The language may have influence to logical thinking as well. It seems that for example root-cause analysis relating with testing failures is done different ways in Chinese and Western organizations.

We have improved product development and finally product quality in ODM mode by introducing verification upstream process (VUP) there. The benefits of VUP will be explained more in next chapters.

2 Verification Upstream Process

2.1 Verification and Validation in Product Development

Verification has been widely understood as a method to prove the compliance with the specifications. If verification is done with known uncertainty, then we know well how product meets its requirements. These are not only the user requirements for the complete product, but also requirements for the components and the subassemblies. However, it is not well known that verification can be determined, in addition to test, by inspection, demonstration, and analysis Mooz et al. (2003). The aim of validation is to prove that the user is satisfied. Validation answers the question “Is this product behaving as the Customer anticipates?” Validation involves the evaluation of the Customer requirements against her or his needs and expectations in the most representative environment achievable. Validation is sometimes defined as an end-to-end verification to show that the whole system meets its requirements under operational conditions Stevens et al. (2000).

Figure 1 describes the difference between verification and validation. Verification compares the product with the specifications. Validation makes sure that the Customer is satisfied, i.e., her or his needs and wants are met. This is

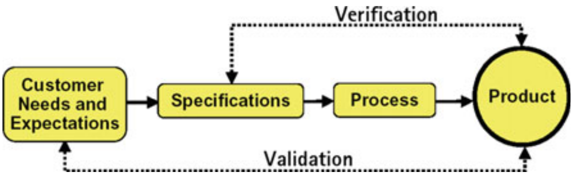

Fig. 1 The difference between verification and validation Perttula (2004)

usually the most important issue of the product development. Verification and validation are different activities, but when it is not needed to highlight their individual purpose, we call them as a single activity, V&V, for simplicity.

Verification and validation have an equal importance in the PD. It is easy to understand that the product must meet the most important requirements, such as those based on legislation. However, validation plays a crucial role in ensuring that the customer shall finally accept the product. By reliable verification, we can be sure that the product meets its requirements. This applies in any kind of working mode, including in ODM.

2.2 *Purpose of Verification Upstream Process for ODM*

VUP has originally been developed by the author for managing quality of component and module suppliers. However, we can implement VUP methodology with ODMs as well. First activities in VUP, in addition to verification requirements development, are relating to ODM's competence and capability assessment and competence development in order to be able to carry out verification activities reliably. Practical goals of VUP are to:

(1) Harmonize verification specifications, methods, facilities and people's competences,
(2) Harmonize verification results reporting templates, tools, and practices for better utilization of results,
(3) Reduce verification workload and overlapping by managing the verification activities as a flow from ODM's R&D through manufacturing verification and
(4) Minimize the overall workload by tailoring verification specifications according to the risk analysis. For example, if the new product is based on previous one not all verifications are needed to be repeated.

The key benefits of VUP are shorter product development time, faster error correction cycle, reduced workload of engineers releasing their time for other duties, and improved product quality. In addition, VUP has increased trust and mutual understanding between module ODMs and ODM customer. Similarly, verification results utilization has being improved. For ODMs, VUP is a good opportunity to increase the quality and efficiency of development process. ODM's product quality is benchmarked continuously and so the areas which need improvements are known all the time.

VUP is based on ISO/EN 17025 standard and Testing Maturity Model Burnstein et al. (1996), which are used as main guiding quality documents. ISO/EN 17025

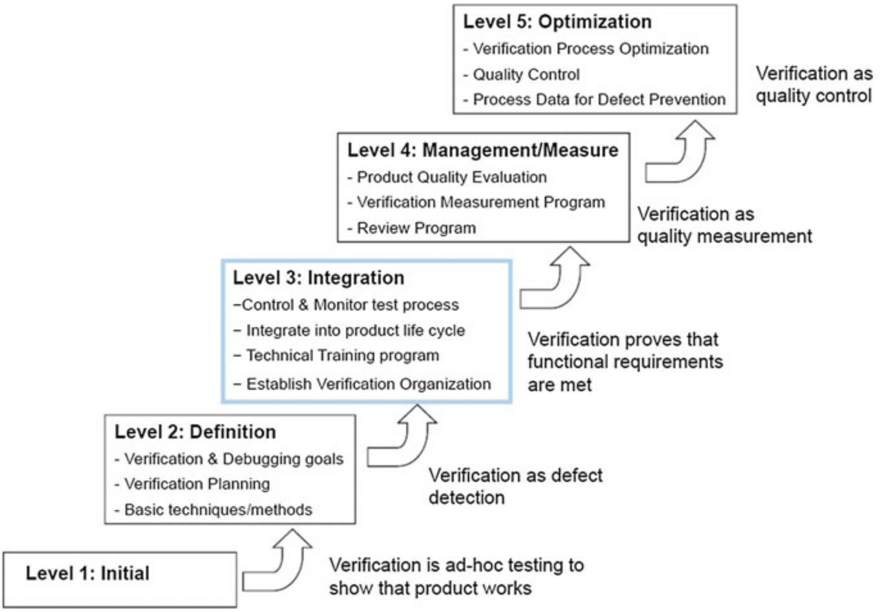

Fig. 2 VUP maturity levels modified from TMM Perttula (2007)

standard sets requirements for testing and calibration laboratories. We can say it includes ISO 9000 standard's items with additional requirements for testing and calibration laboratories. Testing maturity model (TMM) has been developed from capability maturity model (CMM) first for software creation organization's maturity assessment. The author has modified the TMM with its five maturity levels to be suitable for all kind of development projects including HW and mechanics (Fig. 2).

Maturity levels of VUP

Level 1 Initial level, preassessment in all verification areas (performance, electrical & functionality, reliability and EMC) done, current and potential verification capability assessed

At this level, verification is "ad hoc testing to show that module works"

Level 2 Basic verification practices and methods are in place, most test equipment (according to ODM customer requirements) exist, competence, and capacity are at medium level, basic root-cause analysis capability and verification plans exist. ODM has carried out assessment for its third-party partners and internal assessment are being done regularly
"Verification as defect detection"

Level 3 ODM meets ODM customer's requirements in test equipment and people competences, verification reporting is done according to agreed time schedules and methods. ODM has good root-cause analysis capability and verification is based on established processes. Verification is not repeated at ODM customer because results can be trusted fully
"Verification proves that functional requirements are met"

Level 4 ODM has full root-cause analysis capability and it can prove that corrected errors are not repeated, adequate simulation capability exist in areas where required and simulation models have been done on agreed time. ODM can further develop verification methods and can show that by simulations amount of physical testing has decreased and time to market shortened
"Verification as quality measurement"

Level 5 Optimized level. ODM can show the benefits of different kinds of verification activities by calculations and amount of verification work load has decreased without increasing risks in quality or reliability
"Verification as quality control"

2.3 Implementing Verification Upstream Process for ODM

There are three phases in VUP: preparatory actions, ramp-up phase, and continuous mode. Preparatory actions include requirements development, building of VUP development teams, and defining reporting tools and templates. In the ramp-up stage, ODM reaches desired maturity level which means in practice that verification results can fully be trusted and results are reported using agreed tools and templates. In continuous mode, we are implementing some quality assurance activities to ensure that the maturity level of verification stays at desired level. These three phases of VUP deployment are described in more details in following chapters.

2.3.1 Preparatory Actions

There are three preparatory actions in VUP development including:

(1) To development verifiable requirements for the product. As shown in the Fig. 1 verification is an activity to check that product or module meets its

requirements. Thus the complete set of requirements must exist before development can start. In fact, the development of those ones for product can be a very time-consuming task. For an electronics product, requirements are set for mechanical reliability, electromagnetic compatibility (EMC), product performance, usability, safety, HW electronics, and mechanics functionality.

(2) To create VUP coordination teams at ODM customer for each verification area. Team members need to have good technical knowledge in their areas and also good quality audit skills. In addition, the team members should work in practical product development projects to be able to help ODM to build their practical competence. The VUP team ensures that the VUP requirements are up to date all the time and makes sure that practical VUP implementation will be successful.

(3) To develop verification reporting methods for easy information sharing and verification results usage. In practice, verification results reporting templates were created for each verification item in each VUP area. In addition, common database was created where ODM can download the reporting templates and the latest version of requirements. ODM is supposed to use the templates to report their verification results finally.

2.3.2 Ramp-up Phase

There are six ramp-up phase's actions in VUP implementation for ODM:

(1) To contact the management of ODM and arrange kick-off meeting where VUP methodology is explained and introduction material shared including the VUP team members of ODM customer. Most important outcome from this meeting is to get ODM's full commitment to VUP.

(2) To ensure that ODM has capabilities to start using common VUP database for sharing all VUP related documentation like verification requirements and results.

(3) To carry out preassessment in ODM's product development facility to understand what are its capability and capacity to carry out all verification cases reliably and meeting project time schedules. As part of assessment testing laboratories will be audited to see how different tests are carried out in practice and if there is a need for test equipment investments and, for example, need to train VUP team. Normal action is also to check that all relevant equipments are calibrated and also to understand the status of laboratory environmental conditions. Final action in preassessment is to share with ODM's management the findings from laboratory visit and the outcome of earlier discussions with ODM's VUP team members. Based on this information, improvement actions with time schedules are agreed with ODM.

Typical improvement actions are relating with test equipment calibrations, laboratory's electrical groundings, and improvements in temperature and humidity control and people competences.

(4) To help ODM to complete the agreed improvement actions. VUP team can give training to ODM's staff, recommend which test equipment to purchase and how to use test automation best way. As part of this phase, ODM is supposed to show by piloting with a real product that desired maturity level has achieved. It takes typically 3 to 6 months to complete all agreed improvement actions.

(5) To carry out VUP assessment where ODM's maturity level is checked while visiting the product development facility again. The main purpose of this assessment is to ensure that all improvement actions are completed and verification results from pilot product correlate well with ODM customer's results.

(6) To prepare assessment report to ODM's management. The report summarizes the findings of assessment visit and sets what the VUP maturity level of ODM is.

2.3.3 Continuous Mode

When the ODM has reached the desired VUP level, it will enter into so-called continuous mode. At this phase, the main focus is on quality assurance activities. These include reassessment visits, interlaboratory comparisons (benchmarking) with other laboratories and random correlation studies. In benchmarking, we are interested in both accuracy of test results and how fast testing is done. Figure 3 shows the results of comparison measurements.

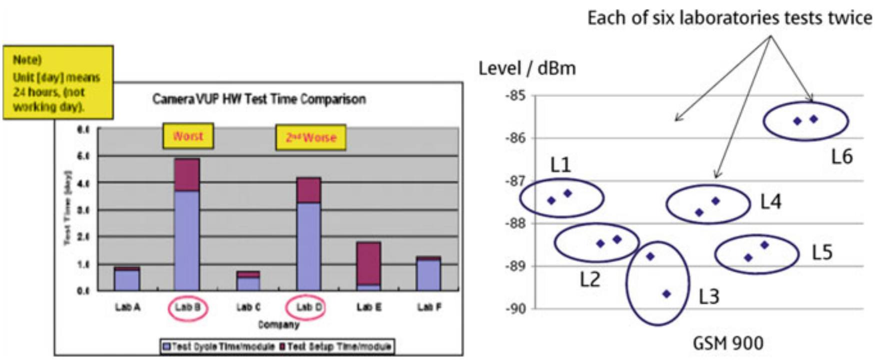

Fig. 3 Comparison measurements between different laboratories. The *left-hand side* of the picture compares the speeds of laboratories and *right-hand side* the accuracy of test results. Picture shows that laboratory *3* is the fastest and laboratory *2* the slowest. We see also that the results of laboratory *6* are away from others and thus may be wrong

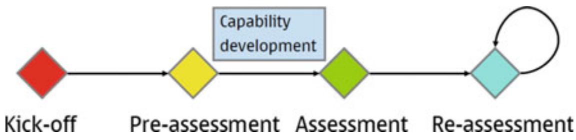

Fig. 4 Phases of VUP. As usual it takes between 6 and 12 months until ODM achieved sufficient maturity level and can move to continuous mode. Reassessments occur once or twice a year

Typical reassessment meeting's agenda includes topics like: participants' introductions, purpose of the assessment day, and basics of VUP, action point review, more detailed discussions in different verification areas including laboratory visits, preparing reassessment report, and finally presenting the report to ODM's VUP team members and ODM's management. The report may include some further action points and recommendations.

By the actions in continuous mode, we know the status of ODM and we can decide whether ODM can stay at desired VUP level, are some improvement actions needed or will ODM be degraded to lower maturity level. In benchmarking, we are focusing on how accurate verification results are and how fast the whole verification process is. Figure 4 explains the different phases of VUP process.

2.3.4 Benefits of VUP

We carried out a survey at an ODM customer site to understand what kind of influence VUP had on module development done by external suppliers. In addition, we wanted to know if there is any influence to module quality, cost, and development time. Questionnaire was sent to 60 persons working in product development, sourcing, and other functions in different positions. All persons had at least basic understanding on VUP. 34 persons answered the survey. Figure 5 summarizes the most relevant quality related answers

Figure 5 shows that over 80 % of people agree (less than 10 % disagree) that VUP is speeding up module development, question 1. Over 50 % think that implementing VUP has significantly reduced R&D costs, question 2. About 90 % agree that competence level of supplier's staff has increased, question 3. Answers to question 4 show that there is possibility that module price may increase; however no one fully agreed this. With question 6, we wanted to know how good quality management methodology is VUP really. Close to 60 % people replied that VUP has greater influence to module quality than other quality systems.

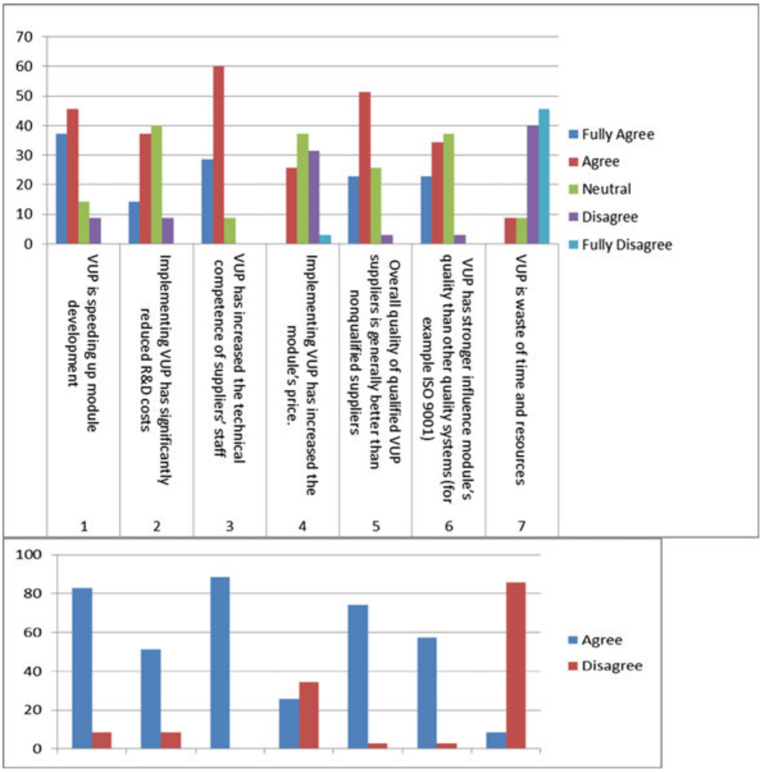

Fig. 5 Influence of VUP to product development. Upper part of figures shows all answers in percentages from fully disagree to fully agree. On the lower part of figure we have combined fully agree and agree as "agree" and similarly fully disagree and agree as "disagree"

3 Discussion

There are many challenges to overcome before getting maximum benefit out of the product development in ODM mode. Naturally, ODM and ODM customer have many differences. We can say that only the differences make this relationship meaningful. Most challenging divergences are related to communication because of physical distances, different cultures, and different languages.

The author has noticed while working for many years with external suppliers and with ODMs that the most important issue is to know what we actually want from an ODM. This means that the product requirements need to be very clear and right. After this there is one activity, verification to prove that product meets its requirements. ODM needs to carry out verification activities so well and reliably that the results can be trusted. When verification is done and results are acceptable, we know that the product meets its requirements and has been done right. VUP is a well-defined methodology to help in one hand the ODM to build its competence and in another hand to guide the ODM customer to make all needed quality assurance activities. Part of quality assurance activities have moved to ODM. VUP also helps in communication between ODM partners because communication methods with reporting templates and common databases will be created and agreed during VUP ramp-up phase. The survey done at ODM customer side shows that it has clearly improved product quality and decreased development time. However, it would be interesting to carry out similar survey at OMD side to understand the influence to VUP to them also.

At the beginning, the greatest challenge in VUP deployment was to get full commitment from the management of ODM customer because a lot of investments were needed to create full set of requirements for the product including its modules and components. One step toward getting commitment was to clarify what kind of problems product development with suppliers had at that time and explain in what areas VUP could help. Problems included long development time because there was a lot of discussion with suppliers about product and testing requirements, test results were not consistent and also test reports were unclear. Because of these, tests had to be repeated at ODM customer side requiring more time and causing increasing cost.

In this study, dialog between academia and industry went pretty well because there were clear problems to be solved and in academia there was research done with relevant results to help solving the problems. In addition, at same time the author prepared his dissertation research in a similar area of product development and acted as a link between industry and academia.

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Understanding the Gaps and Building Bridges for Synergy—How to Promote the Dialogue Between Design Research and Design Practice

Josef Ponn

"What is the impact of design research on practice?" To be able to answer that question it is helpful to understand the nature and circumstances of design research and design practice. Pathways from academia into industry are discussed in general and by concrete examples taken from the personal background of the author of this contribution. A major prerequisite for generating impact is to maintain a dialogue between both parties. The current situation of this dialogue is reviewed, leading to the conclusion that there exist strong gaps and hurdles. Based on the analysis and understanding of these gaps, a proposal is made for enhancing the communication between design research and design practice.

1 Introduction

The goal in industry is to develop products and introduce them into the market successfully. Challenges are among others an increasing complexity of markets, products, processes, and organizations (Lindemann et al. 2009) in combination with tough project restrictions (time, budget, resources). In order to handle these challenges, systematic approaches and methods are needed.

The goal in design research is to deliver contributions for a better understanding of the mechanisms of product development in practice. Based on that understanding the aim is to develop solutions (i.e., knowledge, methods, and tools) to handle challenges and tasks of product development with more effectiveness and efficiency (Blessing 2002). In order to create contributions with practical value, knowledge is needed concerning the real challenges and requirements of industry.

Bearing in mind the goals and challenges both parties are dealing with, there is a **huge potential for mutual benefit**, if design research and practice come together for a synergetic exchange. There already exist many channels through which interaction takes place between industry and academia, but there are also gaps.

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2 Situation Analysis: Understanding the Gaps

The **gaps** between design research and design practice result from the different perspective of each domain. Although in reality the picture is of course not black and white, the discussion is intended to display the basic contrasts. The gaps manifest themselves in following dimensions:

- **Objects in focus:** role of methods versus products
- **Altitude:** level "above the ground" from which problems are viewed upon
- **Working style:** way of approaching tasks and problems
- **Target perspective:** objectives in focus, primary aims, value system
- **Perspective toward change:** focus on current state versus target state

First of all, the **objects in focus** are different. Research primarily focusses on methods, either the investigation of the use of established methods in industry or the development of new methods. Products serve as examples illustrating the application, benefits, and weaknesses of these methods. In industry, the focus is on products. Companies aim at bringing their products successfully into the market at the right quality and cost. Methods are deployed as a means to achieve good results and in order to guarantee an efficient process.

Then there is a basic difference in **altitude** (meaning the level or height "above the ground," from which problems in reality, located "on the ground," are being viewed upon). Researchers tend to fly on a high level, looking for the big picture and the holistic view, building generic frameworks and methodologies. They are working from a top-down perspective. The contents used to develop or evaluate these frameworks often tend to be rather generic. Practitioners on the other hand are often deeply engaged in technical details on an operational level (on the ground), working from a bottom up perspective. They sometimes miss the big picture, for which they would need to gain more altitude.

Furthermore, there is a basic contrast in **working style**, i.e., the way of approaching tasks and problems, which is highly influenced by the boundary conditions of each domain (e.g., time and budget limits). Researchers tend to create sophisticated methodologies and comprehensive procedures. They take into account the state-of-the-art research, trying to get a broad overview by exploring and structuring the problem and solution space. They place value in good documentation and clear reproducible argumentation. Practitioners on the other hand show a clear preference for pragmatic solutions, based on implicit knowledge and experience. Due to the operational pressure of "getting things done" documentation is often neglected. This working style frequently leads to problems in later stages, e.g., when the details of how a certain result was produced are unclear or the responsible person is not available.

Concerning **target perspective,** design research is primarily focused on academic and scientific value, whereas design practice aims at practical value. The goal for the researcher is to generate new contributions to the body of knowledge, whereas the practitioner searches for things that work in order to fulfill the task.

Design Research / Academia	Nature of the gap	Design Practice / Industry
Focus on methods, examples are used to display benefits and weaknesses	**Objects in focus**	**Focus on products**, methods are used to achieve successful results
TOP DOWN perspective, working on the big picture, building generic frameworks	**Altitude**	**BOTTOM UP perspective,** working on specific contents, deeply engaged in details
Tendency towards **sophisticated methodologies,** less severe project constraints	**Working style, constraints**	Tendency towards **pragmatic solutions,** tough project constraints
Focus on **academic value**, searching for new contributions to the body of knowledge	**Value system, target perspective**	Focus on **practical value**, searching for things that work and can be put to use
Focus on the **target state**, change regarded as potential for optimizing the current state	**Perspective towards change**	Focus on the **current state**, resistance towards change, no time for „sharpening the saw“

Fig. 1 Nature of the gaps between design research and design practice

Finally, there is a different **perspective toward change**. Researchers often concentrate on an idealistic target state, change is regarded as potential for optimizing the current state. In practice, although the deficits and pains of the current state are recognized, there is a certain resistance toward change. Or there is just no time for "sharpening the saw." In terms of magnitude of changes, researchers tend to focus on revolution, creating innovations, technical and organizational approaches that lead to significant improvement. Practitioners rather focus on evolution, based on existing designs and procedures that are optimized through step by step adaptations (Fig. 1).

These circumstances lead to **challenges for both parties**. Practitioners in industry are often set in their ways ("always done it like that"). They get stuck with the first idea in mind instead of investigating alternative options. The application of methods and systematic procedures possibly helps to exploit more of the existing innovation potential. But methods have to be known and to be trained before their application leads to considerable benefits for the company.

Researchers on the other hand frequently dwell on the surface of their generic frameworks. In order to deliver solutions that are "practically worthwhile," a deeper understanding of the details of industrial practice would be helpful.

This comparison between design research and design practice was meant to accentuate the basic differences of perspectives in their extremes. The conclusion of this exercise is that overcoming the gaps and **combining forces is beneficial** for both parties.

3 Generating Impact: The Path from Design Research to Design Practice

What is the nature of the **transfer between design research and practice**? The understanding of these mechanisms might help to explain the origin of some of the gaps and give hints toward creating bridges to overcome them. First, channels between design research and design practice are discussed in general. Then, the concrete example of the author of this contribution is illustrated. After that, the role of two topics that were present as a “red thread” throughout the different stages will be reflected and discussed in detail: methods and platforms.

3.1 Channels Between Design Research and Design Practice

There exist many **channels** between design research and design practice. Also, the **contents** being exchanged through these channels are manifold and range from knowledge in general over specific methods and tools to products, technologies, services and people.

This chapter will focus on the **transfer of method knowledge via people** (Fig. 2). One channel is via **students** who are trained in methods by academia and then go directly into industry (path A). Another channel is via **researchers**. Since people often enter the domain of research right after graduation (path B), their knowledge of industrial practice is limited. An idea to change that would be to spend a significant period of time in industry after graduating from university and

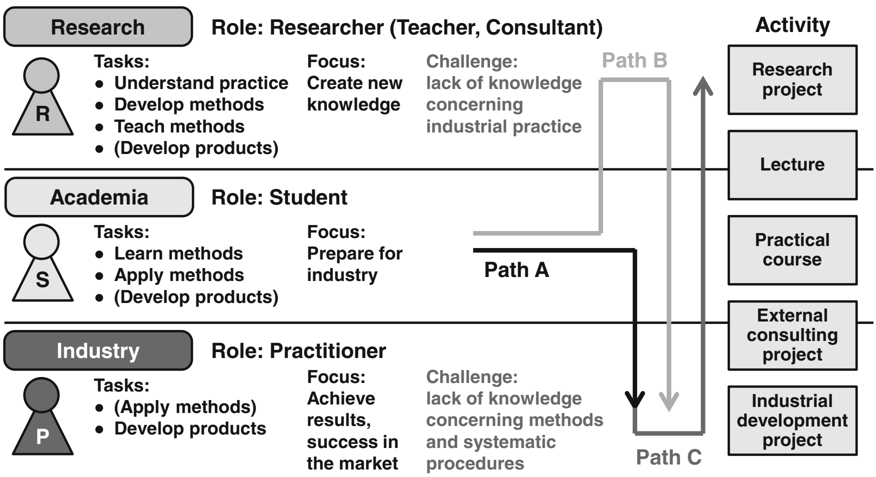


Fig. 2 The general path from design research to design practice

then enter research with a profound background and experience as product development **practitioner** (path C).

The transfer between the domains (research, academia, industry), respectively, between the actors as representatives of these domains (researchers, students, practitioners) takes place in concrete **activities**. In **research projects**, methods are developed by researchers. If these research projects are conducted together with industrial partners, a better understanding for industrial practice can be created (transfer from practitioners to researchers) as a basis for developing practice-oriented methods. In **lectures and practical courses** methods are taught (transfer from researchers in their role as teachers to students). In **external consulting projects** methods are implemented and applied (transfer from researchers in their role as consultants to practitioners). These activities and projects serve as platforms and carriers for the knowledge transfer between the domains.

3.2 From Design Research to Design Practice—an Example

The transfer from academia and research into practice is now discussed by taking the **concrete example** of the author of this contribution, who more or less took "Path B": from student to researcher to practitioner. The focus in each stage along the way will be highlighted to illustrate the change in perspective (Fig. 3).

After studying mechanical engineering with a specialization in product development, the author entered the domain of **research**. In a research project, the focus lay on elaborating methods and guidelines for the development of individualized products (Ponn et al. 2004). The author was further involved in teaching activities, in particular a lecture and practical course on product development and conceptual

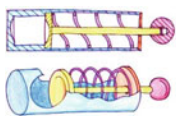
Stages / Functions	Role of Methods	Role of Products
Research / Academia		
Researcher Research project on individualized products PhD on methods	**Develop methods** Build framework for situational method selection, adaptation and application	**nutcracker, juice squeezer, high pressure cleaner, etc.**  low / medium depth, examples for method application, focus on concepts, simple prototypes
Teacher Lecture / Practical course on methods of product development	**Teach methods** Explain purpose / procedure, instruct method application using concrete examples	
Industry		
Methods Moderator methods based team workshops in development projects	**Apply methods** Support specific tasks in development projects using customized methods	**electrical powertools**  high depth, entire process chain from technology to serial ramp-up to product care; supply setup, platform scope
Project Manager for Platform Drives operational development projects	**Develop products** operational topics (communication, coordination), no explicit method focus	

Fig. 3 From design research to design practice—an example

design (Ponn and Lindemann 2011). Topic of the PhD thesis was the situational application of methods (Ponn 2007).

The focus was primarily on **methods** (FMEA, Morphological Box, variant management, etc.). Topics of scientific interest were mechanisms for describing, selecting, adapting, and applying methods successfully depending on the characteristics of the particular design situation. **Products** (such as high pressure cleaner, juice squeezer, nut cracker) were taken to illustrate the practicability of these approaches. The corresponding development processes were situated in an academic context (student designers, prototype development, and emphasis on concepts rather than on industrialization).

In industry, the first job was **methods moderator** at Hilti, a special type of inhouse consulting, where methods (primarily FMEA, creativity techniques and decision making) are applied in development projects. Methods of product design and development are well established and accepted in the company, the strength of this particular approach lies in the situational selection and application of adequate methods with a special focus on practical value and pragmatism. Here, the author could build upon his methodological foundation from his research background and put it into practice.

The current position is **project manager** for platform drives in electrical powertools, another step toward operational product development practice. The job gives a detailed insight into the whole process chain: from technology development to serial implementation to product care. Basic challenges concern operational topics (communication between stakeholders, coordination of the information flow, and finding a common language) as well as strategic topics (taking the right decisions with respect to technology, supply setup, or platform scope).

The path described above led to a significant **change in perspective**, from an academic view on product development and high focus on methodology, toward a more and more profound understanding of the challenges of product development in “real life”.

3.3 The Role of Methods in Various Stages

As a **researcher**, the author was dedicated to develop approaches toward a situational methods support in product development and design (Ponn and Lindemann 2006a). The foundation for that was the characterization of design situations concerning parameters that have an impact on the choice of applicable methods (e.g., novelty of the task, complexity of the task, method experience of the designers, size of the development team, etc.). A generic framework was developed to link design situations (based on their characteristics) to adequate tasks/procedures and methods. This framework was applied for the field of conceptual design, resulting in a morphological scheme for design situations in conceptual design, 18 process modules describing relevant activities within conceptual design and 36 methods to support these activities. Finally, a guideline was created to apply this framework in concrete design activities, including following steps: situation analysis, selection of procedure/task, selection of method, and application of method. The framework includes much of the previous work in the field of method research, e.g., the "key/lock" principle to match basic tasks and elementary methods according to (Zanker 1999).

As a **methods moderator** in industry, the focus lies on customizing known methods (FMEA, creativity techniques, variant decision, cause-effect analysis, etc.) to the needs of the company and the task at hand. Method application at Hilti is typically embedded in moderated team workshops. The success of these workshops depends not so much on the choice of the particular method and the "correct" execution of the method formalism. In the end, many methods are built upon the same basic working principles and represent a kind of formalized common sense. The key lies in getting the right mixture of people together and assure a structured, target-oriented discussion. Another success factor is the right mix between formalism and pragmatism. Throughout the course of a project, an important factor is to combine different methods to a reasonable sequence. Therefore, Günther has established the so-called **methods roadmap** (Günther 2006). Moderated method workshops are hereby linked to other project activities, such as detailing solutions in CAD, simulation and prototype testing.

Taking over the role of **project manager**, there was a shift of focus from methods to project deliverables. The project is broken down into work packages leading to specific results in the form of documents (such as Lastenheft, concept, detailed solution, test plan, technology maturity assessment, risk assessment, etc.) Thus, no explicit importance is placed on methods as a means of their own. However, in order to achieve these project results, a systematic procedure and a structured form of documentation is still regarded as extremely helpful (e.g., a morphological scheme to represent the selected concepts).

Generally, the aim is to reduce the amount of "trouble-shooting" in late phases (serial ramp-up of a product) toward more **frontloading in early phases**. Thus, besides operational project activities, the author is additionally involved in methodological activities, promoting approaches toward an improved requirements engineering. This includes among other things the establishment of the V-Model as an instrument for developing a common understanding between stakeholders (Fig. 4).

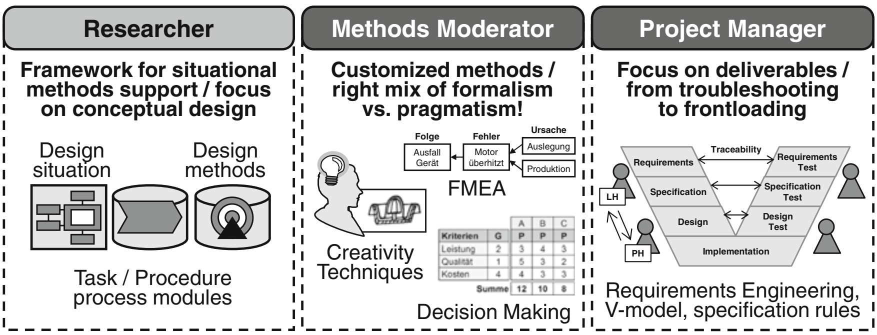


Fig. 4 The role of methods in various stages

3.4 The Role of Platforms in Various Stages

The theme complex of **variant management**, in particular the topics modularization, "Baukasten" and platforms played a special role for the author throughout the stages from researcher to methods moderator to project manager.

As a **researcher**, the author was involved in a collaborative research project on individualized products, a concept that aims at combining customer orientation (offering customers solutions that fit to their individual needs) with the benefits of mass production and off-the-shelf products (scale effects and standards in development and production) (Lindemann et al. 2006). The concept of mass customization or product individualization therefore calls for special forms of variant management, including flexible predefined product structures and processes that allow for an efficient customer-specific adaptation of product properties.

In this context, the author was dealing, e.g., with meta-models of the product structure of variant rich products as well as guidelines and rules for individualized products (Ponn et al. 2004). These exercises were performed on a rather theoretical level. To evaluate the practicability of the developed approaches, a high pressure cleaner served as product example (provided by a partner from industry).

As a **methods moderator,** the author soon came into contact with the platform concept at Hilti. "Platform" is a widely used term in the company; however there exists no clear common understanding on many associated aspects, ranging from the scope of a platform to organizational issues of platform development. Hilti powertools are characterized by a clear modular product structure, and many commonalities over the whole product spectrum exist on subsystem level, especially in the electric drive. The importance of "platforms," e.g., for motors, electronics, and batteries is widely accepted. However, platform development involves a considerable degree of technical and organizational complexity.

In his role as moderator, the author conducted several workshops for platform projects. In early stages of platform development, the focus is on defining the requirements and the right scope for the platform. An established method in this context is the requirements matrix, where each row represents a requirement and each column a different target tool. In later stages, risk assessments (FMEA) concerning the chosen solutions are made. Platform aspects also lead to a higher complexity compared to "normal" FMEAs, where only one product is regarded.

As a **project manager** for platform drives, a major issue from the beginning was the necessity for a clear assignment of responsibilities between drive project (platform) and tool project (platform user). One approach was classification of parts in platform (P), mixed (M), and individual (I). Owner of the P-parts is the platform project, owner of the I-parts is the tool project. A shared responsibility applies for the M-parts, which contain certain dimensions defined by the platform (standardized for all tools on the platform) and certain individual dimensions. Another issue was the definition of rules concerning the "platform freeze," meaning the completion of the platform project. This included the evaluation of change drivers (probability) and change impacts for each component of the drive (Fig. 5).

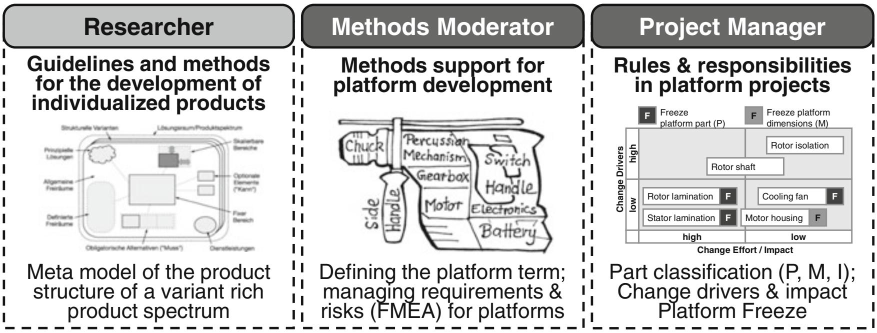


Fig. 5 The role of platforms in various stages

To sum up, there is a significant **overlap of topics** throughout all presented stages, not only in general (e.g., "variant management"), but also in the details. For example, elements of the meta model of the product structure from the research project on individualized products were "reused" in the classification of components in platform drives in the Hilti context (P, M, I).

As a **practitioner** the author still benefits from his background as a researcher in defining guide rails and structures for operational practice. As a **researcher** the author could have benefitted considerably from the knowledge on operational details of industrial practice, which he has acquired since entering the company.

Both domains (research and practice) have much in common, among other things the fact that the solution to many problems and hassles start with seemingly trivial things: agree on the name of objects, find a common language in order to reduce inefficiency and confusion in daily discussions (a glossary helps).

4 Proposal: Promoting the Dialogue by Building Bridges

The **goal of the design research community** is to "encourage design research that is both academically and practically worthwhile" (Blessing and Chakrabarti 2009). The key to reach this goal in the opinion of the author is an exchange that is bidirectional, give-and-take for both parties. Therefore, the **goal of this contribution** is to promote a synergistic dialogue between design research and design practice. Hereby, three major topics have to be addressed:

- **Mindset:** be open to the other perspective
- **Bridging the gap:** reach a "common ground" for discussion
- **Platforms:** set up suitable formats of dialogue and exchange

In the following, a number of concrete approaches will be suggested, that may help to bring design research and design practice closer together. In particular, proposals will be explored toward overcoming the gaps. Based on that "common ground," concrete platforms for exchange and mutual benefit are discussed.

4.1 Mindset: Be Open to the Other Perspective

One major prerequisite for a meaningful knowledge transfer lies in the relation between both parties. There needs to be an atmosphere of trust and the right mindset, i.e., the willingness of each party to listen to each other and try to understand the other perspective. The involved actors of both domains need to be convinced that the exchange is a win-win situation.

4.2 Bridging the Gap: Reach a "Common Ground"

With the right mindset as a prerequisite for the exchange, the next step is to overcome the hurdles that impede an effective and efficient dialogue. Each type of gap between design research and design practice is identified in Sect. 2 of this contribution can be bridged to bring both parties closer together (Fig. 6).

The topics "objects in focus" and "altitude" are related to a **vertical dimension**. Methods (which are the primary focus for the researcher) are positioned on the top and products (which are the primary focus for the practitioner) on the bottom. The gap can then be regarded as the distance from each other in the vertical dimension. Synergy is created when products (here also used as synonym for real life contents and operational project challenges) and methods are combined, i.e., the application of a method leads to the successful development of a product. Or in other words, challenges and solutions are matched.

Design Research	Approaches towards bridging the gap	Design Practice
Focus on methods	**Different object in focus:** Generate stories to combine products and methods / to match challenges and solutions	Focus on products
TOP DOWN, generic frameworks	**Different altitude:** Meet on a common flight level / build shared platforms to fill the frameworks with contents	BOTTOM UP, detailed contents
sophisticated methodologies	**Different working style:** be open to the other perspective → more pragmatism in academia, more systematics in practice	pragmatic solutions
academic value	**Different target perspective:** combine academic value with practical value (not necessarily a target conflict!)	practical value
Focus on target state (vision)	**Different perspective towards change:** define steps towards a visionary target based on profound understanding of the current state	Focus on current state

Fig. 6 Approaches toward bridging the gap

A typical example demonstrating the **vertical distance** is taken from an "Arbeitskreis" on Change Management joined by representatives of design research and design practice. The concern of the researchers is, e.g., to structure the change process in generic phases and subactivities in order to compare the change process between different companies and derive potential for optimization. The concern of the practitioners is, e.g., about seemingly trivial operational issues, such as how to get all stakeholders for a critical change issue together for a short-term meeting, although the calenders are extremely packed.

In order to reach a "common ground," the recommendation for **researchers** is to make their frameworks and methods more tangible for potential users (=practitioners). This includes the demonstration or explanation of the practical value of their method in an adequate format. Scientific publications (the primary output of research activities), however, are not appropriate for that matter. What it needs instead is a practice-oriented guideline or "cook book." Researchers should also add "flesh to the bone" and apply their methods to exemplary contents.

Practitioners who are often deeply involved in operational details, trouble-shooting activities and so on, can benefit from systematic approaches. But their cases must be illustrated in a way that allows the identification of starting points for methodological support. Here the recommendation is to reflect on the concrete activities in order to identify patterns and be able to see the bigger picture. By generating stories on a more generalized level, the door is opened for an exchange with researchers (and confidentiality issues can also be avoided) (Fig. 7).

The topics "working style," "target perspective," and "perspective toward change" are related to a **horizontal dimension**. The pragmatic way of the practitioner, dealing with reality as it is ("the old world"), is positioned on the left side. The sophisticated, visionary style of the researcher, focusing on an idealistic target state ("the new world"), is positioned on the right side of the spectrum.

The **horizontal distance** between both parties is displayed with the help of an example in the platform context (joint activity between academia and industry). The researcher is focusing on a framework for a flexible, adaptive system architecture that allows the easy configuration of modular building blocks. One issue for the

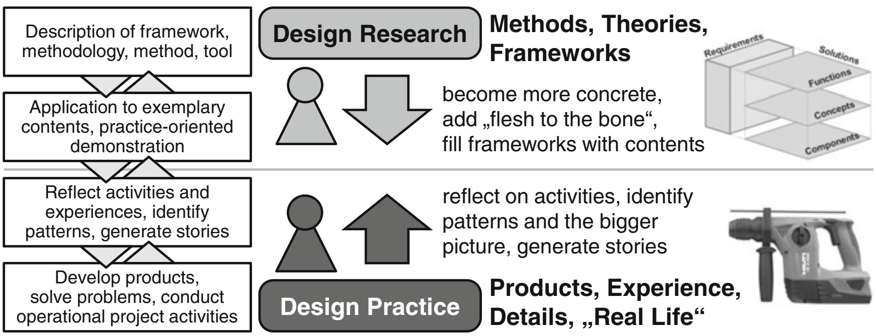


Fig. 7 Approaches toward bridging the gap (*vertical dimension*)

optimization of the architecture is the development of a metric for assessing commonality and its benefits. The practitioner is struggling with the intransparency of the existing portfolio/system architecture. The first pragmatic step for improvement is to agree with all relevant stakeholders on a common language, i.e., common names for potfolio items such as motors and electronics.

The **practitioner** needs to dissociate from the current state, develop a strategic view or visionary targets and be more systematical. The **researcher** needs to develop a profound understanding of the current state and a sense for pragmatism. The key is to combine academic value with practical value, which is not necessarily a target conflict. Scientific approaches should lead to results that are new to the body of knowledge and useful for the end-user (=industry) (Fig. 8).

As a side aspect, the assessment of the level of novelty of a scientific contribution is not trivial. A challenge in this regard is the lack of a commonly accepted structure of the knowledge base in product development/design research. Different topics (such as variant management, change management, complexity management, requirements management, decision making, problem solving, etc.) are highly interdependent and the boundaries are fuzzy. There is a huge variety of frameworks, methodologies, and models available. There is no unified vocabulary, no unique and commonly accepted definition on central terms like "platform," "system architecture," "frontloading," and so on.

To sum up, a common ground as prerequisite for effective discussions can be reached by reducing the distance in the vertical and horizontal dimensions. An idea to get there for academia is to **treat methods as products**, to apply methodologies onto themselves, a concept suggested by (Pulm 2004). This could mean, e.g.,

- Establish a process for methods development and transfer into the market (=design practice), according to industrial standards (such as quality gates, maturity levels of methods, etc.)
- Apply methods of variant management and complexity management to design research: reduce unnecessary variety and complexity in frameworks and methodologies, establish a robust but flexible "system architecture" of the body of knowledge of product development.

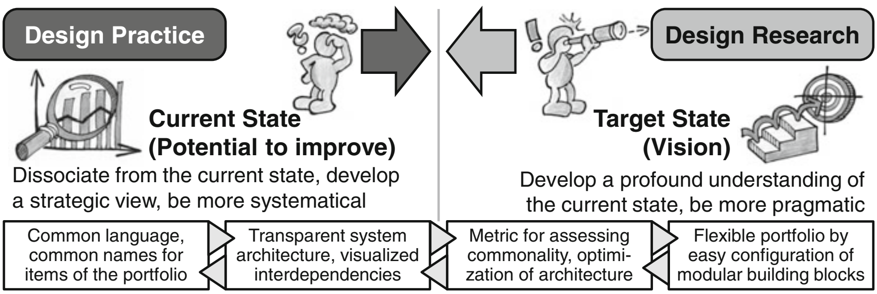


Fig. 8 Approaches toward bridging the gap (*horizontal dimension*)

4.3 *Platforms: Set up Suitable Formats of Exchange*

Having established the preconditions, such as a relationship characterized by mutual trust and a mindset to overcome the gaps and reach a "common ground," there are many concrete **platforms** between industry and research for realizing the dialogue, in particular (Fig. 9):

- **People as binding links:** the most important channel between research and practice from the point of view of the author is via people and personal contacts, e.g., through a mentoring program between practitioner (mentor) and researcher (mentee). Students are also important binding links. The exchange can be realized, e.g., in the context of a master thesis, conducted in an industrial environment, coached by representatives from academia and industry.
- **Joint projects:** another vehicle for the exchange is joint projects, e.g., research projects in close cooperation with industrial partners or consulting projects where methodology is applied on a task defined by industry. A platform to bring representatives from different companies together for discussing selected topics is working groups ("Arbeitskreise") moderated by academia (e.g., working group on Change Management).
- **Knowledge bases:** an additional form of sharing the knowledge is through publications (books, articles, and newsletters) or web-based portals [e.g., CiDaD (Ponn and Lindemann 2006b)]. However, this can only be a supplement to personal contacts and joint projects. In addition, the format in which the content is presented and accessible to industry is important. What industry is looking for are not scientific essays, but "cookbooks" that allow quick understanding.

Many of these platforms are already well established today, promoted also by the growing network of former students and researchers having gone into industry and cultivating the relationship with their alma mater. However, the dialogue can be enhanced by overcoming the illustrated barriers and gaps.

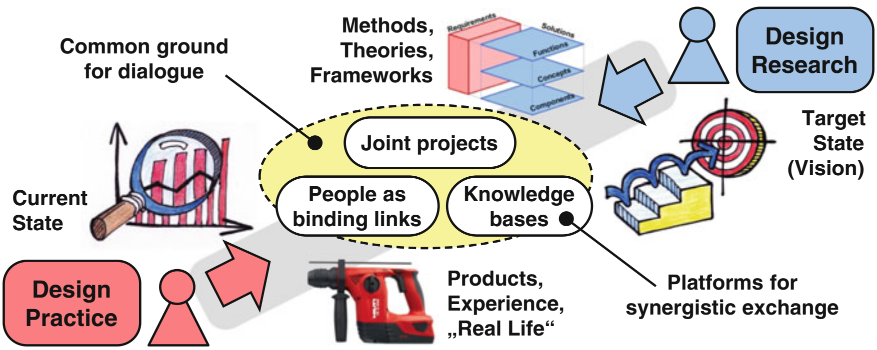


Fig. 9 Shared platforms on "common ground"

5 Conclusion

The relationship between research and practice in the field of product development and design is characterized by a natural difference in perspective. The impression arises that researchers and practitioners live on separate "planets." Having spent a significant period of time on both "planets," the author is convinced of the huge potential for mutual benefit. The synergies can be increased if both parties overcome these natural differences. Therefore, this contribution was dedicated to exploring pathways for "bridging the gap." The key messages are:

- **Right Mindset** create an atmosphere of trust, be open to the other perspective
- **Common Ground** bridge the distance between both domains (research context and industrial context) for making the dialogue more effective: researchers need to explain their work using "cookbooks" and examples, practitioners need to describe their problems at a general level and create "stories."
- **Platforms for Synergy** the major link between research and practice is created by people. Joint cooperation models (e.g., mentoring programs, consulting projects, industrial working groups moderated by academia) and alternative career models (taking the route from student to practitioner to researcher) help to promote the exchange and to build strong platforms for a synergistic dialogue.

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Development and Application of an Integrated Approach to CAD Design in an Industrial Context

Salehi Vahid

Abstract This chapter presents an integrated approach to their use in four main sections. After presentation of the results of a literature survey on the field of parametric associative CAD design systems, the chapter will present the results of a descriptive study which has been accomplished to identify the challenges, problems, and weaknesses involved in the current use of the parametric associative CAD systems in the automotive design process. The next section presents a prescriptive study in which the different phases and subphases of a newly developed parametric associative approach (PARAMASS) are described, based on the identified factors and indicators in the previous section. By means of designing an inlet valve assembly, the different phases of the developed approach are demonstrated and presented. Finally, a quantitative evaluation of the important factors of the developed integrated approach will be presented.

1 Introduction

The development of modern computer-aided design (CAD) systems and the change from 2D design to parametric 3D modeling was one of the greatest challenges for many designers. Today, designers are confronted with modern CAD systems which allow them to connect their design knowledge and intention with the created CAD models and assemblies. But in a real industrial context, the implementation and adoption of modern parametric CAD systems is not uncomplicated. Some of the reasons are that during the implementation, important aspects like product, process, and organization of the company are not fully considered. The focus this of chapter is the application of parametric and associative (PA) CAD systems in an industrial context especially in power train development in the automotive industry. The motivation behind the chapter is that the conversion of design intent and infor-

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mation from geometric modeling CAD Systems to "intelligent" modeling (where intelligent modeling means that the created CAD components contain rules and formulas which are embedded in the parametric and associative CAD parts and assemblies) is not easy. Many designers have difficulties to identify possible methods of incorporating their knowledge or design intentions into such CAD systems, and in particular how to connect the "design-intelligence" which is appended to CAD models with the geometrical entities. Although accomplished very much, many modern and capable CAD systems are not able to capture the intention of the design experts totally and unmistakably. According to VDI Richtlinie 2209 (2006) during the design process with a parametric CAD system there is a certain "thinking process" necessary which includes a modeling approach for creating the parametric models in a rigorous way. Furthermore, there is some preparatory work necessary which includes the definition and determination of the design, manufacturing, calculation, process, and organizational aspects like geometrical, physical, and process parameters of the product (VDI Richtlinie 2209 2006). It has to be clarified how the identified and determined design parameters can be prepared and provided for the downstream processes like manufacturing, calculation, or assembling. Because of this, a new method is needed which helps designers to handle this preliminary preparation and consideration phase during the work with PA systems and helps to create well-structured CAD models and assemblies. This chapter describes the stages of a research programe aiming to provide such an integrated approach, using the Blessing-Chakrabarti research methodology (Blessing 2004). This methodology comprises four main phases, which correspond to the remaining sections of this chapter: a research clarification stage through literature study; a descriptive study stage involving empirical analysis (in this case through questionnaire study and interviews with designers and investigation of existing parametric parts and CAD components in an industrial context); a prescriptive study phase involving exploration of new approaches which define different stages of how to work with PA CAD systems (the approach itself is called PARAMASS which means parametric associative design) and finally a second descriptive study phase to evaluate the benefits of the new approach.

2 Literature Survey

There are different understanding and meanings of the term parameter and parametric associative CAD design. In mathematics, the term parameter refers to a factor that controls the values of other factors with respect to a relation (Shah 1995). In computation, a parameter is the argument or series of arguments of a function with takes values as inputs. A parameter is also the placeholder for the value of a variable. A parametric associative CAD model is a computer-based geometrical depiction of a design that has certain characteristics that can vary: the characteristics are controlled by nongeometrical components called parameters. The term parametric design in engineering is a process of designing with parametric models in a virtual surrounding (a "parametric CAD system") where geometrical and parameter variations are natural. According to Shah, there are basically two modes of parameter and parametric modeling in which one can create/modify the geometry of parts and assemblies in CAD systems. These are the traditional nonparametric and parametric construction modes (Shah 1995). Furthermore, these modes are classified into different distinct models construction approaches. The first mode which is the nonparametric includes two model approaches which are "non-construction history" and "with construction history." The second mode which is the parametric mode includes five model approaches which are 2D constraints with 3D history, 3D variational, parametric family catalog, feature macros, and persistent features. Shah defined that parametric systems solve constraints by applying sequentially assignments to model variants, where each assigned value is computed as a function of the previously assigned value. Unlike procedural systems, the order of the assignments is flexible, determined by a constraint propagation algorithm (Shah 1995).

Related to the design process, associativity describes the fixed relationship between geometrical entities. The first approaches of associative relationships can be linked to associative dimensions. Associative dimensioning means that the dimensions are actually associated to the objects that they dimension (for example a rectangle as an object). If the object moves, the dimensions will move with it and if the size of an object changes (i.e., changing the length of a rectangle) the dimension value will change also. The associative representation stores a record of the construction technique used to create the primitive. The benefit of this type of representation is that the construction history can be fully captured and reexecuted later. In the case above, the designer may choose to change the value of the rectangle lengths, and reevaluate it. On the basis of the associative representation, the drafting system can reexecute the construction (Shah 1995). Furthermore, the associative relationships include, for example, the connection of two different 3D CAD models or the connection between 3D CAD models and downstream process-related elements (such as finite element models, tool paths, and other derived information). In an associative system, any modification in a 3D model is automatically propagated to the downstream applications and connected geometries (VDI Richtlinie 2209 2006). Normally in parametric CAD, designers are able to describe a geometric feature with several parameters. Moreover, the designer is able to modify the geometry by changing the geometrical parameter values instead of deleting geometric entities (AIT 1995).

3 Methodological Approaches

This section presents a brief review of previous work on methodological approaches to design using PA CAD systems. The complete results are given in (Salehi and McMahon 2009a). The first approach developed by Mendgen (1998) presents the VDI 2222 procedure based on some basic rules related to parametric design. These basic rules define that parametric CAD models should be (a) well- efined

(b) simple, and (c) complete. Mendgen divided the parametric design process into six phases which include:

- Building the modeling elements and their constraints to each other; In this case, the constraints (i.e., coincidence, parallelism, planar) between the geometrical parts and assemblies should be defined.
- Structuring in single components: In this step, components can be divided into different modeling features and in later product development stages the modeling features can be joined in one component. This approach can be used in creating different features by means of Boolean operations. (c) Coupling and uncoupling: According to Mendgen this step is important for constraint-based modeling because this step is necessary to work out the constraints between the features.
- Classification in detailed modelling: In this step, all collected model information about the structure should be considered.
- Changes: According to Mendgen, in this step, it is important to think about possible changes to CAD models, so designers are able to create dynamic and flexible CAD models.
- Clean modelling: In this step, it is very essential to name all parts and features and so it will be easy to find the created components. This aspect considers only the identification of part properties and attributes.

Mendgen developed an assistance tool for parametric CAD systems based on TCL (Tool Command Language) language which is called “constraint control.” The main focus of the approach according to Mendgen is the application of a method in geometrical constraint design (parallelism, tangency, coincidence, etc.) without any associative relationships. Furthermore, the method developed by Mendgen is based on VDI 2221. One of the weaknesses of Mendgen’s approach is that there is no logical relationship between the defined steps which are defined in the developed system “constraint control.” From the functional aspect of parametric design which includes “parametric” and “associative” design information, Mendgen does not define a certain method to represent the available parameters and associative geometrical elements. Furthermore, the relationships between the parameters and associative geometrical entities which are important during the creation of a complex CAD part and assembly are not considered. The structural consideration aspect of parametric associative design which includes a transparency and clear modeling process is only partially considered by Mendgen. That means that there are only very rough statements like “structuring in single components and dividing in different modeling features are necessary.” Furthermore, structural aspects of the CAD component have to consider the important design information inputs (i.e., design environment and product requirements) which are the basis of the parametric design and also design outputs which have to be delivered by designer for the downstream process like manufacturing. Therefore, the structural aspect of the parametric associative design process should be able to organize the required information in consideration of the above-mentioned aspects. The process-related aspects which include downstream processes like FEM and CAM are not considered by Mendgen. In case of integrated parametric associative CAD modeling and because of the fixed creation of associative relationships between design and FEM or CAM process, there is a method necessary which considers the process-related aspects, for example, how to structure the associative geometrical information in the downstream processes. The reviewed work of Mendgen shows that related to parametric associative design, the integrated aspects of a method are also missing. Furthermore, the work of Mendgen defines only some basic rules which should be considered during parametric design and the methodological aspect is not considered.

For a better identification of the above-mentioned problems and challenges the authors have undertaken a series of studies in an automotive industry environment. The main target of this descriptive phase was to address the important points which have been identified in the literature survey. Furthermore, the descriptive study should help to capture the experience of the parametric associative CAD users in an industrial context. The relevant design research methodology and the results of the descriptive phase will be presented in the next section.

4 Results of the Descriptive Study

The descriptive study was started with a questionnaire, the goal of which was to get more information about current knowledge of the designers and their work experience with parametric associative CAD systems in an industrial context. The aim of the descriptive study in the Blessing–Chakrabarti research methodology is to deepen the understanding of the research issues identified in the literature study. In the present work, it was undertaken by questionnaire, interview, and studies of existing parts in a large European automotive company and with engineers from its suppliers. The first part of the questionnaire contained general questions about design activities, experience, durability, and working skills with PA CAD systems. The second part contained questions related to functional and process aspects of PA design. The questions served to exemplify problems during the design process with PA systems and to address the issues which have been identified in the literature survey (Salehi and McMahon 2009a).

The basic conditions of the descriptive studies are listed in Table 1. The respondents of the questionnaire were designers whose work experience was on average over 12 years. But the parametric associative CAD system experience of the respondents was between 1 to 5 years. A key result of the questionnaire was confirmation that there is a significant need for a new approach to the use of PA CAD systems. 67 % of the respondents were of the opinion that it is very important to concern themselves more strongly with the modeling process before starting to design with such systems, and therefore they have to make some preparations of how to design and structure their PA parts and assemblies (Salehi and McMahon 2009a). In addition, 86 % of the respondents think that there is a huge potential to improve the application of PA design. When setting the

Table 1 Basic conditions of the questionnaire

Environment	Automotive industry and suppliers
Participants	153 power train engineering designers from automotive company and suppliers
Collection methods	Questionnaires
Time constraints	90 min for 26 questions
Team size	Groups of 10 people in different CAD design workshops
Number of cases	153 questionnaires
Total duration	5 months (from creation phase to the analysis of the questionnaire)
Role of researcher	Accompanying the designers (explaining and responding to questions)

questionnaire, the authors thought that a lot of methods would have the disadvantages of being time consuming and therefore not applicable in real design environment. But 52 % of the respondents said that they are ready to invest time in a new method of PA design system. Furthermore, 71 % of the respondents denied having an exactly defined method and approach during their work with PA CAD systems and the remaining 29 % who claimed to have a method said that many of the parts produced were poorly structured. We had hypothesized that failure to apply methods would be because of time pressure, but for only 19 % of the designers it is quite difficult to spend time for application of particular methodologies. In addition 85 % of the respondents also stated that during the preparation phase, the right methods of how to identify, classify, and determine the required parameters and associative relationships are missing. Another important question was the use of the full functionality offered by PA systems and only 14 % of the respondents identified that they use the possibilities which such systems offer very well (for example, fully parameterized parts and associative connections) (Salehi and McMahon 2009a). By means of this question, it becomes very clear that there is also potential to improve the efficiency in the application of PA functionalities. In general, because of the complexity of PA CAD systems there is a significant readiness of the designers to apply methods which help them to reduce the complexity and increase the transparency of the created CAD parts and assemblies—76 % of respondents would be interested in a method if it would help them during the work with PA design.

The goal of further questions in the study was to analyze the PA modeling process used. Only 24 % of the respondents indicated that they were able to find the right parameters and associative relationships in large and complex CAD parts and assemblies. This problem becomes bigger if they try to change parameters and geometry of “foreign” components (these are CAD parts which are designed by other designers or by supplier). Only 9 % of the designers are able to identify and determine the relevant information and they agreed that it is quite difficult to change CAD parts and assemblies created by other designers. The next important point was that 86 % of the respondents agreed that in regard to such components and assemblies it would be very helpful and desirable if there is more information about the construction and structure of the PA part and assemblies. The designers

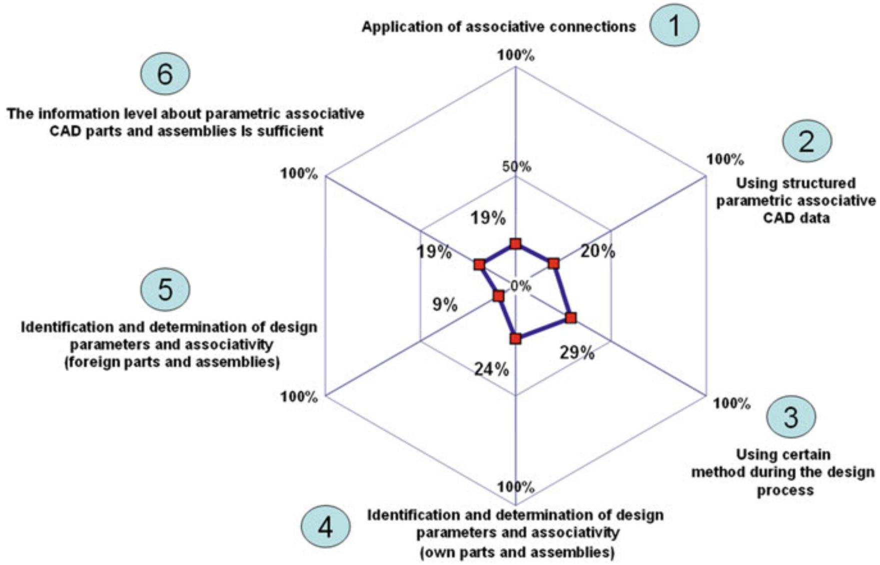


Fig. 1 Important results of the questionnaire (Salehi and McMahon 2009a)

appreciate the idea to have a description of the construction and structure of the CAD parts and assemblies (see Fig. 1, which shows the proportion of respondents responding in the affirmative to each question topic).

A further important aspect was the use of associative connections between parts and assemblies. This aspect has shown the greatest gaps and weaknesses. Only 19 % of the respondents agreed with the question "I use different kinds of linkages offered by PA systems in my parts and assemblies (linked drawings, geometry elements, FEM, etc.)". This suggests that designers have not the right methods to handle associative connections. Furthermore, because of the lack of a method most of the designers have had bad experience with such associative relationships. In general, the results of the questionnaire confirm the issues which have been identified during the literature survey. In addition to the summary of the important results of the questionnaire in Fig. 1, more extensive details are given in (Salehi and McMahon 2009a).

The questionnaire study was followed up with interviews which have been done with 11 experienced CAD coaches and designers, the basic conditions of which are shown in Table 2. The most important aspects and results of the interviews with CAD experts and coaches can be summarized as follows (Salehi and McMahon 2009a):

- During the work with PA systems, designers have difficulties to identify, determine, and represent relevant parameters and associative relationships;
- The created associative relationships are not well thought out and elaborated. Designers create many associative relationships between the geometrical entities without being aware of the consequences;

Table 2 Basic conditions of the interviews (Salehi and McMahon 2009a)

Environment	Automotive industry and suppliers
Participants	11 CAD trainers and CAD support
Date collection methods	Interviewing, documentation
Time constraints	120 min per each interview
Team size	2 participants (researcher and interview partner)
Number of cases	11 interview partners
Total duration	2 Months (from creation phase to the analysis of the interview)
Role of researcher	Interview leader, documentation

- A preliminary consideration and preparation of the created parameters and associative relationships would be a great asset for the designer. This aspect improves the identification, determination, and representation of the created associative relationships;
- Designers are confronted with problems which are not related to the product but are rather related to the logical aspect (relationships between parameters and associative geometries);

Parametric associative CAD parts and assemblies modeled by other designers are often not well structured, and therefore it is quite difficult to change them or to find relevant design information.

The results of the interviews showed the same important aspects that have been identified during the analysis of the questionnaire. They demonstrated that most of the designers have problems in preparing the required parametric and associative design information inputs and outputs. Furthermore, for most of designers it is difficult to identify, determine, and structure the parameters and associative relationships.

5 The Overall Approach of a Generic Integrated Approach for Parametric Associative CAD Systems

Based on the input from the literature and descriptive studies, a novel approach to the methodical application of PA CAD systems has been developed. It is based on three different main phases which comprise the top level of the approach (Salehi and McMahon 2009b).

1. Specification phase for PA CAD parts and assemblies

   1.1 Identification and determination of parameters.
   1.2 Identification and determination of associative relationships.

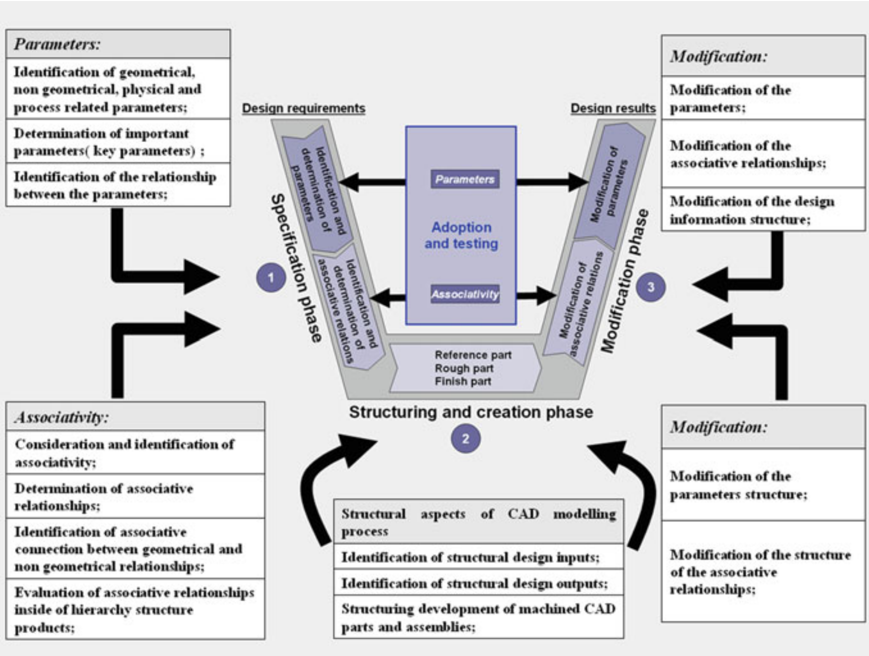


Fig. 2 Generic integrated approach of parametric associative CAD systems

2. Structuring and creation phase of PA CAD design.
    2.1 Structuring and creation of parameters and associative relationships on a part structure level.
    2.2 Structuring and creation of machined parts on associative assembly structure (Reference part, rough part, and finished part).
3. Modification phase of the parametric associative CAD design.
    3.1 Modification of parameters and associative relationships
    3.2 Modification of the created structure

Figure 2 shows the different phases and subphases in diagrammatic form, and their relationship to the issues identified in the literature and descriptive studies. A detailed description of the phases is given in the next section.

6 Application of the Integrated Approach for Parametric Associative CAD Systems

The stages of the approach to PA CAD are shown in Fig. 2 and are based on the V-model approach to systems development. The V-model is a graphical representation of the systems development lifecycle (VDI Richtlinie 2206 2004). The

V-model is a guide for the basic procedure based on system engineering process (originally from software engineering) and is adapted to the requirements of mechatronics. It describes the logical sequence of important substeps in the development of systems. Furthermore, the V-model describes a generic procedure for designing systems, which is to be given a more distinct form from case to case (VDI Richtlinie 2206 2004). For example, in case of the system design it is established to develop a cross-domain solution concept which describes the main physical and logical operating characteristics of the future product. For this purpose, the overall function of a system is broken down into main subfunctions. These subfunctions are assigned suitable operating principles or solution elements and the performance of the function is tested in the context of the system. The V-model summarizes the main steps to be taken in conjunction with the corresponding deliverables within a system validation framework. It describes a process that represents the sequence of steps in a project life cycle development. The left side of the V-model represents the decomposition of requirements, and creation of system specifications. The right side of the V-model represents integration and modification of parts and their verification. The V-model deploys a well-structured method in which each phase can be implemented by the detailed documentation of the previous phase. The model recognizes that there are two types of maturation in system development. In V-model representations, time and maturity move from left to right. Iteration is essential in system development, and all iteration is done vertically. The left leg of-V-model investigations center around what concept is best and what architecture is best for that concept. For example, commercial products usually face the dilemma as to whether batteries should be standard, unique, replaceable, or not. In the right leg of the V-model, investigations are directed at exploring integration and modification anomalies to determine their root cause and to correct them.

Furthermore, during the development of the developed integrated approach described here all the designers mentioned that the method should also consider the different stages of the product development process and normally the designers starts from a concept level and then the CAD models become more detailed. The relevant factors of the V-model in describing these aspects are (VDI Richtlinie 2206 2004):

- The V-model is used in different industries, including automotive and aerospace. Furthermore, the V-model is a very well-known approach which has been used and applied by the designers in their product development process;
- The V-model approach considers the concept level of the product development process, which produces a system concept description is considered (usually described in a concept study);
- The V-model considers the system level, which produces a system description in performance requirement terms is considered;
- The V-model is divided in subsystem/component level, which produces first a set of subsystem and component product performance descriptions, then a set of

corresponding detailed descriptions of the products' characteristics, essential for their production is also considered.

Related to the developed parametric and associative approach, the designers stated that it is quite important that the different level of the product development process and product structure should be implemented inside the developed method. By means of the V-model, it was possible to integrate the different level of the product development process and structure from concept to the detailed phase. Furthermore, the different level of the systems and components (assembly of part level) are integrated inside the developed approach. This was an aspect which was not considered during the method development process by the author and after the first trial of the developed method this was one of the important aspects which has been identified and required by the designers during the method application. The next section will define the different steps of the method.

6.1 Specification Phase for PA CAD Parts and Assemblies

The method approaches according to Pahl and Beitz (2003) and VDI 2222 (Vajna 1998) contain a specification or planning phase which is one of the important aspects of the design methods in widespread use. The results of specification phase are to gain information which can be converted into useful and essential design knowledge. The developed specification phase of the approach is divided into two different substeps. These are identification and determination of parameters and associative relationships. The selected approach to capture the gained "knowledge" and information during the specification phase for PA design information is a checklist which is in the form of a parameter structure matrix (PSM) and an associative structure matrix (ASM). The definitions of each of these matrices will be given in the next section.

6.2 Identification and Determination of Parameters

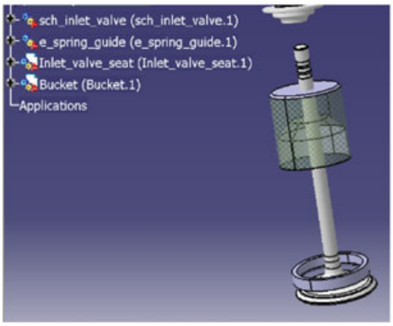
The final results of the questionnaire showed that 76 % of the respondents confirmed that during the modeling process they were not able to find the right parameters in large and complex CAD parts and assemblies. This problem becomes bigger if the designers need to change the parameters and geometry of "foreign" components and assemblies (CAD parts and assemblies which are created by other designers, e.g., by suppliers). Furthermore, because of the different kinds of existing parameters many designers are overextended to identify, determine, and structure the available parameters in their parametric CAD parts and assemblies.

The results of the descriptive study (results of the literature survey and carried out questionnaire) demonstrate that the relevant parameters during the design process with PA systems can be classified into three different categories:

- Geometry parameters: These are geometry indicators like size, height, breadth, length, and diameter or object properties which classify the product. These parameters are also known as “driving parameters.” By modification of driving parameters, the generation of a new variant of the CAD model is possible (Vajna 1998).
- Physical parameters: The physical parameters define further properties of the CAD model. These are, e.g., material of the CAD model. Combined with the geometrical parameters the physical parameters can be the basis of calculations and analysis (Vajna 1998).
- Process parameters: These are parameters which define the selected process of the selected technology. Process parameters can be for example machining-processing data or heat treatment requirements (Vajna 1998).

The defined parameters and PSM of the assembly structure (exploded) of an inlet valve shown in Fig. 3. The structure of the inlet valve assembly contains four different CAD models which are the inlet valve itself, the spring carrier, the valve seat, and the bucket tappet. The exact definition and relationships between the components will be explained in the next section.

The starting point of the identification and determination of parameters is the definition of all possible parameters in the current design stage. In case of designing an inlet valve, the parameters which describe the geometrical artifact are valve stem diameter, valve stem cotter, throat valve seat, total valve seat face thickness, height of valve seat, height of valve seat face, head diameter, throat angle, valve seat angle, total length, and grinding length of the valve. Furthermore the above-mentioned geometrical parameters can vary for different engine types with different cylinder bore diameters. In this case, the PSM approach can be used to identify, determine, and document this kind of geometrical relationships and dependencies. In later steps of the CAD modeling process, this knowledge can be implemented in the CAD



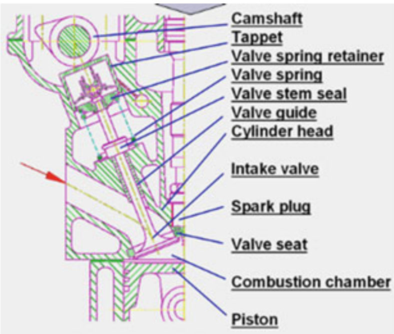
Category	Geometry parameter									Physical Parameter			Process Parameter		
Organisation	CAD									CAE			CAM		
Parameter name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Valve head															
2. Valve radius	X														
3. Valve angle	X														
4. Valve stem diameter															
5 Valve height															
6. Valve neck radius															
7. Valve stem				X		X									
8. Throat angle	X														
9. Valve height	X														
10. Surface											X				
11. Roughness											X				
12. Material											X				
13. Valve head Surface	X													X	
14. Valve stem face				X			X							X	
15. Clearance between valve														X	

Fig. 3 The PSM of the inlet valve (Kolbenschmidt 2012)

model and can be captured from the PSM structure. For a better capturing, documentation and collecting of the above-mentioned parameters and their relationships to each other a checklist is defined which is based on the PSM (Fig. 3). The framework of the PSM is based on the logic and structure of the design structure matrix (DSM) approach (Bartolomei et al. 2007). A DSM can represent the abstraction of the relations among components of a product, teams concurrently working on a project, activities or tasks of a process, and/or parameters within the system, and by means of this abstraction it is possible to find higher level interrelationships that are more generic and comprehensive. Abstraction in this way supports systematic thinking (PTC 2005). In the current work, the PSM is materialized as an n×n adjacency matrix of geometry, physical and process parameters with their relationships to each other, and with identical row and column headings. In a PSM, the "X" in a cell is used to indicate the coupling and relationships between the different kinds of parameters. Furthermore, the defined parameters are clustered (clustering is a valuable technique for examining the structure of a system). The clustering technique applies graph theoretic cluster algorithms to reorder the rows and columns of the matrix by grouping highly related nodes, called clusters (Bartolomei et al. 2007) in three different organizational categories which are CAD, computer-aided engineering (CAE) and computer-aided manufacturing (CAM). The clustering processes are generated automatically by defined procedure and macros (in Visual Basic Languages) in PARAMASS tool. Furthermore, this tool was developed to support designers during the creation and generation of the PSM. It helped to collect and document the created PSM and the required information. The developed PSM approach is used for modeling the parameter architectures based on the different kinds of parameter categories and classes which are available on different CAD parts, assemblies and their relationships to each other. By this means, designers get a better understanding of the available parameters and are able to plan how to integrate the identified parameters in their created CAD parts and assemblies. In addition, a generic approach is needed to inform the other participants in the design process of the required design parameters. In case of the inlet valve, the PSM approach can also be used to develop a catalog of modular valves for different engine types and families (Salehi and McMahon 2009b).

6.3 Identification and Determination of Associative Relationships

After the identification and determination of the required parameters, it is also important to clarify the identification and determination of the required associative relationships between the geometrical entities. Related to the design process, associativity describes the fixed relationship between geometrical entities and objects. The product geometric entities include assemblies, components, solids, faces, edges, vertices, surfaces, curves, and points. In the literature, there are a lot of terms like "Adapter, Skeleton modelling" which describe the associative



	Associative geometrical interface analysis	Driven geometry											
	Part name	1	2	3	4	5	6	7	8	9	10	11	12
1	Intake valve								X			X	X
2	Camshaft			X									
3	Tappet												
4	Valve spring retainer	X		X									
5	Valve spring	X					X		X				
6	Valve stem seal	X											
7	Valve guide	X							X				
8	Cylinder head												
9	Spark plug								X			X	
10	Valve seat	X							X				
11	Combustion chamber								X				X
12	Piston								X				

Fig. 4 Identification and determination procedure of associative relationships

relationships between the geometrical entities (PTC 2005). A skeleton model "is the framework of a design, and acts as the 3D layout of the assembly. Like 2D layouts, skeletons serve as a central location for storing design criteria relating to the assembly, specifically surface geometry, points lines and curves" (PTC 2005). Adapter and skeleton models simplify the design creation and visualization, help to manage relationships, and to provide control over external references. The act of creating associative relationships between the geometrical entities is also called "referencing." Therefore, the models which contain the basic associative elements are called the "Reference models," and will be used here to replace all the possible definitions which can be used to describe the models which contain the basic geometry elements (i.e., adapter and skeleton models). Reference models contain basic geometrical entities or parameters (i.e., points, lines), are characterized by an exactly defined geometrical interface, use linear associative relations, are hierarchically ordered, can be defined by simultaneous or concurrent engineering teams and are considered as an geometrical interface and touch point to the downstream processes (CAM, CAE). The procedure of how to identify and determine the associative relationships between the geometrical entities and objects is shown in Fig. 4 (Salehi and McMahon 2009b).

The starting point of the procedure to identify and determine the associative relationships between the geometrical entities is the investigation of the geometrical interface and determined parameters of the CAD component. For the investigation of the geometrical interfaces, it is necessary to analyze the components which are in the surroundings of the created CAD component. The target of this step is at first to identify the surrounding geometry and in the next step to determine the associative entities and objects which are relevant for the creation and design of the reference model. During the determination of the associative relationships, it is necessary to distinguish between geometrical entities which have an impact on the parametric associative CAD component and those which have no impacts on the geometry. There are two different kinds of associative relationships between the geometrical entities (Salehi and McMahon 2009b). These are "driven" and "not driven" relationships. "Driven" relationships have a direct impact on the CAD components

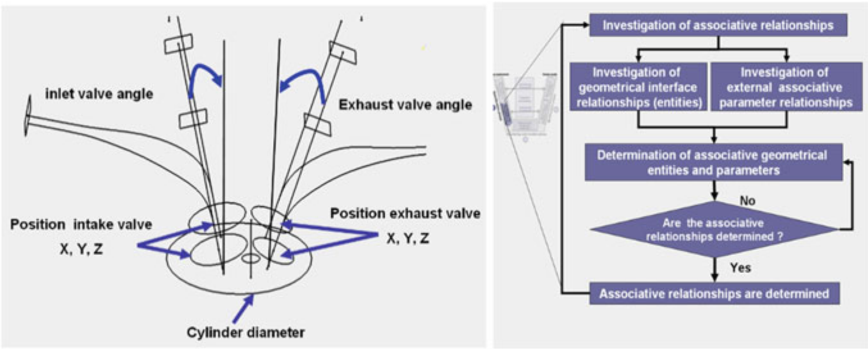


Fig. 5 Reference model of the inlet valve

which are based and connected with them. An example for such relationships is the associative connection between a 3D CAD model and a 2D Drawing. If the 3D model is changed geometrically, the 2D drawing is updated to reflect the change. In this way, every change of the 3D model has a direct impact on the 2D drawing. By contrast, a "Not driven" associative relationship does not have any impact on the other geometry. In case of the design of the inlet valve, the relevant parameters have been identified in the step before. A geometrical interface analysis is now used to help to identify the important associative relationships for the inlet valve. For a better capturing and collecting of the above-mentioned associative connections, a checklist which is based on an ASM has been created. The ASM approach contains the associative relationships between the geometrical entities. The framework of the ASM is again based on the logic and structure of the DSM (Salehi and McMahon 2009b). The ASM is materialized as an n×n adjacency matrix of CAD parts and associative relations with identical row and column headings. Furthermore, by means of the ASM the relationships between the associative geometrical entities can be clustered. In case of the associative design of an inlet valve, the analysis has shown that there is a relationship between the inlet valves, cylinder head, and the cylinder block. Furthermore, the position angle of the inlet valve and axis can also be taken from the cylinder head (Fig. 5).

6.4 Structuring and Creation Phase of the Parameters and Associative Relationships

The structuring and creation phases help to order the identified and determined parameters and associative relationships between the geometrical entities in the specification phase. Furthermore, predefined CAD parts and assemblies are created to structure the PA design information inputs and outputs. The structuring approaches of models and assemblies can be "top-down" or "bottom-up." A top-down design

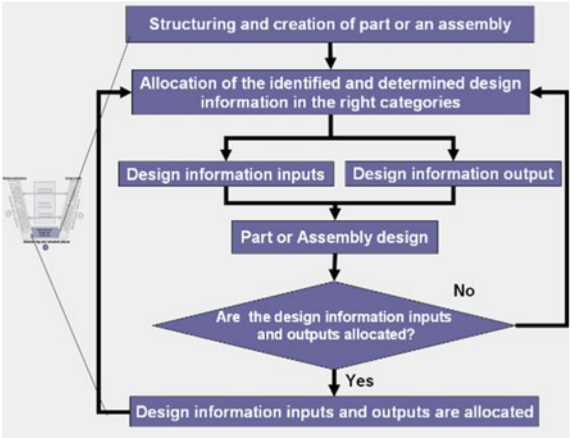


Fig. 6 Structuring of parametric associative design information inputs and outputs (Salehi and McMahon 2009b)

environment supports transitions from high level, conceptual assembly models stressing the function of the assembly to detailed models of the individual components. The "bottom-up" approach starts with designing a single CAD part on the low level of the product structure (Shah 1993). At the end of the design process of the created single components, all the CAD parts and assemblies will be merged to a new model or an assembly. The approach selected in the present work is based on the "top-down" approach. That means that the structures which are predefined are created and given top-down (Shah 1993). The starting point of the procedure to structure and create the identified and determined parameters and associative relationships is to identify if the CAD component is a single part or an assembly. After the identification, the predefined structure of a CAD part or an assembly can be selected. In the final step, the identified design information inputs and outputs which contain the parameters and associative relationships can be arranged and created (Fig. 6).

The predefined structures of the approach are (a) parametric associative assembly structure (PAAS) and (b) parametric associative part structure (PAPS) (Salehi and McMahon 2009b). The PAAS is based on associative relationships between different CAD parts which represent the hierarchical structure of the designed parts and assemblies. The PAAS is hierarchically ordered and contains three different models which are connected by means of associative relationships. These three parts are (1) Reference model, (2) Rough part, and (3) Finished part. The idea behind the three parts is that the designer can work from the conceptual design stage to the more detailed stages of the design process with parametric associative CAD systems. Furthermore, the design process participants are able to identify the different parts which are created in PAAS so that a concurrent and simultaneous engineering environment can be enabled (Salehi and McMahon 2009b). For example, manufacturing engineers who are interested in created rough part can capture their required parametric model information. Furthermore, based on the designed rough part the machining process steps can be created by the difference between the rough parts and machining components like bore elements. The first part of the PAAS which defines the associative elements part is the architecture of the conceptual design elements and contains all the technical specifications of the CAD component as well as environmental geometry and constraints. The architecture is a set of logical and parametric features of an object or system that can be used to build the CAD model. Furthermore, the reference model contains the input information which describes the basic element of the CAD component. These basic elements are axes, coordinate systems, lines, curves, surfaces, solid geometry, parameters, styling geometry, and contextual geometry like standard, purchase, and carry over parts. Furthermore, the design engineers are able to modify the designed components by only changing the basic geometry and parameters in the associative part. The second part of the PAAS is the design process of the rough part. The rough part contains the basic geometrical feature information and the assembly of the geometrical features by means of Boolean operations (i.e., union, trim, etc.) (Salehi and McMahon 2009b).

The next predefined structure is the PAPS which are divided in four different parts. These parts should help to structure the identified parameters which are necessary for the downstream processes and for the CAD design participants. The first part of the PAPS contains the input information which is necessary to design the CAD components and describes the basic geometry. The input information is associative geometry like points, lines, curves, and contextual geometry which describes the geometrical surroundings on the part level. The second part of the PAPS describes the area where the geometry should be created and maintains the main result of the design stage. The third and the fourth part of the PAPS are created to enable the exchange of information which is necessary for the downstream processes. In this case, these two areas are CAE engineering and CAM engineering process partners. Figure 7 shows the PAAS and PAPS approach (Salehi and McMahon 2009b).

Figure 8 represents the structuring stages of the inlet valve starting with the definition of the reference model which contains the basic geometry including position of the valve (in X, Y, and Z direction), valve head diameter of the inlet valve, vertical axis of the inlet valve, and the position angle of the inlet valve. Based on the reference model and by means of associative connections, the next stage is the design of the geometrical rough part which contains basic features, Boolean

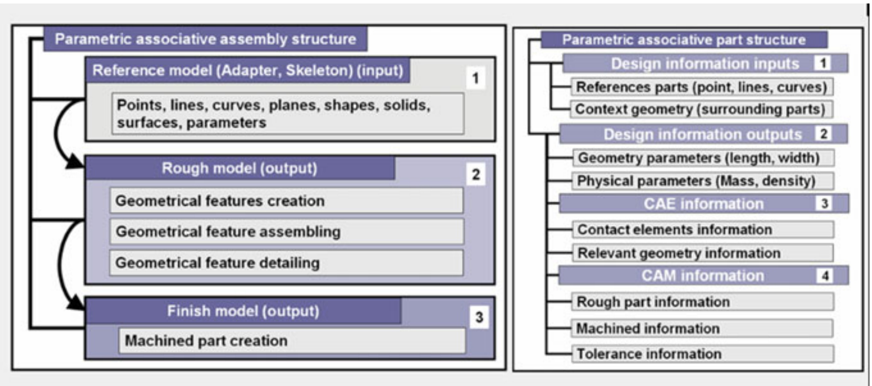


Fig. 7 Structuring of design information inputs and outputs at part and assembly level

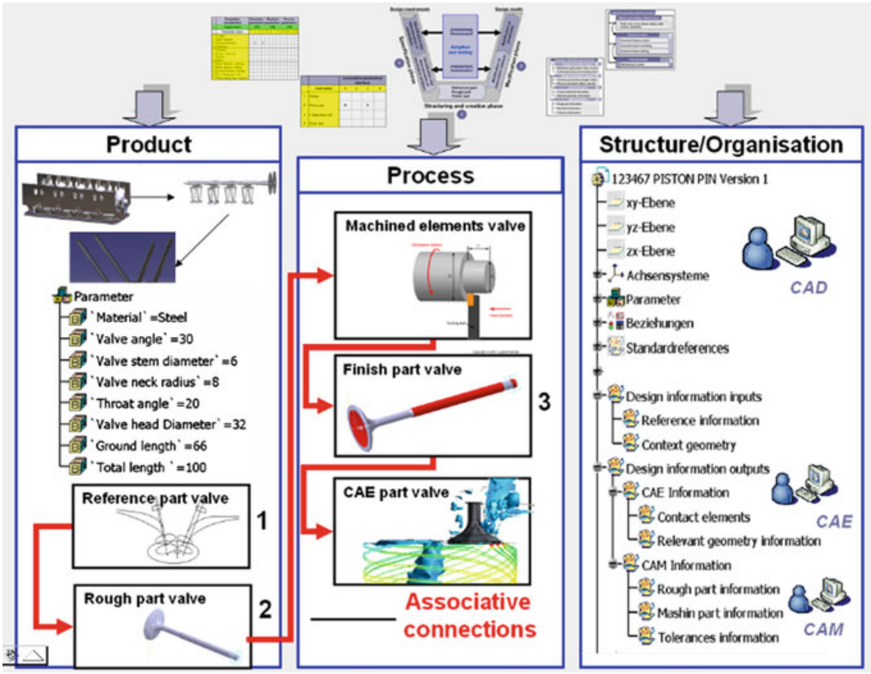


Fig. 8 Structuring of design information inputs and outputs

assembly of the created features and the geometrical detail information (i.e., rounding and edge trimming). The third stage contains the finish part of the inlet valve which is the difference between the rough part and the machined part elements (i.e., turning and fine grinding) (Salehi and McMahon 2009b).

6.5 Modification Phase of the Parametric Associative CAD Design

The last phase of the presented approach involves the possible modification of the created parameters and associative relationships and helps to test and evaluate these. The most important point during the modification phase is to check (a) the consistency of the created parameters to ensure that they can be changed and the CAD parts and assemblies can be regenerated without failures and (b) the consistency of the created relationships between the geometrical entities and objects to ensure that in case of geometrical changes the associative relationships still work.

7 Evaluation of the Developed PARAMASS Approach

The evaluation of the impact of a new method is one of the most important and challenging parts of the implementation process. The significance of evaluation is addressed in several papers and publications such as (Griffin 1998), (Norell 1998), and (Reetz 1997). The focus of the evaluation of the PARAMASS approach was to demonstrate the changes and improvements which were the result of adopting the approach. The measurements of the identified indicators were based on use cases (quantitative measurement) and the goal questionnaire metric (Basili and Weiss 1984) approach (GQM) (qualitative measurement). Here only the use case approach will be explained in detail. The quantitative indicators are characteristics of a product development process or in this case a method that can be measured, for example, by the means of determining the time needed for performing the method step. A number of measurements that could potentially be used for evaluating the impact of the developed approach were collected from literature and from the experience gained in the application of case studies. During the quantitative evaluation of the approach, it was very important to demonstrate if the identified indicators and factors were significantly changed or not; the evaluation exercise was not aimed at identifying the total benefit of PA CAD systems in the design process if there are significant changes from application of the PARAMASS approach. For this evaluation, two different groups of designers were engaged. The first group worked without any specific method or guidelines and the second group had to work and apply the PARAMASS approach () during the CAD modeling process with the PA CAD system. Each group was composed of six designers involved in

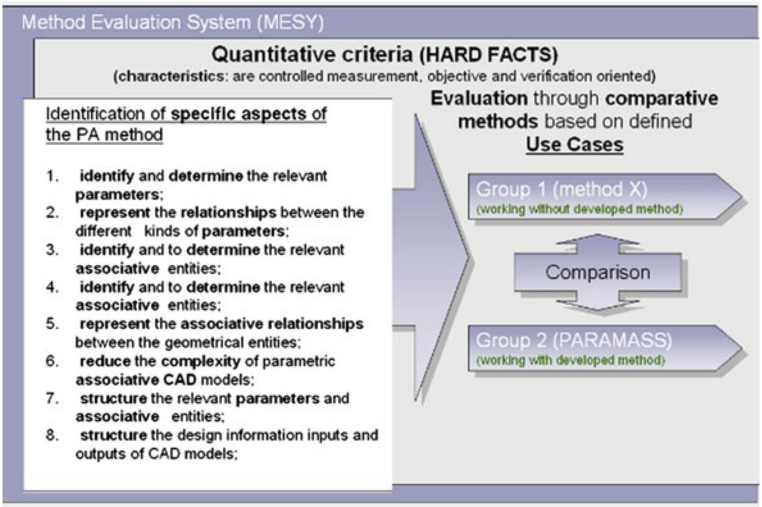


Fig. 9 Quantitative evaluation of the identified factors of PA CAD design

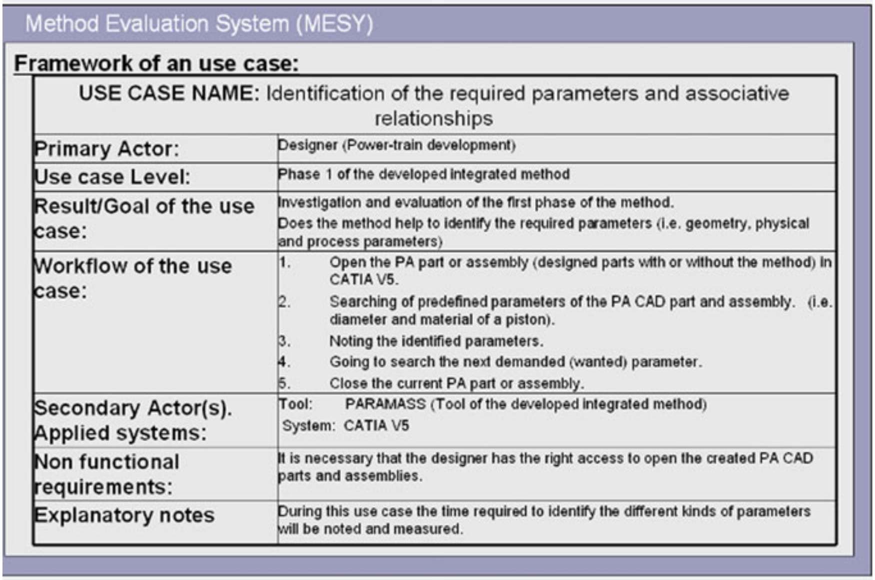
the test activities. Furthermore, it was ensured that the participants of these two design groups had the same background in terms of design experience and CAD system experience. Both of the groups had the same PA design task and had to design new PA power train CAD components (i.e., valve train or piston, etc.). The overall process and the important factors which were investigated and evaluated during the tests are shown in Fig. 9.

In the method, evaluation system created to measure the changes through the application of the developed approach; it was very important to link the evaluation process to the key indicators and factors which were identified during descriptive Study I and the literature survey. The most important question was "how it will be possible to evaluate and quantify the changes through the developed method?" The selected quantitative approach was based on use cases adopted from software and business process evaluation. According to Jacobson "A Use Case is a narrative document that describes the sequence of events of an actor (an external agent) using a system to complete a process. It is composed of a collection of scenarios describing: (i) alternative ways of achieving a goal, (ii) unwanted endings, and (iii) the reaction to potential exceptions that could arise at different times during otherwise normal scenarios (Kolbenschmidt 2012). The general benefits of the applied use cases are:

- They encourage designers to consider the characteristics of tasks and their environment.
- Usability issues can be explored at a very early stage in the design process of the method.
- Scenarios can help to identify and compare quantitative targets and likely task completion times.
- Scenarios can also be used to generate contexts for evaluation studies.
- Only minimal resources are required to generate scenarios.
- The technique can be used by developers with little or no expertise.

Furthermore by means of the structure of use cases, it is possible to describe what, by whom, and in which way the designers have to act. In this way, it can be ensured that during the tests all of the participants exactly know what they have to do and how they should act (Kolbenschmidt 2012). The use cases present one or more scenarios that describe the interaction between the processes, developed methods and those who affect and are affected by it in order to achieve a specific goal. Figure 10 shows the template and the framework of the defined use cases.

Related to the evaluation of the developed approach, it was very important to create the use cases in a way which allows the evaluation of the different phases of the approach. Therefore, use cases were created which allow evaluating the different phases. Figure 11 shows the structure of the use cases defined for the evaluation of the different method steps. During the definition of the relevant use cases, it was quite important to select the right scenarios and examples. Therefore, the identification of possible scenarios was discussed and developed with the CAD designers and in this way it was ensured that realistic scenarios were generated.



Method Evaluation System (MESY)

Framework of an use case:

USE CASE NAME: Identification of the required parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 1 of the developed integrated method
Result/Goal of the use case:	Investigation and evaluation of the first phase of the method. Does the method help to identify the required parameters (i.e. geometry, physical and process parameters)
Workflow of the use case:	1. Open the PA part or assembly (designed parts with or without the method) in CATIA V5. 2. Searching of predefined parameters of the PA CAD part and assembly. (i.e. diameter and material of a piston). 3. Noting the identified parameters. 4. Going to search the next demanded (wanted) parameter. 5. Close the current PA part or assembly.
Secondary Actor(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Non functional requirements:	It is necessary that the designer has the right access to open the created PA CAD parts and assemblies.
Explanatory notes	During this use case the time required to identify the different kinds of parameters will be noted and measured.

Fig. 10 Framework of the developed use cases

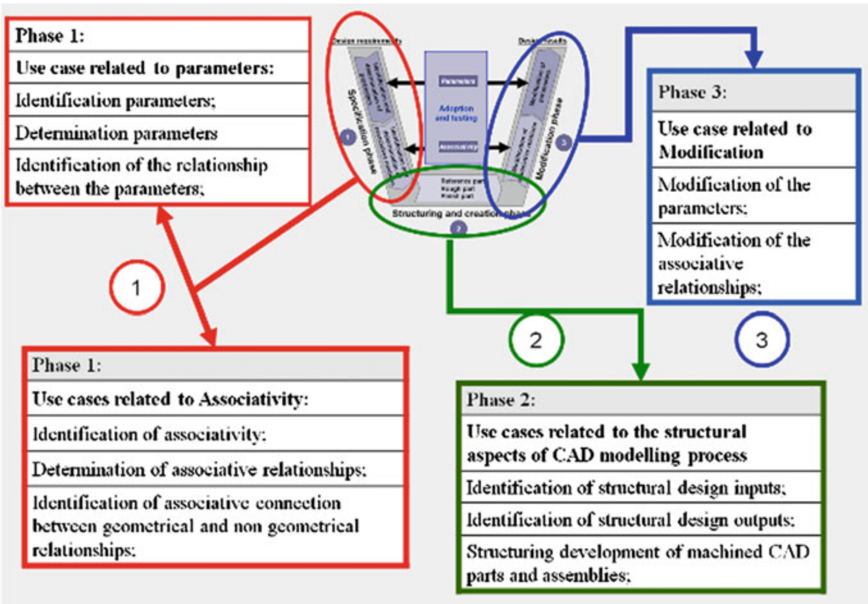


Fig. 11 Use case structure of the defined approach

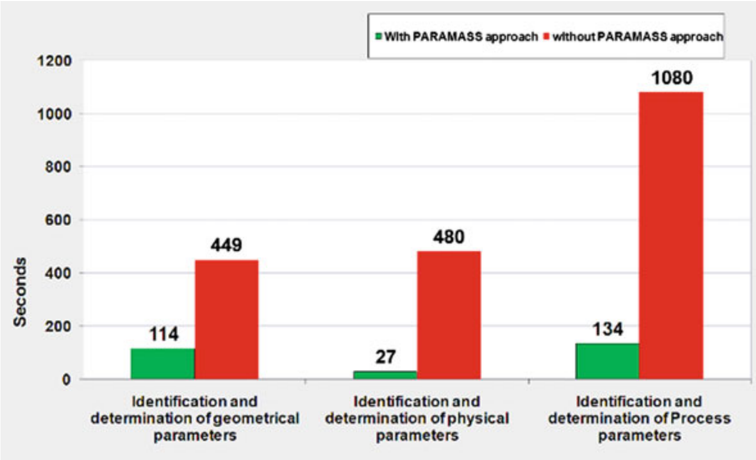


Fig. 12 Measured work time during the work with and without the PARAMASS approach

Furthermore, the definition of the possible scenarios was implemented in the regular team meetings of the test participants. In this way, all the process participants had the same understanding about the content of the use cases and the progress. At the end of the quantitative evaluation, 120 use cases were defined for the three phases of the developed integrated approach (Fig. 11).

Another aspect which was also important was the question of "how to document the performance of the designers?" For that reason, a protocol was defined to collect the measured times during the application of the use cases. In this way, it was possible to list the times measured during the design process with and without the PARAMASS approach. Two aspects were documented in the defined protocol. The first one was the measured time and the second one was the fulfillment of the task—i.e., where the designers able to complete the defined tasks?

In this way, it was quite easy to compare the measured values. Figure 12 shows the total time which has been measured during the application of the use cases and represents the compared values with and without the PARAMASS approach. It shows that using the developed approach designers were able to identify and determine the required parameters and associative relationships faster than without any specific method. But the focus of the evaluation was not simply to demonstrate if the developed method is faster or not, but also to demonstrate if the approach helps designers to have a better understanding during the identification and determination of the parameters and associative relationships. The quantitative improvements of the developed approach were confirmed through the statements and comments of the designers during the interviews and questionnaire carried out to evaluate the PARAMASS approach for usability aspects. The designers also stated that, i.e., without the PSM and ASM approach in most of the cases they had to investigate the whole history tree to find certain parameters of the designed CAD component and assemblies. Depending on the complexity of the created CAD components, this aspect can be a very time-consuming issue.

8 Discussion of the Results

By means of the developed method, evaluation approach, it was possible to assess the different phases of the PARAMASS approach from qualitative and quantitative points of view. The defined use cases are able to collect and document the different steps of the evaluation in a very clear way. That means that the actors who are engaged in this process are defined and named. Furthermore, it was very important to involve designers in the use case definition process to ensure that the defined scenarios and use cases were realistic. It helped to identify the important parameters and associative relationships which can be defined and implemented in the evaluation process. In addition, the evaluation process needs a very accurate documentation of the results. Because of this, a measurement protocol was created in which the different scenarios and evaluation process were documented. By means of the measurement protocols it was possible to have a very clear documentation of the performance of the designers. Furthermore, these protocols can be used to compare collected data in a very systematic way. During the tests, it was important that the designers should only apply the defined tasks and the documentation of the results should be done by a consultant or by the researcher himself.

9 Conclusion

The following chapter presented an integrated approach to their use in four main sections. At first, the following chapter demonstrated the results of a literature survey on the field of parametric associative CAD design systems. It becomes very clear that during the design process with parametric and associative CAD systems there are methods and approaches necessary of how to identify, document, and determine the different kinds of parameters and associative relationships which are necessary during the design process with this kinds of systems in the automotive design process. The next section presented a prescriptive study in which the different phases and subphases of a newly developed parametric associative approach (PARAMASS) was described, based on the identified factors and indicators in the previous section. Furthermore by means of PSM and ASM, it was possible to identify, document, and determine the different kinds of parameters and their relationships with each other. By means of designing an inlet valve assembly, the different phases of the developed approach were demonstrated and presented. Finally, the use case approach helped to evaluate the important factors of the developed integrated approach. The above-mentioned aspects demonstrates significant issues which are necessary to measure, quantify the changes, and important aspects during the implementation phase of the developed integrated approach. By means of the use case approach, it was possible to quantify the result caused through the application of the developed PARAMASS approach.

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Adoption and Refusal of Design Strategies, Methods, and Tools in Automotive Industry

Stetter Ralf

Abstract Design research has resulted in a deepened understanding about the design process as well as characteristics and proceeding schemes of single designers and design teams. Additionally, numerous strategies, methods, and tools were developed in the last decades. Not all the results could be successfully applied in industrial practice. This chapter seeks to contribute to the exploration of the causes for failure or success in a certain branch of industry—the automotive industry—from a certain view point. The objective is not to present a concise and complete exploration of the phenomenon of adoption and refusal of design strategies, methods, and tools but instead to contribute explanation hypotheses for certain partial phenomena. The chapter first explains the view point and the source of insight, presents the design research outcomes to be transferred, and discusses some specialties of the specific industry branch. Then a model of the transfer of design research results into industry is presented. This model presents the basis for the later detailed discussion of the insights.

1 Sources of Insight

The conclusions presented in this paper are based on a retrospective analysis of the author as an actively participating individual, an extensive literature review, earlier research (Lindemann et al. (2002), Stetter (2006) and Stetter et al. (2005)), numerous discussions with other researchers and engineers, and logical deduction. The author was developing a part of a car which can account for up to 10 % of the whole value of the car—the seating system. He was working initially as engineer in the company and now for several years as consultant for the same development department. Also before, the topic of his dissertation was the introduction of methods in industry. In his different roles, the author was (and is) an

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integral part of the organization who carried his own responsibilities for a part of the company's core processes. One may ask why insights of the retrospective analysis may lead to interesting and valid results. In the case of qualitative, exploratory research a retrospective analysis of participating individuals can help to investigate the underlying causes and complicated phenomena in addition to other research methods. The limitations of this investigation method are the limited capabilities of human beings to remember correctly and the possibility that memories are unconsciously adapted to concepts of current interest. Accordingly, the results presented in this chapter, which are results of a retrospective analysis of actively participating individuals, an extensive literature review, and logical deduction, should be weighted as results of qualitative, exploratory research.

2 Design Research Outcomes

The experience described in this chapter is to a large extent based on two implementation approaches. The first one is called early determination of product properties (compare Bernard and Stetter 1997). This method developed at the institute of product development at the Technische Universität München in Munich, Germany supports the designer analyzing and verifying product properties as early in the design process as appropriate in order to improve early decision making during product development. The main idea of this method is sketched in Fig. 1.

It is important to note that during a design process, when decisions are made and knowledge about product properties (curve 3) is gained, design freedom (curve 2) is lost (Bernard 1999). An early knowledge of product properties is therefore most desirable because the engineering change costs (curve 1) rise progressively during product development. In later stages of the experience rather the general idea of front-loading than the discrete parts of the method were transferred. Central was also a systematic process for seating systems (compare Lauber and Stetter 2008). The core idea is shown in Fig. 2.

The requirements for seating systems in terms of function, comfort, and ergonomics are manifold. This process combines the application of virtual seat surface models which represent comfort and design characteristics with a conscious use of physical models. The initial point for this process is a profile of objectives in form of a web diagram. The characteristics in such a profile can be distinguished into parameters that can be mathematically described and implicit characteristics. The characteristics are the input information for single-factor simulations which lead to a technology model. This technology model is used for verification simulation purposes, i.e., for a holistic verification if the technology model has the potential to fulfil the objective profile. This first control loop is repeated until the technology model is appropriate according to virtual simulation to fulfil the manifold objectives. Then the large control loop is initiated by a production of foams and a physical process, i.e., drive testing of complete seats. As a consequence of the use of the virtual models, only few cost-extensive physical models of the seating system have to be built and tested.

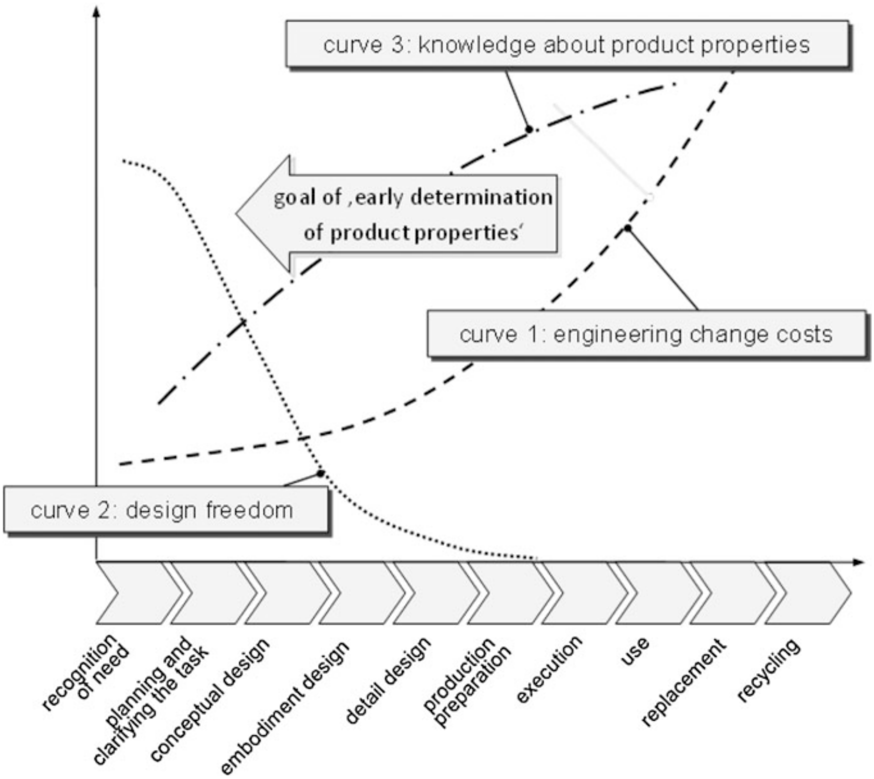


Fig. 1 Early determination of product properties

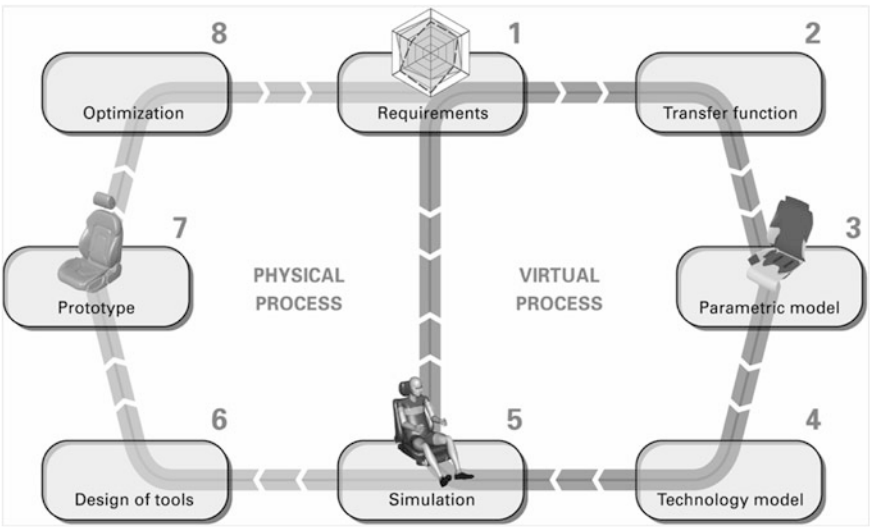


Fig. 2 Systematic process for the application of simulation techniques (Lauber and Stetter 2008)

Both implementation approaches can be considered successful as the processes were used over several years. The specific lessons learned and the right platforms for academia–industry interaction are described in Sect. 6 of this article.

3 Characteristics of the Design System

In Germany, more than 700,000 persons work in automotive industry. The design departments in automotive industry are facing specific challenges resulting from product complexity, process complexity, and strong competition worldwide. Figure 3 seeks to summarize some influences of this specific design system.

The main instruments of process guidance are stage-gate process charts displaying only the most important product development stages. Interestingly, these schedules are only to a comparably small degree influenced by synthesis activities like direct geometry development (Stetter and Pulm 2009). On the contrary, the schedules are largely depending on analysis and production preparation tasks. Typical analysis tasks that have a major influence on schedules are endurance testing or homologation testing. Production preparation tasks which influence schedules are preproduction series and the procurement of production tools and assembly systems. Design is therefore only weakly reflected in the process planning and design is usually not the decisive force in the process. The organization is up to now mainly following the modules of a car. There are large departments such as car

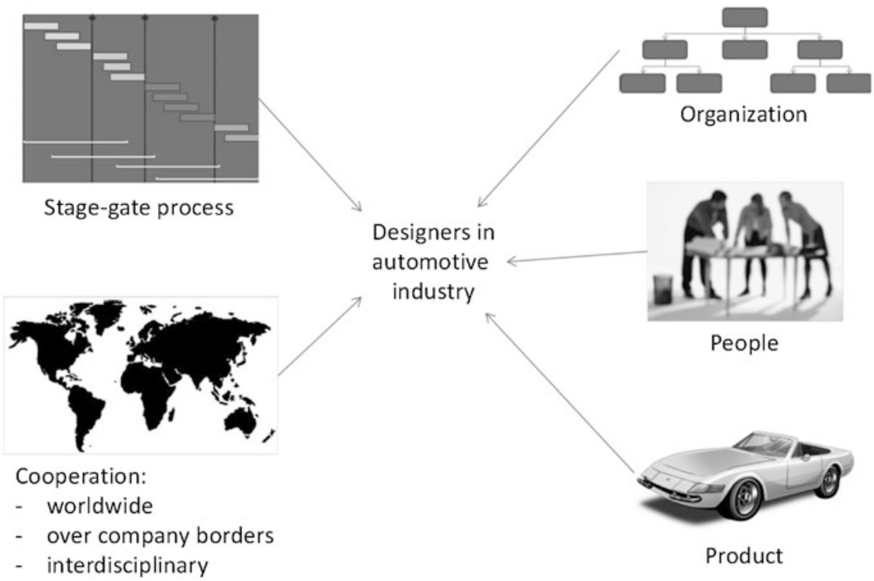


Fig. 3 Influences of the design system in automotive industry

body, drive train, and suspension. Additionally, there are usually concept departments which can concentrate on design. Such departments usually never develop serial products but hand over concepts to the departments strongly focused on product modules. The design activities are consequently spread over several departments and a prominent share of the development time is used for coordination activities. The development of a car involves usually development departments in different countries and even continents in order to satisfy the needs of a global market. Supplier companies play a prominent role in the production but also in the development of cars. Also these companies operate worldwide and seek worldwide possibilities for synergies. Very often cars are produced in several markets, the design and development needs to consider the needs and potential of all the different production sites and personnel. The electronic content of cars is increasing, reaching a share of 40 % of the value for premium cars. This requires interdisciplinary work throughout product development; the synchronization of different disciplines is consequently a major challenge. Further, strong influences are the people in the process and the highly sophisticated and evolved, highly complicated and complex product—the car.

In the current product development processes in automotive industry, below the top level rather chaotic processes can be observed which still lead to successful products. This kind of chaos becomes apparent if different disciplines and departments use different definitions and notions for the same items or if no single person has an overview over the functionality even of submodules; if different disciplines and departments carry out the same activity with different tools and procedures and even with a different outcome; and if extensive product and process changes in late phases are necessary in order to arrive at a functioning product.

4 Analysis of Transfer Possibilities

This section seeks to explore the transfer of the results of design research into the described industry branch. The direct result of research is knowledge such as understanding some proceeding schemes of designers. However, the diffusion of knowledge is, in the opinion of the author, very difficult to explore. Therefore, this chapter focuses on more tangible results of design research—the strategies, methods, and tools developed in either a prescriptive manner or in a combination of a descriptive and a prescriptive manner. This focus is shown in Fig. 4.

The transfer of such results happens during an amount of time and probably in several stages or steps. The transfer can consequently be understood as a process itself. In order to structure the findings in the chapter, a model of this transfer process is proposed.

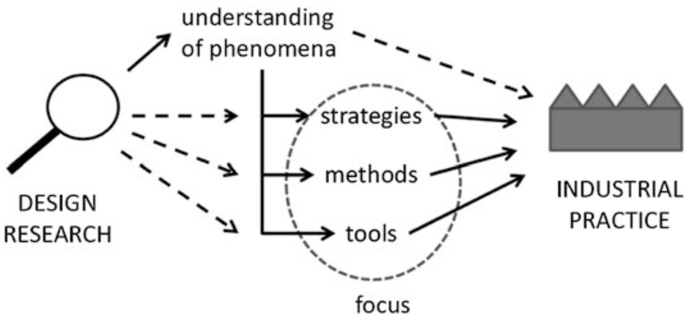


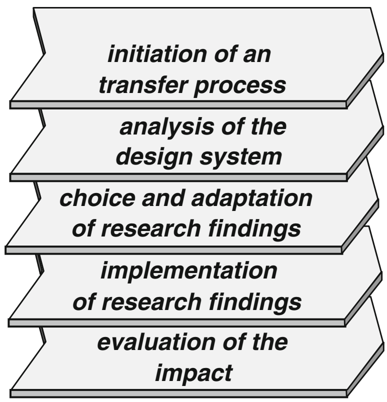
Fig. 4 Focus of the discussion

5 Underlying Model

The process of transferring design research results to practice needs some kind of a starting point—the initiation of this transfer process. Based on the hypothesis that not each strategy, method, or tool is appropriate for each design system, a form of analysis of the design system might be helpful for the transfer process. If such analysis takes place, also the choice and adoptions of the strategies, methods, and tools should be based on the analysis results. For more complicated strategies, methods, and tools specific implementation activities such as training or pilot applications can be necessary. Finally, following the philosophy of continuous improvement, an evaluation of the impact can enable an improvement of the transfer process itself. The model of this process is shown in Fig. 5.

It is important to note that this model should only be understood as a logical structure for exploration or discussion. It is not meant to indicate that a certain procedure has to be followed for successful implementation processes.

Fig. 5 Model of the transfer process for research results



6 Detailed Discussion of the Insights

6.1 Initiation of a Transfer Process

At the earliest point in a transfer process of research results, someone in the company needs to be aware of these research results. Very often, the general awareness goes back to the university education of the designers in the company. During the education, the designers got in contact with research findings in their lectures or they were using strategies, methods, or tools in their tutorials or projects. Especially, designers or design managers with a Ph.D. degree very often keep in contact with their institute and get information about current research results. This information channel seems to be very important for the initiation of transfer processes. Other information channels are consultants and partners such as suppliers or competitors (usually some cooperation between competitors exists). Theoretically, also journals and other publications as well as the internet could be sources for this awareness. However, it seems that only few designers read scientific journals and that not many designers and design managers are really searching the internet for strategies, methods and tools—at least not if they do not have an indication from someone they know personally.

6.2 Analysis of the Design System

Design systems can be very different within one industry branch or even within one department. In the field on method implementation, many publications (e.g., Stetter 2000) indicate that a good knowledge of the field of application is a cornerstone for success. This section tries to look at a somewhat typical design system in automotive industry rather close and to identify reasons for adoption and refusal of strategies methods and tools.

6.2.1 Consequences of Interdisciplinary Design

As mentioned above, design in automotive industry happens in an interdisciplinary manner which requires integration of domain-specific solutions and processes. One main problem concerning this integration is that the integration has to take place in different dimensions: functionally, geometrically, electronically, and according to the software structure—or more demonstrative: between modules and between disciplines (Stetter and Pulm 2009). Furthermore, it has to happen on different levels of detail. The functional integration is especially difficult, since in a complex mechatronic system even functions, which are far away, have to be integrated. Another prominent problem is that the effects of one discipline on the others are hard to predict. The software, for instance, should be independent from the electronic network, but changes in the electronic network may require changes in the software and failures in the software might disturb the whole electronic network (also due to security measures in the software); other problems might be electromagnetic compatibility (based on the geometry of the electronics), etc. Within strongly interconnected products, the integration can also only take place in the whole product in order to get final information on the behavior of the product. Consequently, integration needs many supporting methods and covers a big part of the design process.

6.2.2 Balanced Versus Focused Design

The term “balanced design” is usually used in statistical testing and planning for design of experiments (DoE). In the DoE, a Balanced Design (Balanced Experiment) is a factorial design in which each factor is run the same number of times at the high and low levels. In this chapter, balanced design means a procedural scheme where all parts and aspects have the same importance. Obviously, this is a rather theoretical perspective as some differences in importance always occur. The point of emphasis in this discussion is the observation that in industrial practice design is sometimes even more focused than in most of the procedure proposition from academia. Very often, only one characteristic is crucial and can only be evaluated if all the steps over detail design and manufacturing preparation are performed. One example is the comfort of a car seat. This factor can only be evaluated if foams from realistic production tools are present. The automotive industry seems to employ an extremely focused design strategy with positive results. Design research often proposes approaches where abstract concepts are created and then in a stepwise or nearly stepwise procedure are developed toward more concrete stages. It seems that currently little methodical support is present to support focused design which concentrates on crucial points. Strategies and methods which support this kind of concentration but still ensure that the risks of such approaches (limitations of the design space, unforeseen crucial points) are considered and systematically addressed might be helpful for design in automotive industry.

6.3 Choice and Adaptation of Research Findings

The results of an analysis of the design system present a good basis for the choice and adoptions of the strategies, methods, and tools. This section tries to report some typical observations concerning potential for choosing and adapting design research results.

6.3.1 The Product as One Main Carrier of Knowledge Management

During the last decades, numerous approaches of knowledge management were tried in leading companies. Companies have identified knowledge as an invaluable asset and have tried to secure this knowledge in some form. One important observation might be that designers in automotive industry very often analyze the product predecessor (or more often the predecessor of the module for which they carry the responsibility) in order to gather knowledge. If one looks at the predecessor module with open eyes he/she can see the solutions which were chosen because of certain advantages. The designer can compare complex functional characteristics with the characteristics of the predecessor and identify approaches to tackle certain problems. For automotive industry this works rather well with the direct predecessors, because these are available all around the company and are used as company cars. However, older products are not available any more leading to the risk to repeat mistakes. It is important to note that even rather simple modules are only described in a simplified manner in computer systems because details such as detailed surfaces or elasticity are not documented. Also the complex functional characteristics are only partly described. The physical product seems to be a key possibility to secure knowledge.

6.3.2 Evolutionary Versus Revolutionary Approaches

On a very abstract level, the strategies and some of the methods and tools which are developed and proposed by design research can be distinguished on the basis of the question if they rather support an evolutionary or a revolutionary approach to design (Stetter et al. 2011). This distinction is based on scientific works by Bamberger (2000), Robinson et al. (2005) and Kittel and Vajna (2009). Evolution can be defined as a gradual process of change and development. Concerning the support of design, the following characteristics could be identified, which designate a purely evolutionary approach: the process starts with an existing product and its components; the main process depiction is a circle; changes are carried out altering the product or its components (at the absolute end of the continuum these changes would be arbitrary as opposite of a completely planned approach); appropriate tests are carried out in order to test the "fitness" of the generated solution alternatives; iterations are the essential element of the approach; flexibility is the central advantage of such approaches. On the contrary, revolution is in general understood as a sudden, complete, or marked change in something. For the designation of a purely revolutionary approach, the following characteristics can be used: the process starts with necessities, needs, or wishes of customers or society or with an independent vision; the main process depiction is a linear procedure scheme; the development of the product and its components proceeds from abstract to concrete in a well-ordered, systematic manner; tests are mainly necessary for verification purposes (not for orientation); iterations are theoretically not necessary and the chance to achieve something totally novel and/or optimum is the central advantage of such approaches.

Why is this difference so important for the acceptance of the results of design research in industry? Most of the processes in industry are evolutionary; the cars and their components are refined in many steps. Many design research results are more compatible with a rather revolutionary approach as such approach was due to its theoretical potential often promoted by academia. It might be that designers sense that some strategies, methods, and tools would direct them to a more revolutionary approach and subconsciously refuse to transfer them into their daily work.

6.3.3 Procedural Support Versus Model Support

It is nearly impossible to have a full overview as to which of the results of design research are frequently adopted and used in industry and which are not. Still, based on the experience mentioned above and frequent discussions, a few observations can be reported. In today's industry, very well-accepted methods are the Failure Mode and Effects Analysis, systematic collections of specifications for the clarification of the tasks (though usually less structured and less complete than often demanded by design science), the general concept of "front-loading," all kinds of evaluation methods ranging from pairwise comparison to value analysis, and the methods which build upon the methodology of Altschuller (compare, e.g., Koltze and Souchkov 2010). Comparatively, seldom can the use of methods like function structures, physical effects, and systematic variation (compare, e.g., Pahl and Beitz 2006 or Ehrlenspiel 2009) be observed. Assuming that this suspected difference in acceptance is realistic, one may ask for probable causes for this difference. Two major directions can be distinguished—either the methods which designer dislike do not support them or they are just difficult or unpleasant to use. It is rather probable that the methods proposed by design science can in theory support designer—to better understand their product, to create alternative solutions, to be able to abstract from the current problem situation. So it is likely that the methods disliked by designers in industry are difficult or unpleasant to use. Function structures describe a product model which should be used in order to describe a product on an abstract level. In some schools of design science, many rules for "right" function structures are given. The procedure to generate such models is taught at universities but is not formalized and there is little help provided to perform this process. It seems to be one cornerstone of the successful transfer of design research to provide procedural guidance to the designer.

6.4 Implementation of Research Findings

Research in the field of method implementation (e.g., Stetter and Lindemann 2005) indicates that not only the choice of the right method and a sensible adaptation is necessary, but also a conscious implementation. The main goals of activities such as training or pilot applications are to win and retain acceptance. From the observations in automotive industry, one factor seems to be crucial: the awareness by and the demand from the management (this corresponds to the observations of Wolf 2011). Designers are, due to high competition and high pressure (compare Pulm and Stetter 2009), only able to expend extra effort for strategies, methods, and tools, if this effort is desired by the management. It could be observed several times that one department manager implemented certain methods or tools. Then the department manager changed, the successor did not oppose the methods and tools, but also did not support them, as he was not convinced concerning their effectiveness. After a short period of time, the usage of the methods and tools declined and other activities became more important. This phenomenon is rather crucial because of the high fluctuation rate on the management level. Strategies, methods, and tools need an extremely high acceptance level by the designers so that they might have the possibility to convince a new department manager.

6.5 Evaluation of the Impact

The impact of methods on a product development process can be both higher effectiveness and higher efficiency (compare Becattini et al. 2012). The philosophy of continuous improvement proposes an on-going effort to improve products, services, or processes and always includes some instances of "check activities." A positive vision of the transfer of design research results might be that it is also happening continuously—starting maybe with smaller methods to tools which require higher initial effort to full-scale strategies. The persons involved in the process usually need some affirmation concerning the effectiveness of the research results either for themselves or the superiors. The evaluation of the impact of strategies, methods, and tools is however aggravated by many facts; the most severe are (compare Stetter 2000):

- the measurement indicators problem: in order to allow continuous controlling and a cyclic transfer approach, the impact of the transfer of research results has to be evaluated before the effects in terms of greater customer satisfaction, shorter lead times, and reduced product cost can be measured (compare Wildemann 1993);
- the probability problem: the effect of improvements in the development process can sometimes be disguised by probabilistic effects (compare Giapoulis 1998);
- the attribution problem: the direct attribution of beneficial effects to a single transfer process of design research results often causes considerable difficulties (compare Reichwald and Conrad 1995).

In order to cope with these problems, several aspects need to be considered and a concept for evaluating the impact can be used (compare Stetter 2000). The core of the concept comprises indicators that have to be used as a result of the measurement

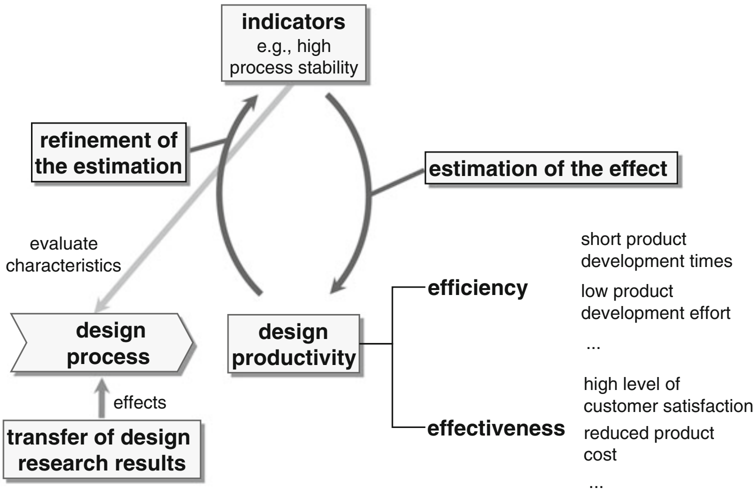


Fig. 6 Concept of evaluating the impact of the transfer of research results

indicators problem. Indicators can either be quantitative measurements or qualitative criteria. Quantitative measurements are characteristics of a product development process that can be measured, for example, by the means of determining the time needed for performing a certain process step. When using quantitative measures a triangulation, i.e., use of a variety of sources, should be performed in order to validate collected data. The measurements can be obtained without too much extra effort, if existing systems for reporting are expanded, for example, if working hours are not only attributed to projects but also to process steps. Qualitative criteria are based on a subjective evaluation. For instance, a subjective evaluation of the transparency can be a helpful indicator for evaluating the impact of a method or tools in the early stages.

Such indicators evaluate certain characteristics of the design process and can be used to estimate the design process productivity. The capability to estimate the effect of indicators on the design productivity can be enhanced by cyclic learning. A refinement of the estimations should take place at the end of transfer projects. The concept of evaluating the impact of the transfer of design research results is sketched in Fig. 6.

7 Transfer of Research into Practice

The main insights presented in this chapter are:

- the distinct characteristics and challenges of the respective product development process and the product itself need to be understood in detail by the academic partner in order to allow the transfer of research into practice;

- a transfer of research into practice is a process requiring certain steps such as analysis and evaluation and a high level of trust on both sides;
- academia needs to respect certain characteristics of industrial design processes such as the evolutionary nature of design in industry in order to create useful research outcomes.

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When and How Do Designers in Practice Use Methods?

Burkhard Wolf

Abstract Designers in practice do not use methods as explicitly as design teachers and researchers expect it. Observing good experienced designers one often can discover methodical skills and intuitive systematic approaches. Methods—as they are taught in design courses at the university—can only be found in the daily routine, when it is demanded by the management, e.g., in the companies' design project guideline.

1 Design Departments Have to Come up with Good Solutions in a Short Time

The overall goal of a design department in industry is very easy: Coming up with good solutions in a short time.

This demand is easily understand, but for the targets "good" and "short" designers have to struggle all the time. Each single decision in the design process is a compromise between good and short (fast). To find the best compromise, it is common sense that a systematic approach is helpful (Pahl et al. 2007; VDI-Richtlinie 2221 1993; Wolf 2011). Design research has developed numerous tools and methods for this purpose. In design classes, many of these tools and methods are taught and practiced. A company with a powerful design department tries to support their designers with an agreed design process model and by providing a set of selected tools and methods which are rated useful for various design situations in the company.

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2 Project Management and Toolbox of Methods

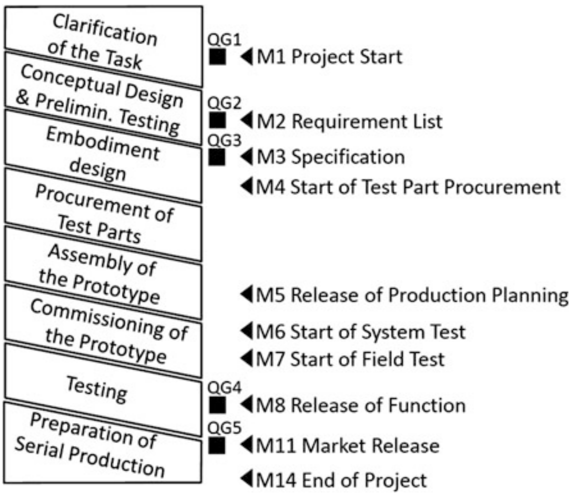
The company, the author is working for, supports a systematic approach among other things by a standardized plan for a design project and by a toolbox of methods. A 70 pages booklet called "design guideline" describes the project plan. The so-called quality gates and milestones are the core of this project plan (see Fig. 1). The project team passes the Quality Gates (QG) together with the steering committee of the respective design project. The project team carefully prepares all requested documents for these meetings. Standardized checklists are used to cross the quality gates efficiently.

As a part of the project plan, some methods are applied since they are required to pass the quality gates

- project draft (description of the technical content, resources, budget, and schedule)
- requirement list (technical requirements translated from the market needs)
- product specification (description of the preferred solution)
- review plan (when to discuss which topic with whom)
- qualification plan (how to ensure the functional performance of the product)

The approval of the project draft is the formal start of a design project. Requirement list and product spec are widely accepted methods taught in design classes. The review plan proved to be useful to enhance designers to discuss their ideas and solutions with the appropriate colleagues at the right time (Frankenberger 1997). With a qualification plan, one tries to systematically ensure the functional performance of a product. The so-called qualification engineers support designers to select and apply a suitable method for a particular step in a design project.

Fig. 1 Project plan for design projects (simplified)



Despite the doubtless benefit of these few methods (Jänsch 2007; Pahl et al. 2007) and the support by the qualification engineers, the actual application is often experienced arduous and time consuming (Geis et al. 2008; Jänsch 2007). It subjectively does not appear efficient (Birkhofer et al. 2005) and the author can confirm the resistance to methods of many possible users described by Geis et al. (2008). The strict demand of the management and the company's documentation system proved to be the most important drivers for an explicit use of methods.

The above-mentioned "tool box of methods" is a collection of methods which are rated useful by designers and managers in design projects in the past. These methods are described in the companies' intranet (see Fig. 2).

Experts are available to support the application of the tools and methods. Courses in these methods are offered as part of the companies' internal education program. The tool box contains, so far, the following parts:

Method	Task/Goal	Outcome	Contact Person/ Expert
project planning in R&D	Planning and steering of projects with PPMS and QlikView	The project is reasonably planned	J. Smith 1234
systematic definition of requirements	development objective matches the market requirements	Customer value and acceptance testing for each requirement documented in the requirement list	H. Spec 2345
solution finding methods (intuitive and discursive) and evaluations methods	generating a pool of ideas for solving of problems and contradictions	the superior concept is chosen and can be realised	E. Wallace 1345
risk management	comprehensively assuring crucial and complex developments	Documentation and evaluation of systematically identified risks.	J. Risky 3456
testing methods for designers	efficient planning, performing and analysing of tests	Efficient test procedure with clear objective and documentation of results	R. Testing 4567
design of experiments	Understanding complex relations with little effort of experiments	Functional relations of the command variables of the process are established.	S. Carter 5678
Methods of Simulation	Evaluation of concepts and functional demonstration without parts of "steel and iron"	best concept identified, problems discovered early, effort of experiments reduced.	M. Brown 6789
endurance validation	forecast of endurance based on in-house tests. time advantage by the use of time-lapse tests	Components resist the loads in practice in the long run	R. Valid 7870
reliability management	Increasing the availability by reducing incidents and breakdowns	The customer expectations concerning availability are met	J. Green 8901
design review guideline	quality intensification of technical solutions and design processes	The ideal solution is going to be realised. Tasks and responsibilities are documented.	S. Oliver 9012
value stream optimization	Making processes transparent and identifying weak points	Transparent and efficient processes by elimination of waste	G. Value 9123
systematic process of problem solving	Refining interpersonal and methodical skills	Efficient collaboration in teams and systematic problem solving	R. Valid 7870

Fig. 2 Methods portal of the companies' intranet

- project planning
- systematic definition of requirements
- solution finding methods (intuitive and discursive)
- evaluation methods
- risk management
- testing methods for designers
- design of experiments
- endurance validation
- reliability management
- design review guideline
- value stream optimization
- systematic process of problem solving

In addition, the qualification engineers scan further available methods. If designers or managers see a benefit of such methods, the qualification engineers try to adapt them to the companies' needs. Together with the designers, they plan and facilitate the necessary steps in order to apply established and new methods in an efficient way.

3 Influence of Project Management and Design Education

The above-mentioned methods are a small selection of the ones described in educational books and guidelines for designers (Pahl et al. 2007; VDI-Richtlinie 2221 1993). Almost all designers the author is working with have at least a basic education in systematic design and design methods. For this reason, it is difficult to find out how they would work without the systematic background (Jänsch 2007). On the other hand, in practice, designers develop their own "methods" unknowingly and implicitly when they instinctively aim to become more efficient, as described in (Ehrlenspiel 1999). A common approach one can observe in practice is the multiple correction of a first solution idea. This is described, e.g., in Dylla (1991) and Ehrlenspiel (1999). It appears as the opposite of abstraction: finding a quick solution for a design task, being happy and perhaps proud to make progress and then—instead of calling this first idea into question or looking for other solutions—just correcting it in several aspects (function, cost, manufacturing, etc.). Observing the daily routine, it is impressive, how often this "natural approach" is used and how seldom designers use their methodical possibilities explicitly (Birkhofer et al. 2005; Günther 1999; Jänsch 2007; Wolf 2011).

Methods and outcomes from design research which are *not* required to pass the companies' quality gates can hardly be found in the daily work of the observed design department. Frequently, designers—above all students and beginners—intend to use methods for solution finding. Behind this intention, the author assumes the hope to be creative solely because of using such methods. Nevertheless, an actual use of a distinct method like brainstorming, method 635 or even morphological matrix is astonishingly rare despite the fact these methods are well known and they are comprised in the mentioned "toolbox of methods."

On the other hand, there is a class of methods with a completely different reputation: simulation and calculation of crucial parts and mechanisms is standard in the company. Such "tough" methods to improve the embodiment design are generally seen to be efficient. Their usefulness appears to be obvious, since an optimized layout can be achieved much faster using these analyses methods than relying on estimation, experience, and test. From this aspect, simulation and calculation methods are very different compared with methods to improve the design process itself. In the observed company, a particular department for simulation and calculation supports the designers on a very high level. Designers appreciate this service and use it intensively.

Designers in the analyzed company see the project management guideline as the most important system to lead through the design process. A strong demand of the companies' management underlines this. Apart from the requirement list, controlling resources, cost, and schedule dominate the approach of the project management guideline.

4 Lessons Learned

Designers in industry improve rapidly their knowledge in construction material, production, machine elements, strength characteristics, etc. According to other references (Birkhofer et al. 2002), the author got the conviction that methodical skills do not evolve in parallel.

An explicit application of design methods and supporting tools can be seen almost only when it is demanded by the management or the companies' documentation system (Wolf 2011). Designers—and the author includes himself in this criticism—only seldom manage to overcome the hurdles of working as they did as students: being keen to follow a systematic plan, abstracting and looking for the right method for the actual task at hand. The most promising supporting factors in terms of using methods and approaching systematically seem to be the following:

- being demanded by the management
- having the wish to improve the own procedure
- having the personal experience that it saves time
- knowing realistic and convincing examples from the own working field (López-Mesa 2003)
- making oneself aware of the actual benefit after having applied a method
- ease of use (Birkhofer et al. 2002; Geis et al. 2008; Jänsch 2007; Jänsch and Birkhofer 2004)
- knowing for which problem the method is appropriate and for which not (Jänsch and Birkhofer 2004)
- being able to adapt the method to the actual problem (Birkhofer et al. 2005)

Some of these supporting factors give an idea on how to introduce methods: Making designers aware of the importance of reflecting the own procedure. Finding convincing examples for the benefit of using methods is a much bigger challenge than it seems to be. Post-method learning helps to become aware of the benefit and the limits of a particular method.

Another lesson the author learned in practice is the inspiring effect of solving concrete design tasks collaboratively in a well-working team. Such sessions proved to be organized easily. Designers enjoy the working atmosphere of struggling together for a good solution. Doing this frequently evolves a culture of mutual confidence which is important to encourage the participants outlining the weak points of their preferred ideas (Wolf 2011).

In such design reviews, CAD models presented with a beamer are helpful to give an overview and introduction on the design. For detailed discussions, this medium has turned out to be too volatile. Large printouts of CAD models and drawings simply attached to the wall emerged to be much more helpful for the interaction between the participants. Usually, the presenting designer carefully selects the most helpful views and sections in advance. This procedure is more efficient than doing it life within the CAD system during the design review. Furthermore, paper sheets do not disappear during a design session. So everyone can sketch, comment, and highlight crucial points. And everything is documented for a wrap-up. The CAD models projected with a beamer can be a helpful addition but not supplementing the paper.

It is self-evident that a rough documentation is helpful for the discussion. But most designers usually do not like this. Again the management must claim a documentation which should be done in a visible and easily readable manner for all participants during the design session.

Such simple design reviews are fun and they very often lead to commonly achieved results which are obviously much better than the sum of the solutions of the single designers. Therefore, design sessions turned out to be attractive for designers.

5 Platform Needed

Industry wants to improve the design process in practice. Academia wants to understand the design approaches in practice and needs realistic opportunities to analyze it and to test tools and methods. The international workshop “Impact of Design Research on Practice 2013” (IDRP13) in Munich for the participants from industry was a very valuable interaction—above all among the colleagues from industry. It turned out, that we have similar questions and similar approaches. Nevertheless, an exchange of best practices and the profound discussion among each other and with the design researchers was widening the horizon and inspiring.

For designers in industry, a platform for discussion and exchange with people from other companies has turned up to be meaningful. Design researchers could chair such a platform. They can help to open the minds and to questioning the frequently continued and hardened convictions and habits in design practice. The common aim is to find out the most relevant and promising results of research that make design practice more efficient and attractive.

Design researchers can use such a platform to get insights in actual design processes. Here we face the difficulty of confidentiality. Companies are sensitive as far as innovation projects are concerned. A discussion and publication of the design process as such is usually uncritical. Collaboration on interesting—and therefore confidential—projects needs confidence among the involved people. A high level exchange platform will lead to a network, which overcomes mistrust and leads to win–win projects for industry and academia. Experienced designers, perhaps former design researchers who now have technical responsibility in a design department can moderate. In addition, the author proposes design researchers to accompany important design projects from outside the company. At first sight, this distance does not seem to be useful. But with such an approach, one easily can analyze relevant design projects—even crucial ones—instead of studies. In addition, one is able to analyze a design process without interfering it. The platform can be the base of struggling for the best way of collaboration in a concrete situation in order to respect the interests of all partners.

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Success Stories

Together, the chapters provide over a hundred pathways through which design research successfully impacted practice. The pathways are: products, methods and tools, training courses and educational programmes, people, organisations of practice and conferences. Some of these success stories are shared below:

- As quoted in "Are Methods the Key to Product Development Success? An Empirical Analysis of Method Application in New Product Development", in summing up the findings of the extensive innovation study conducted by the Product Development and Management Association (PDMA) in the USA, Barczak et al. (2009) note that: "In terms of aspects of NPD management that differentiate the 'best from the rest', the findings indicate that the best firms [...] use numerous kinds of new methods and techniques to support NPD." The structured use of methods can indeed be a very effective way to help generate new ideas and improve companies' ability to innovate (Fernandes et al. 2009).
- Booker (2012), quoted in "Preparing for the Transfer of Research Results to Practice: Best Practice Heuristics", lists very impressive measurable improvements made by design teams employing some well-known design methods, such as FMEA or DFA. Cordero (1991) demonstrates use of methods and success of NPD with regard to the use of computer-aided design/manufacturing/engineering. Sun and Zhao (2010) identify a positive correlation between the use of multiple methods (including TQM, QFD and value analysis) and the speed of new product development. Griffin (1993) and Barczak et al. (2009) likewise confirm that certain methods can help to reduce product development cycle time. The use of methods shortens the development runtime and improves time to market. Projects with faster time to market meet with greater financial success. ("Are Methods the Key to Product Development Success? An Empirical Analysis of Method Application in New Product Development").
- Based on a study of 410 new product development projects conducted with feedback from experienced product development managers and project managers in 209 manufacturing companies that operate their own new product development from bases in Germany, Austria and Switzerland, it was found that applying methods in new product development led directly to superior financial

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performance of the developed product, and indirectly to a greater degree of innovativeness, better cross functional collaboration and shorter time to market. While no specific success stories are given in this survey chapter, it shows the overall positive influence of use of methods on product success. The companies that were used in the survey provided a list of methods they used which include, but is not limited to, the following: Customer interviews and observations, Creativity Techniques, Scenario Analysis, Design for Sig Sigma, FMEA, QFD, Concurrent Engineering, DFMA, CAD/CAE, Rapid Prototyping, etc. ("Are Methods the Key to Product Development Success? An Empirical Analysis of Method Application in New Product Development").

- The Functional Basis, its utilization as a building block of the Design Repository, and the function-to-failure mappings have made impacts in education and in the practice of industry. Functional Basis pays dividends in better designed products and more critical thinking by students in engineering design courses. 90 % of the functions described by a group of practicing aerospace engineering designers could be described by the Functional Basis, with two-thirds of those function descriptions matching a Functional Basis term exactly. This study suggests that the Functional Basis has good validity in an industry engineering design context. There has been measurable acceptance (interest and preliminary use) of function-based methods within design teams of US automotive (GM, Ford, SAE), aerospace (NASA, JPL) and product innovation companies (NuScale, Xerox, Daimler, and Raytheon) as well as national labs and Department of Defence agencies (National Center for Defence Robotics, DARPA). ("Impacts of Function-Related Research on Education and Industry").
- An original framework for transferring results of design research into practice, specifically addressing the need of creating a consortium of companies interested in being part of both the mass dissemination process of already tested methodologies and in pilot experiences and preliminary dissemination activities with the latest design research developments. e.g., introductory workshop, then Basic TRIZ course, then supported learning practice on case studies, then final workshop and results. An original metric (for evaluating the impact and viability of adoption of design methodologies in practical contexts) is developed. The metric has been applied to six case studies of industrial interest, for consolidating acquisition of skills through practical application of more theoretical elements from design methodologies, by employees of industries that have already received a basic training in Network of Problems (NoP). The NoP approach is one of the OTSM-TRIZ instruments that aims at coping with the analysis of complex problems during a problem-solving process. Tests show substantial promise of improvement in analysing complex industrial problems. ("A Framework for the Dissemination of Design Research Focused on Innovation").
- Advanced Product Design and Prototyping (APDAP) is a joint venture between Indian Institute of Science (IISc.) and Tata Consultancy Services (TCS)—the biggest ICT firm in India under the Tata conglomerate. Set up in 1996 at IISc.,

APDAP provides cutting-edge technology and innovative solutions to the Industry, so as to enable them to compete in the global market. APDAP's capabilities include Industrial Design, Product Engineering, Prototyping and tooling and manufacturing, where TCS's knowledge and skills in marketing is married to IISc.'s knowledge and skills in science, technology and product development. Typically IISc. professors work as consultants to product development projects; those from the design department use methods and tools from various areas of design, and students as short-term interns who work with in-house engineers at APDAP to develop solutions for the real world. APDAP has carried out over 200 projects with 50+ companies from around the world, which include the likes of Tata Motors, General Motors, General Electric, Proctor & Gamble, etc. ("Impact of Design Research on Practice: The IISc Experience").

- Innovation, Design Study and Sustainability Laboratory (IdeasLab) at the Centre for Product Design and Manufacturing, IISc. developed the SAPPhIRE model of causality, in order to describe how engineered as well as biological systems work. The project led to the development of a tool—Idea-Inspire—for systematically providing stimuli for ideation in solving technical problems, using biological and technical systems as stimuli, with SAPPhIRE model as its ontological framework. Idea-Inspire has been patented by IISc. A project taken up demonstrated its efficacy to support design of a lunar vehicle mobility platform. It has been subsequently customised for companies including Indian Space Research Organisation (ISRO) and IMI-Vision, UK. The SAPPhIRE model has been used as a backbone for developing a host of other pieces of knowledge: as a basis for an integrated model of designing and a new method for assessing design novelty; as the basic ontological framework for providing in-service information for engineering designers at Rolls-Royce, and for providing product-in use information to engineers at Pratt & Whitney. ("Impact of Design Research on Practice: The IISc Experience").
- International Conference on Research into Design (ICoRD) has been the first and only series of international conferences in India that focuses on design research. The idea behind its initiation was to provide an opportunity for researchers in India, most of whom would find it hard to manage resources to attend such conferences abroad, to continue to remain in touch with cutting-edge research at the international level, which is a precursor to doing high quality research. Since 2006, ICoRD has grown from 30 to about 120 papers in its five editions, and has grown in size to attract from 70 to about 200 researchers, about half of them being from the international community. One of the major strengths of ICoRD is its student-friendliness; it uses incentives to attract students to participate in this event with the hope that it would encourage some of them to take up design or design research as a career. Success of ICoRD can be seen in the growing platform it provides, not only in the number of people and papers where very little existed before 2006, but also in the growing spread of institutions in which it is held. ("Impact of Design Research on Practice: The IISc Experience").

- The Royal College of Art and the Imperial College London jointly run a 34-year old, hugely successful (double masters) programme called Innovation Design Engineering (IDE). This two-year full-time programme involves a series of themed but student-directed projects in the first year, prior to major group and solo projects in the second year. A highlight of the course is the industrial embedding of some of its student projects, e.g., in partnership with the BBC, Elmar, Ford, Guzzini, Hutchison Whampoa, LG, Nokia, Philips, Pramac, RIM, Sony, Swarovski, Thales, Alenia, Unilever, and Vodafone. While traditionally, graduates gained subsequent employment in corporations and design consultancies, the past 5 years has seen a significant shift with the greater proportion of graduates setting up their own businesses and consultancies on completion of the programme. In a recent project with Airbus, 1st Year IDE students explored the value of implementing design thinking insights in engineering practice and the relative merits of decisions based on optimisation versus win–win scenarios for aircraft cabin design. Illustrious past students include Jonathan Ive of Apple, Lord Dyson, etc. ("Industrial, and Innovation Design Engineering").
- The two point exponential approximation based approaches and for controlling the magnitude of change of design variables to ensure convergence during optimization developed by Fadel's group at Clemson University, USA has been used both by scholars in structural optimisation in academia and by professionals at industry and at NASA to reduce computational cost. They also developed a solution for packaging or layout optimisation problems, considering complex non-convex shapes and a multiplicity of criteria. The method has been used to develop hybrid vehicle applications for the Tank Army Command (TACOM), for the GM Corporation for computing the luggage packing capabilities of new vehicles. That code, which remains currently in use, is still outperforming other similar existing codes. ("Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA").
- Summers' group at Clemson developed "Lamelle Query Systems" for Michelin in 2005–2006, where 'design exemplar' was used as a software prototyping tool to define geometric algorithms to match repeated line-arc-line patterns for tire tread inserts within bounding tolerances. This was the first industry sponsored project that employed the principles of the design exemplar as a CAD Query Language, recast into a dedicated system that was delivered to Michelin to support tire designers in reusing stamping tooling to construct the lamellas, or tire inserts, resulting in an annual estimated savings of several hundred thousand dollars. His team also developed 'a lazy parts identification method' for BMW with Dr. Mocko, which is currently being integrated as a best practice design process within the BMW development teams. ("Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA").
- Mocko's group at Clemson applied techniques from the Design Structure Matrix (DSM) and Design Mapping Matrix (DMM) to enable changes in engineering requirements, systems architecture, and validation and verification tests to be

evaluated. Contributions from this research were applied to several automotive systems of BMW to help identify key engineering requirements and tests during conceptual product development and generational redesign. Dr. Mocko and the students developed a conceptual design method to support distributed conceptual design space exploration. The process and information was developed in collaboration with industry partners and has resulted in an Options Exploration method currently in use at Johnson Controls Incorporated ("Clemson Engineering Design—Applications and Research (CEDAR) Group—Clemson University, Clemson, SC, USA").

- C-K theory developed at Mines Paristech France provided a framework to describe, analyse and evaluate innovative design processes/projects, as it helps analyse the multiple outputs of innovative design projects. This kind of evaluation is spread in many firms. As a general design theory, C-K theory helped to analyse existing design methods. C-K theory was also used as a "conceptual model" to design methods and processes for managing innovative design processes. KCP is a method derived from C-K theory to support innovative design processes that need to involve many participants. C-K theory helped analyse the limits of traditional methods of collective creativity. C-K theory formalisms are taught today in different countries in various contexts: engineering schools, management schools, business schools, design curricula, entrepreneurship schools, and universities. Study of the impact of its education showed that it significantly increased the capacity of students to resist fixation. C-K theory has been disseminated in many academic fields. ("Multiple Forms of Applications and Impacts of a Design Theory—10 Years of Industrial Applications of C-K Theory").
- Students are the biggest impact of the work at Center for Design Research (CDR) at Stanford University, USA on practice. For instance, Vinod Baya, after Ph.D. from CDR in 1996, worked on the project of Generative Design Knowledge Capture. Much of the work was sponsored by NASA, and centered on capturing the design rationale that went into parts that were generated by CAD and CAE systems. One system that emerged from this project, DEDAL was an intelligent tool that can index and retrieve multimedia information about devices being designed. Baya went on to work at NASA as the chief architect of many knowledge management, collaboration and search and retrieval systems. He then went on to apply his expertise in analysing socio-technical aspects of information technology systems to advise on a broad array of technology areas at Price Waterhouse Coopers, where he is now a Director for the Center for Technology and Innovation. Baya, more than the systems he built, with his ability to analyse the implications of socio-technical systems that manage information, has made the most impact on design. Many graduates of CDR go on to highly influential design and technology positions in established firms. Numerous CDR graduates, for instance, now work for the software company SAP. Philipp Skogstad (Ph.D. 2009) is Head of Development Processes and Tools at SAP. ("People with a Paradigm: The Center for Design Research's Contributions to Practice").

- CDR research led to development of drawing and collaboration technologies to support design collaboration that are now part of offices and studios everywhere. It is more commonly the case that researchers from the CDR who worked on collaboration and knowledge systems research then continued to local industry to create these influential products. CDR collaborated with Tao Liang (did Ph.D. at CDR in 2000) at Xerox-PARC on then-novel web-based editing tools for DocuShare, and on special configurations of DocuShare for education. The lessons learned in CDR-based roll-outs of DocuShare-based knowledge capture and reuse tools helped Xerox to understand larger issues of tool adoption and use. Liang then went on to become Principal Software Development Engineer at Skype, and architected and developed the Skype Web RTC platform, which shares many features from research at CDR. ("People with a Paradigm: The Center for Design Research's Contributions to Practice").
- Several of CDR's most notable instances of design innovation came as the result of "spinoffs" from sponsored research. Louis Rosenberg (Ph.D. 1994), for instance, was working on design research sponsored by NASA to support remote tele-operation of robot arms for the Mars Exploration Rover; he noted that people enjoyed using the force-feedback joystick that was used in the flight simulator experiments. Rosenberg and fellow CDR researchers Tim Lacey and Bernard Jackson started a company, Immersion Technologies, to develop consumer-grade haptic devices, which is a successful company supplying such devices worldwide. ("People with a Paradigm: The Center for Design Research's Contributions to Practice").
- From the very beginning, there is a long tradition of collaboration between industrial partners and the Institute of Product Development at Technical University of Munich, Germany. Most of the partners are engaged in developing and producing their own, global products. Most of them are located in southern Germany and in different European countries. Within the past 40 years more than ten spin-outs successfully started their business as consultants, suppliers of specific software, engineering-services or their own products based on their experience gained during their studies and research in the Institute. Within the Department of Mechanical Engineering of TUM there are more than 5000 students, in addition to 400–500 research assistants pursuing their Ph.D. All students undergo a rigorous training in methodical design. Most of the students (about 80 %) after their Master's take up a job in industry. The others join consultancy firms, start their own company or switch to a Ph.D.-programme. About 100–120 aspirants graduate with Dr.-Ing. every year. Among them, about 90 % take up jobs in industry, while others join patent offices, consultancy firms or start their own business. Until recently, all professors of the Institute had to work for more than 10 years in industry before becoming a Professor. This affords a chance to learn product development and engineering design in practice, with specific boundary conditions as well as all the aspects of integration. ("Impact of Design Research on Practitioners in Industry").
- An approach to understanding the nature of complexity and their management in industrial projects has been developed by Maurer at Technical University of

Munich and has been demonstrated in an industrial project. In the industrial application, results from the complexity assessment approach applied were decisive in selecting suitable strategies for complexity management. Only with the clearly approved strategy on hand one or several methods of complexity management were finally selected and implemented. The approach has subsequently been the basis for a start-up business led by the author. (“Facing Complex Challenges—Project Observations”).

- Faceted classification has been around in library classification for many years, but it is only in the past 20 years that it has begun to be widely used computationally to assist in information search and discovery. Since the eighties, research teams at the Universities of Bristol and Bath that included the author developed approaches to computational faceted classification (that anticipated many of the capabilities of a modern computing environment—viewing arbitrary objects, hyperlinking, metadata and tagging) simultaneously with several research teams around the world. By 2012 it become a default approach for user interaction in e-commerce. The work has been applied by the group of McMahon in several application areas including manufacturing process selection, management of in-service information and of business data, design for emotion, with a view to developing guidelines for engineering use. It is an exemplar of how results from research carried out by, not one research group, but a research community, influences successful transfer of research results to practice. (“Faceted Browsing: The Convoluted Journey from Idea to Application”).
- A framework model—Company Strategic Landscape (CSL)—defines the elements related to the product development operations and the production of a company. The CSL-framework model developed by Riitahuhta’s group at Tampere University of Technology, Finland describes the key issue entities for structuring product and the contents of the relations between the issue entities. The key idea in CSL-framework model is the relation between the internal structure of the product and the delivery process. The Integration of different domains has been a starting point of Mechatronics Paradigm. As a reference, container handling equipment in ports is a good example of multidisciplinary technology applications, presenting how integration over disciplines enables incremental technical concept development. Both these methods have been implemented in industry. (“Successful Industrial and Academia Cooperation in Technology Industry”).
- Singapore University of Technology and Design conducted three studies. The first study considered the authorship of industry professionals across the design research literature within the last 2 years, and found that of the 192 papers surveyed, while 174 papers were authored exclusively by academics, 18 had authors from industry, the military, government or hospitals. This total of 9.4 % of papers represents strong partnerships, as publishing in academic journals is not a typical component of design practice, and that papers within the academic venue are written by authors affiliated with non-academic organisations is a significant indicator of relevance of the published research to industry. The

second study samples 134 publications in the same design journals since 1990 to determine the number of publications with industry involvement and the types of knowledge transfer occurring in design research. It found that 39 % of articles in the top five design research journals exhibit evidence of knowledge transfer between research and practice. Given the sample size, the 95 % confidence interval for this sample is ±8 %, meaning that between 31–47 % of published research is shared with industry. The third study provides a survey of design experience of engineering design researchers in academia—yet another indicator of impact of design research on practice. 50 % of those surveyed were found to be named inventors on patents (this number is higher than the percentage of named inventors across engineering faculty in general); a large number had consulting (71.1 %) and industrial experience (81.5 %); 71.1 % taught a product design course; and 63.1 % developed tools for innovative design. The results indicate that the participants were well-versed in research, practice, and education, typically engaged by design researchers in academia, and practiced design as an integral part of their academic work, which should correlate to a higher potential of transferring their research to practice. ("Changing Conversations and Perceptions: The Research and Practice of Design Science").

- Five further case studies are provided in "Changing Conversations and Perceptions: The Research and Practice of Design Science" to illustrate various kinds of integration of design research and practice. One was a case of an automotive partnership in which an industry need was met by developing new design tools. In another, a fundamental design language was developed and applied to reverse engineering, automotive design, design of manufacturing machines, and international standards. In the remaining studies, the authors considered the value of cases with educational elements, such as one used in training future air force leaders in design research. All these cases were part of development of commercial products. ("Changing Conversations and Perceptions: The Research and Practice of Design Science").
- The objective of the Function-Behaviour-State (FBS) Modelling project at the University of Tokyo, Japan was to model function in a computational manner and to apply the modelling scheme to conceptual design support and the design of the self-maintenance machine. This was implemented into an FBS modeller, and was applied to develop a conceptual design support and to the design of a self-maintenance photocopier. Led by the authors, a framework for a self-maintenance machine and the development of its design methodology, its reasoning system, and its prototypes were proposed. These included control type self-maintenance machine and function redundancy type self-maintenance machine. A self-maintenance photocopier was also developed in collaboration with Mita Industrial Co. Ltd. in 1989. The first self-maintenance photocopier was introduced into the market in 1994. ("Development of Function Modeling and Its Application to Self-maintenance Machine").
- *StrategyPlan*—a method that captures long-term goals and a strategy with clear guidelines for product development was found very effective in practice. In 2 × 2-day workshops a simplified scenario technique was applied for forecasting the

future of certain Product-Market-Constellations with surprising proximity of the forecasted picture and the reality 3–5 years later. The scenario technique has helped enormously for decisions of general product development directions—as a result own expertise was build up and a new device was developed securing the market leadership 4 years later. *Brainstorming* was the preferred method when searching for new product fields or goals completed by visualising the ideas to improve associations and to expose contradictions. No more than 12 people with diverse backgrounds was found effective. *IdeaPool*—Product ideas from employees or from outside the company were centrally filed in a summarised form. All ideas for new products or innovative features were centrally collected in a standardised table and regularly evaluated in a small cross-functional team including management. Combination matrices like the *Morphologischer Kasten* were used in feasibility studies to help visualize alternatives and to optimise patent descriptions, even though such matrix methods were seldom applied in projects under time pressure. (“Experience with Development Methods at Three Innovative Hidden Champions”).

- General Morphological Analysis (GMA) is a key PSM method that can improve the effectiveness of idea and concept generation phases within the design process. It encourages identification and investigation of boundary conditions. The enormous number of options generated by GMA can be whittled down using Cross Consistency Assessment (CCA), where all of the parameter values in the matrix field are compared with one another on a pair-wise basis. In the generic form GMA has been employed in over 150 projects, e.g., Army boots, future submersible systems, ground target systems, new styles of infantry soldiering—a mixture of Public and Private sector, and academic projects. Multi-Criteria Decision Analysis (MCDA) process helps subjective and personal preferences of an individual or a group in making a decision. These judgements are then synthesised throughout the structure to select the best alternative. MCDAs have been applied extensively in industry, partially via a range of commercially available software such as Decision Lens, Expert Choice, and Macbeth. (“Design as an Unstructured Problem: New Methods to Help Reduce Uncertainty—A Practitioner Perspective)”.
- In a case of implementing design research outcome to practice, several aspects needed to be considered for successful implementation of distributed product development. Team members are forced to use computer-based communication media since personal meetings are time consuming and expensive. There are two important aspects for successful communication in distributed design: communication media (with a focus on computer-based sketching) and the organisation and structuring of product data (with a focus on thinking in functions). It is very important that there is a common understanding of how the data is stored and organised. A proven approach is to structure the data in one root assembly. This structure needs to be complete and consistent to prevent misunderstandings and create a standard over different products. Grieb and Quandt did this is by thinking in functions, as parts change through time and projects, but the functions (generally) stay the same. These measures have been

applied in their organisation leading to significant improvement in the distributed development process of their organisation. The basic knowledge needed to develop this approach came from design research. ("Executing Distributed Development in Industry and the Influence of Design Research").
- Generative design using KBE: An automated and generative modelling design tool was developed by Luleå University to explore the design space and further optimise products without introducing unnecessary risk. The approach shifted design from 'create a model and analyse it, create another and analyse that' to 'preparing a flexible "parametric" model that through automation can be used to explore variants'. This bridged the knowledge gap in the company that despite the company's engineering and manufacturing skills, its conceptual design capabilities were not competitive, and product and production costs could not readily be committed in due time. Once the technology was introduced in a subsequent business project it became a success. The ability to define and evaluate many alternatives enabled the definition of a robust product design, something that would have been nearly impossible without the ability of an automated, generative modelling approach. Product design using KBE tool was efficient and had a significant impact on the design process. Since then the tool has been matured and integrated into engineering operations. ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View").
- Service models had become common within the jet engine marketplace; for engine OEMS, this meant that ensuring correct and relevant information from in-service situations became a business responsibility and a design opportunity. How can a manufacturer make use of the increased responsibility and control over the product through life? For GKN Aerospace (Volvo Aero at the time) this also had implications as a partner and supplier to the OEM. The result of the research was the successful integration and demonstration of Functional Product Development—a design system supporting a product service system approach. ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View").
- Establishing a robust geometry assurance process is crucial to realise manufacturing process stability, and the conditions are set already in the engineering design phases. There was a need to enable design for geometrical variation and stability. GKN worked with Chalmers together with other industries, and initiated an exploratory research study that led to adoption of engineering design tools for geometric variant design available in Chalmers. Technology validation studies were performed on realistic industrial application cases. This proved successful, and the Ph.D. student was hired by the company to exploit the results within the company. At present the basic tool is being established at the company, and the specific research challenges may still take years to introduce into practice; yet the main principles from Virtual Geometrical Assurance could be readily deployed in a shorter timeframe. ("A Collaborative Engineering Design Research Model—An Aerospace Manufacturer's View").
- Over the past few years, the organisational function "product architecture" was systematically integrated as an independent central organisational unit, taking

active part in the concept phase of the engineering design process. This was to address a host of issues, including the following: establishment of a consistent and generic product structure for the whole organisation as a basis for standardisation throughout the design process; management of product related documentation standards; systematic planning of the necessary technical solutions based on a detailed functional product specification; and to bring transparency through similar reporting of the technical progress to ensure a well-focussed concept design phase. The concept for product structure was implemented, by Kreimeyer and his colleagues at MAN Truck & Bus AG., Germany, on a design project using prototypical software tools to refine and validate the new process, and transferred to a PLM environment. Currently, the process is being stabilised through risk management and further design projects that utilise the approach. ("Implementing Product Architecture in Industry: Impact of Engineering Design Research").

- Verification Upstream Process (VUP) has originally been developed by the author for managing quality of component and module suppliers. However VUP methodology can be implemented with ODMs as well. The key benefits of VUP are shorter product development time, faster error correction cycle, reduced workload of engineers releasing their time for other duties, and improved product quality. The process was implemented with a major ODM customer, and a survey was conducted with the customer to understand what kind of influence VUP had on module development, module quality, cost and development time. Over 80 % of people surveyed agreed that VUP speeded up module development; over 50 % thought that implementing VUP had significantly reduced R&D costs; about 90 % agreed that competence level of supplier's staff had increased; the survey indicated that there is possibility that module price may have increased; and close to 60 % people replied that VUP had greater influence to module quality than other quality systems had. ("Verification Upstream Process, a Quality Assurance Method for Product Development in ODM Mode").
- Ponn did his Ph.D. at the Technical University of Munich, Germany on a research project on situational application of methods (FMEA, Creativity Techniques etc.) and guidelines for the development of individualised products. Products (high pressure cleaner, juice squeezer, nut cracker etc.) were used to illustrate practicability of research results, with development processes situated in an academic context rather than industrialisation. Acting as methods moderator at Hilti, a special type of in-house consulting that uses such methods, Ponn could transfer his research knowledge of method application in practice. As a project manager for platform drives in electrical power tools, his main focus is on operational product development where method application is a means. The aim is to reduce the amount of "troubleshooting" in late phases, by more frontloading in early phases. The author is involved in methodological activities so as to promote approaches towards improved requirements engineering, including establishment of the V-Model as an instrument for developing a common understanding among stakeholders. ("Understanding the Gaps

and Building Bridges for Synergy—How to Promote a Dialogue Between Design Research and Design Practice").

- Based on a questionnaire study of experienced designers in industry on the experience of using current Parametric Associative CAD systems, a clear and significant need was identified that led to a new approach to the use of Parametric Associative CAD systems. The approach is in the process of being operationalised within BMW. ("Development and Application of an Integrated Approach to Cad Design in an Industrial Context").
- A method for early determination of product properties, developed at the Institute of Product Development at the Technical University of Munich, Germany, supports designers in analysing and verifying product properties as early in the design process as appropriate in order to improve early decision-making during product development. The initial point for this process is a profile of objectives in form of a web-diagram. The characteristics in such a profile can be distinguished into parameters and characteristics that can be mathematically described. The characteristics are the input information for single-factor-simulations which lead to a technology model that can be used for verification if the technology model has the potential to fulfil the objective profile. Simulation using virtual models is repeated until the technology model is appropriate, according to virtual simulation, to fulfil the objectives. Then a larger control-loop is initiated by production of foams and a physical process. As a consequence of the use of virtual models, only few cost-intensive physical models have to be built and tested. Both the approaches (virtual and physical) were successful as the processes were used in Audi for many years. ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry").
- In today's industry very well-accepted methods are Failure Modes and Effects Analysis (FMEA), systematic collection of specifications for clarification of the task, the general concept of "front-loading", all kinds of evaluation methods ranging from pairwise comparison to value analysis and TRIZ methods. ("Adoption and Refusal of Design Strategies, Methods and Tools in Automotive Industry").
- The company Heidelberger Druckmaschinen AG, for which Wolf works, supports a systematic approach by a standardised plan for a design project and by a toolbox of methods. A 70 = page booklet called "design guideline" describes the project plan. So called quality gates and milestones are the core of this project plan. The tool-box contains methods, found useful by designers in the past, for the following: project planning; systematic definition of requirements; solution-finding methods; evaluation methods; risk management; testing methods for designers; design of experiments; endurance validation; reliability management; design review guidelines; value stream optimisation; and systematic process of problem solving. Designers in the analysed company see the project management guideline as the most important system to lead through the design process. Apart from the requirements list, controlling resources, cost and schedule dominate the approach of the project management guideline. ("When and How Do Designers in Practice Use Methods?").

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