Lehrstuhl für Produktentwicklung
der Technischen Universität München

Handling of Strategic Uncertainties in Integrated Product Development

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Vollständiger Abdruck der von der Fakultät für Maschinenwesen der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs

genehmigten Dissertation.

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Prüfer der Dissertation:	1. Univ.-Prof. Dr.-Ing. Udo Lindemann
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Die Dissertation wurde am 29.04.2008 bei der Technischen Universität München eingereicht und durch die Fakultät für Maschinenwesen am 17.09.2008 angenommen.

FOREWORD OF THE EDITOR

Problem

Innovation projects have to face external and internal uncertainties, resulting from lacking or incomplete information on the market, customers' behavior, competitors' moves, or unexplored technological fields. Generally, the level of perceived uncertainty increases with the degree of innovativeness and novelty of the product, as one cannot draw from past experience in these cases. The mentioned sources of strategic uncertainty are highly interconnected and can have a propelling effect on each other. In the case of radical innovation, where the actual usage in the customer's system is often not known in advance, the uncertainty on the market side will not only be carried over to the technical side, but will also lead to increased complexity and uncertainty in the derivation of technical solutions. Thus, the early phase of product development, in which pivotal decisions for both market and technology are made, is characterized by an especially high level of uncertainty. Yet, the effective and holistic handling of the implied uncertainty is rarely addressed in prevailing procedural product development models.

Objectives

The aim of this work is to develop an enhanced approach supporting product development teams, as well as sponsors of innovation projects in effectively dealing with implicit and explicit uncertainties they are facing. The purpose of such an approach is to promote the deliberate and regulated acceptance of risks in order to realize highly innovative business and technology ideas which might otherwise be subject to abandonment.

Results

This thesis describes an extended approach for the handling of strategic uncertainties in Integrated Product Development, consisting of a procedural model and its associated tools and methods, as well as the consideration of individuals' and teams' behavior in uncertain situations. In the integrated model, fields of uncertainty are defined and subsequently explored through options. This approach integrates a real-options perspective into the established logic of integrated product development, in order to allow for the exploration and control of risks associated to radical innovations. The simultaneous acquisition of information and generation of solution options is methodically supported, leading to an integrated holistic decision base. In addition, measures for addressing human limitations in dealing with complex and uncertain problems are being derived and integrated in the model.

Conclusions for industrial applications

The uncertainty and complexity in radical innovations can become a major reason to avoid risky - yet possibly also highly rewarding - breakthrough innovations. The discussed approach aims at enabling the development team to effectively explore and deal with the risks of such an innovative development. At the same time, the sponsors of these ventures gain transparency on the proceedings on the "fuzzy front end" of innovations and receive prompt feedback on a project's chances of success. In addition, the model integrates often diverging commercial and technical issues in innovations. Overall, the ability of an enterprise to successfully originate innovative solutions is enhanced, which represents a major source of competitive advantage in technology-driven and dynamic industries.

Conclusions for scientific researches

The analysis of prevailing procedural product development models yields characteristic shortcomings in the handling of simultaneous strategic uncertainty on the market and technology side. The discussed approach presents an extension of the Integrated Product Development framework in order to support the development of such highly innovative products. The developed approach is capable of handling a larger number of uncertainty areas, for example, on the operative side through the provided options generation and matrix evaluation logic. The model can contribute to the further understanding of effective radical innovation management and provides a base for further research in the interface of psychology and behavioral sciences and engineering with regards to the implications of cognitive limitations for engineering design models.

Garching, December 2008

Prof. Dr.-Ing. Udo Lindemann
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ACKNOWLEDGEMENT

This dissertation was submitted to the Technische Universität München in Mai 2008 is the result of my work completed as an external researcher at the Institute of Product Development in the years 2005 until 2008.

I am indebted to my doctoral advisor Prof. Dr.-Ing. Udo Lindemann for the support and encouragement throughout this research project. When I approached him with rather uncommon proposal for a research project dealing with radical innovations he saw more chances than risks on both the academic and practice-oriented side. In particular, his provision of scientific freedom as well as guidance and participation in the case studies provided the basis of the present work.

I want to thank Prof. Dr.-Ing. Gunther Reinhart for taking over the position of second examiner of this dissertation. His intense review and propositions of improvements that are grounded in empirical experiences largely enhanced the reasoning in this thesis.

Also, I want to thank Prof. Dr.-Ing. habil. Boris Lohmann for being the chairperson of the examination committee and for the handling of the dissertation process.

Representative for the colleagues at the Institute of Product Development I want to thank Matthias Kreimeyer for the collaboration and the valuable input ranging from structuring of conference papers to specific academic processes at large.

On the industry side, I want to thank Dr. Richard Piock, Dipl-Wi-Ing. Ludwig Harrer, and Dipl-Ing. Heinz Knuppertz for opening the doors of their respective companies for discussions and active collaboration in ongoing research projects. Specifically I would like to thank Mag. Michael Lackner and Dipl-Ing. Peter Weingartner for their openness and friendly cooperation throughout the years. As a team they remarkably personify one of the central elements of this thesis, namely target-oriented and joint collaboration in commercial and technical aspects.

I want to express my deepest gratitude to my long-term partner Isabel who always encourages me in my ventures and who provided both mental and pragmatic support to this work.

Finally, I am very grateful to my parents for their unwavering faith and support. The education and support they offered me have built the basis of this work.

Munich, December 2008 Markus Lorenz

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1 Introduction

1.1 Starting Point and Problem

To be successful in a competitive environment today, organizations need to identify business opportunities early and need to address them consequently [GAUSEMEIER, FINK et al. 1998, p. 317]. In general, those innovation activities deal with uncertainties of various kinds [ZHANG, DOLL 2001, p. 98]:

- Customers: uncertainty about the development of markets and customer needs, for example: Is the market as big as expected? Are customers accepting the new product? Are they willing to pay the appropriate premium?
- Competition: uncertainty about the competitors' product development pipeline and about their reactions to the product launch, for instance: Is the competition working on similar or even superior developments? What are the competitors' moves with regard to the presentation and introduction of a new product?
- Technology: uncertainty about the acceptance of a new technology, for example: Is the technology deployed in the new product reliable under general user conditions? Can it be reasonably integrated into the customers' workflow?

More dimensions of the uncertainty inherent in innovations like the adoption of required skills in the organization or external regulatory and legal issues [SEIDEL, STAHL 2001, p. 90] can be thought of. The challenge of dealing with uncertainty becomes even more apparent in radical or breakthrough innovations. Ettlie and Bridges [ETTLIE, BRIDGES et al. 1984, p. 692f] stress that radical innovations require a unique strategy and structure, namely an aggressive technology policy and concentrated decision-making both on the market and technology side.

In a basic framework Ansoff [ANSOFF 1962] classifies development activities along the two major dimensions market and product development in order to categorize growth and innovation activities. By considering ways to grow via existing products and new markets, there are four possible product market combinations which can be summarized in a matrix shown in Figure 1-1:.

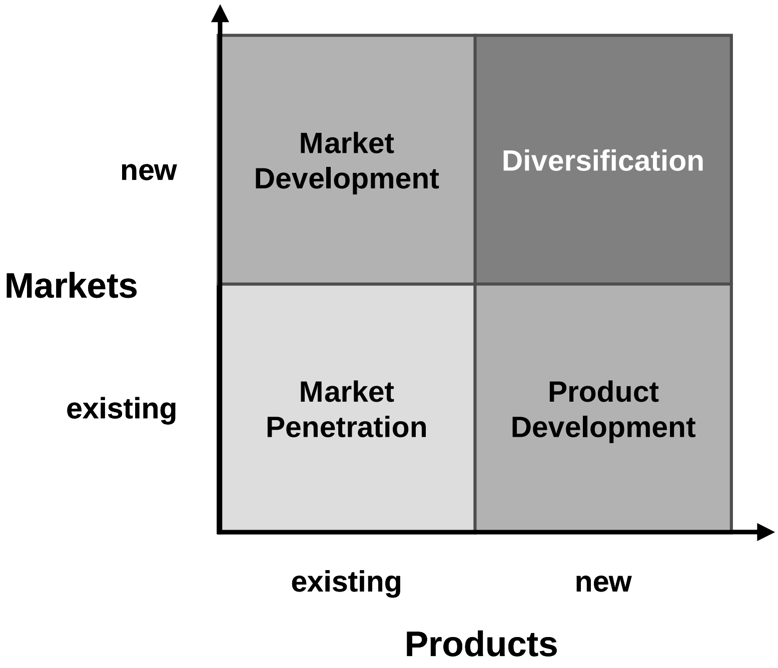

Figure 1-1: Ansoff's matrix [ANSOFF 1962]

The four quadrants of the matrix can be interpreted according to the inherent risk potential of their respective activities:

- Market penetration: Is the least risky strategy since it utilizes many of the firm's know-how and existing resources in gaining market share with existing products and markets;
- Market development: Implies a market risk through the pursuit of new market segments or new geographic regions, for instance: "Can a successful consumer brand be expanded to new regions or to industrial segments?";
- Product development: Implies technology risks which occur when a new product needs to be developed for a well-known customer group;
- Diversification: Is the riskiest of the four growth strategies, since it combines both the uncertainties inherent to market and technology developments.

Gausemeier and Fink [GAUSEMEIER, FINK et al. 1998, p. 233] have expanded Ansoff's matrix to allow for a differentiation along existing, modified, new and future products as well as markets. Consequently, the resulting strategies and their implied risks and chances are displayed more clearly. Taking production technologies into consideration, Gausemeier, Lindemann et.al. [GAUSEMEIER, LINDEMANN et al. 2004, p. 65ff] add a third dimension by describing a further important source of uncertainty and complexity.

A study by Adams [ADAMS 1962, p. 64ff] on the risk of failure and the management effort with regard to product innovations quantifies the magnitude of risk and effort in each of the cells in Ansoff's matrix: According to Adams, the risk associated with diversification is 10 times higher than in the penetration scenario, and the required management capacity is 15 times higher. (See Figure 1-2)

Adams thus calls this strategy the "suicide square" because of the risks connected with moving simultaneously into unfamiliar markets, products and possibly new technologies. These risks are amplified if the unfamiliarity with problem occurring in these ventures draws the management's attention way from the core to the new business. They are further compounded if a fundamental change takes place in the core business, while the management is distracted by the new one.

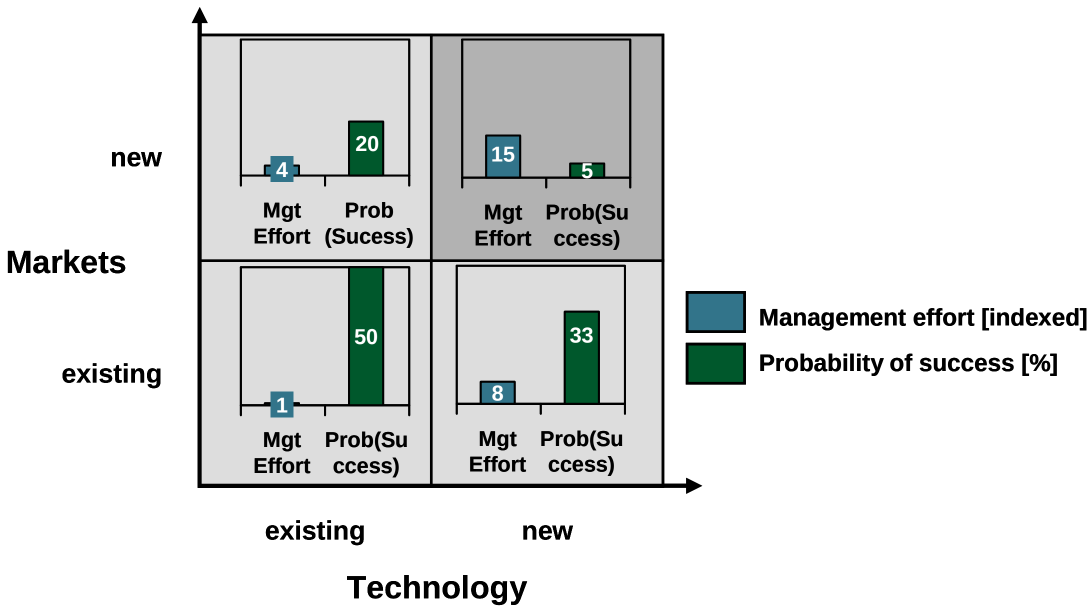

Figure 1-2: Risk and management effort in Ansoff's growth scenarios

Following this rationale, companies are rather reluctant to engage in diversification activities, which induce a risk on the market and technology side. Unless the expected reward from these activities is over-proportionally high, institutions will most likely refrain from such strategic moves.

However, there are circumstances in which companies are forced to move into a new market and technology at the same time and thus need to take a risky development path. Nokia, the Finnish Telecommunication equipment supplier, is frequently quoted as an example of a successful diversification strategy [For example FOX 2001]. At a turning point in its corporate history the company deliberately moved into diversification. Nokia was founded in 1865 as a wood paper mill in southern Finland and evolved into an industrial conglomerate active in paper and household products (e.g. diapers, tires, rubber boots as well as cables for electric and telephone utilities) by the 1980s [ABETTI 2000, p. 209; NOKIA 2007a]. As typical of the Finnish economy as a whole, Nokia's main trading partner was the Soviet Union but after the decay of the latter Nokia was threatened by bankruptcy [FOX 2001]. Subsequently, Nokia turned its focus to the mobile telecommunications market and targeted consumers, which represents a switch from engineered mechanical goods with an industrial customer market to consumer electronics and can thus be regarded as a diversification in Ansoff's sense. The move was drastic as illustrated by Figure 1-3, showing the turnaround in business segments. More important, it was successful which can be proven by Nokia's market position in 2007: It had a market capitalization of €87bn and held a leading market share of in the world's mobile devices market [NOKIA 2007b].

External effects—in Nokia's case the collapse of the Soviet Union as a major customer—may force companies into such drastic business development and innovation steps. Christensen [CHRISTENSEN 1997] cites more examples of various industries where shifts in technology have induced a vast number of market and product moves in established companies.[1]

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[1] Well-known examples include IBM's and Seagate's reactions to the development of 5,25 inch and 3,5 inch floppy drivers for the home computer market.

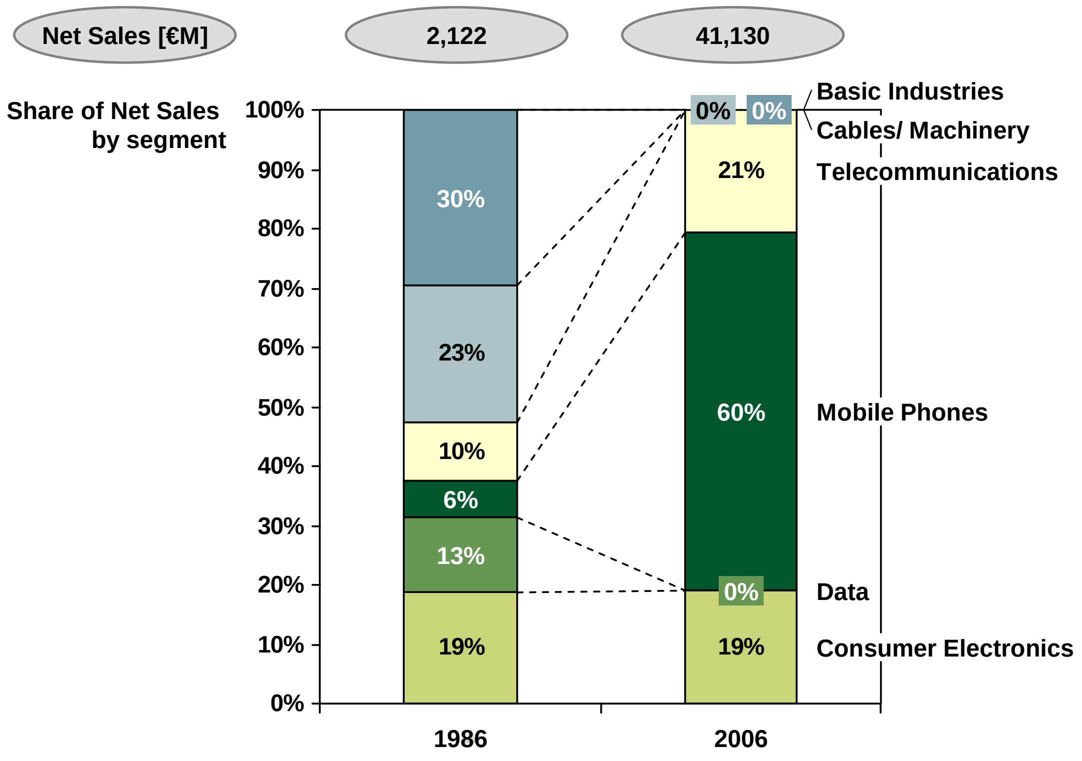

Figure 1-3: Nokia's revenue split by business segments in 1986 and 2006

Following the argumentation that diversification activities are often not advisable due to their high inherent risk but also recognizing that companies may need to undertake such radical innovation steps, this thesis shall provide methodological support for radical innovations that are decisive for companies and take place under a high degree of uncertainty.

Two underlying hypotheses on the effective handling of such product development activities are guiding the research:

First, the technical and commercial uncertainty and risk inherent to radical innovations cannot be avoided and should therefore be made explicit in order to make risk-adjusted decisions possible.

Second, uncertainties and activities on the market and technology side are highly intertwined, where the level of uncertainty and interference is highest in the early stage of innovation processes. Thus, the focus for uncertainty handling is shifted to the front end of the development process.

This study is to develop an integrated product development approach that aims at

- making the inherent market and technology risk and uncertainty in radical innovations visible;
- moving critical decisions made in the innovation process into the front end by creating an option space on the market and technology side;
- integrating market and technology decisions and thereby aligning the innovation activities within a company;
- and finally improving the output of the innovation process with regard to its market reception and economic results.

In order to achieve these goals, an integrated procedural model together with its associated methods and tools is developed and applied in a current radical innovation context.

1.2 Motivation and Scope of the Study

1.2.1 Empirical and Literature-based Motivation

This research is motivated by empirical observations of the author as well as a perceived gap in the literature on the topic of integrated product development under uncertainty.

The author has examined and participated in several projects concerned with radical innovations in technology-driven fields. An intuitive example is the development of an innovative packaging system aiming at retort food solutions. The product consisted of a special processing and filling machine and the corresponding paper-based laminate packages enabling a new processing and packaging solution for reportable food products. As opposed to fresh or frozen food products, retort food such as canned vegetables and meat is treated in an autoclave process at temperatures of 130°C at 100% humidity for two hours. This food preservation technology is applied to approximately 20% of the world food market, representing 90 billion packaged units per year and compromising a market value of €10 Billion [EUROMONITOR 2005]. The business idea of an established player in the beverages machinery industry, herein called PackagingCo, was to enter this large market with an innovative carton-based packaging material. According to Abetti and Stuart [ABETTI, STUART

1988, p. 40f], this innovation idea can be classified as radical and potentially even highly radical, as it is a system utilizing a new technology with a potential to make the dominating technology of using metal cans and glass jars obsolete.[2] Figure 1-4 gives an overview of the key components for such a packaging system.

Figure 1-4: Carton-based packaging system for retort food

Several technological challenges are posed in this innovation venture. First, paper and polyethylene as key elements of the packaging would normally not withstand the heat and pressure in an autoclave. An innovative compound structure is necessary here. Second, the portioning and packaging processes for vegetables, fruit or other chunky products are new to the company. On the market side, the business idea might be compelling, because carton packages are perceived as more convenient for opening and storage and also as more ecological and efficient, since they allow for dense packaging on the shelf and during transportation.[3] Furthermore, this concept is expected to satisfy the retail industry's ongoing

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[2] In 2005, over 90% of the retort food was packaged in metal cans or glasses.

[3] In contrast to the rectangular base of carton boxes, the round base of glass jars and metal cans creates about 20% empty space on the shelf, which can be derived as follows: If four jars or cans with radius *r* are placed on a quadratic space on a shelf, they will consume $(4r)^2$ shelf space while only utilizing $4\pi r^2$ for the containers themselves, thereby leaving 1-0,25 π or 21,4% of the space unutilized.

striving for innovations. At the same, the product has to surmount considerable obstacles on the market as the new solution breaks with several industry paradigms and means a significant switch especially to the processors of retort food, who are typically operating machinery which is written off and in some cases older than 30 years. Hence, they are generally very reluctant to invest into a new technology with a perceived risk. Internally the project had to overcome several challenges in market and technology areas of which the most important ones were:

Market and commercial aspects:

- projection of the relevant market and its relevant segments (e.g. pet food, canned vegetables, canned meat);
- defining key selling factors that should be stressed by the new product (e.g. cost, advantages over can and glass, ecology);
- selecting the ideal lead customer and preparing the market access (e.g. processor, retailer, consumer goods, brand manufacturer);
- setting up a revenue model for the new system (e.g. pay per output model, equipment sales model);

Technological aspects:

- design and engineering of carton-based boxes for the sterilization process in autoclave (i.e. against heat and humidity) and for shelf lives of more than a year;
- choice of ideal filling technology (e.g. pouring, conveying, pumping);
- design and engineering of an autoclave process for an effective sterilization of the content while protecting the packaging substrate.

This example shows the considerable number of decisions and the room to maneuver on the one hand, and the embedded risk and uncertainty on the other hand. In order to solve problems in their respective domains, managers and engineers typically learn to deal with uncertainties in their operative tasks and make frequent use of appropriate methods such as market research and analysis for the sizing of a market, or of morphologic boxes for the identification of possible technical solutions. However, from the author’s observation it becomes increasingly complex and challenging to handle the inherent uncertainty when strategic uncertainties are concerned and when the commercial and technical uncertainties are interlinked or dependent on each other. In the case of radical innovations where new markets are addressed with new technologies, a great number of such intertwined issues typically arise. The above-mentioned example of a new processing and packaging system involved several such incidents. One of these is illustrated in Figure 1-5, which highlights key issues in the selection of target segments and key technologies.

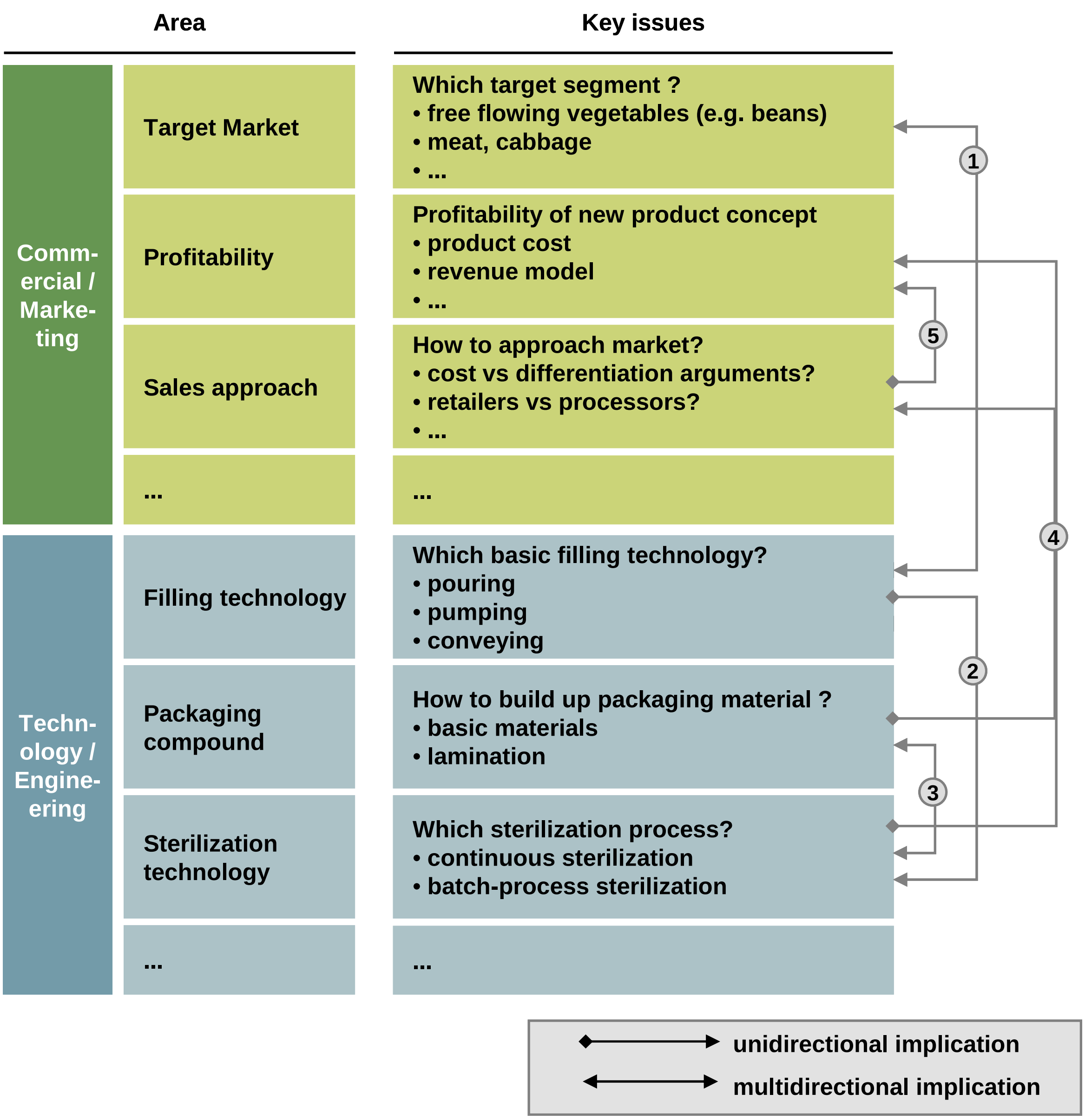

Figure 1-5: Interdependencies between commercial and technological areas in the development of a new packaging system for retort food

Connection 1, for example, indicates a bidirectional relation as the choices of target market segments and packaging technology are interrelated. Connection 4 represents a unidirectional relation, since the choice of packaging compounds and sterilization technologies influences the products' profitability and the optimal sales approach. For instance, high investment solutions might require financing or leasing options in the revenue model in order to reduce the risk potential carried by clients. Persons involved in product development and design regularly report that such cross-functional interdependencies and uncertainties cause enormous difficulties. Managers claim that there is only little structural support to handle these crucial but complex issues in the design process for market and technology innovations.

Likewise on the academic side, research efforts have been directed towards a deeper understanding and modeling of the so-called "*fuzzy front end*" [KHURANA, ROSENTHAL 1997]. The term fuzzy front end generally relates to the "*messy*" start of a product development project, before the commitment on one specific concept including the necessary resources is set.[4] This phase is broadly considered as one of the most important, but also of the most difficult challenges in innovation management [KIM, WILEMON 2002, p. 269]. Ehrenspiel [EHRLENSPIEL 1999, p. 236ff] assumes that the more innovative a product is, the less its associated process can be planned.

In the more economics-oriented literature, Herstatt and Verworn [HERSTATT, VERWORN 2003, p. 7] claim that differentiated explanations and process models for the "fuzzy front end" are lacking especially in the context of breakthrough innovations.

Based on the development of a model and procedure for the integration of market and technology-related aspects in product development, this thesis will apply the derived methods and tools for radical innovations within mid-sized companies in the context of case studies and draw a comparison to procedures and methods observed at successful innovators.

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4 The nomenclature on the fuzzy front end and its components is still heterogeneous. Koen, Ajamian et al. [KOEN, AJAMIAN et al. 2001] propose a construct defined as the New Concept Development (NCD) model which consists of five front end elements.

1.2.2 Scope of the Topic between Engineering and Management

The topic of new product development - in particular when targeting radical innovations - is cross-functional and involves several hierarchical and functional units, e.g. senior management, corporate development, marketing, R&D, and production. The need for a close collaboration, especially in the early phase of the developments, is undisputed in academia and practice [For example BOUTELLIER, GASSMANN et al. 2000, p. 29ff; ULLMAN 2003, p. 118ff ; LINDEMANN 2005, p. 12ff; EHRLENSPIEL 2007, p. 309]. Ehrlenspiel proposes the method "integrated product development" as a holistic approach to overcome the problems that arise in product development because of the division of labor [EHRLENSPIEL 2007, p. 188].

Lindemann, Stetter et al. [LINDEMANN, STETTER et al. 2001, p. 41] investigate the application of methods which aim at the support of integrated product development models in industrial practice. They conclude that in spite of the high degree of acceptance the degree of implementation of such methods is still unsatisfactorily low.

Although it is commonly agreed on that commercial and technical issues must be integrated into the early phase of the product development, a focus on strategic aspects in the managerial literature and one on technical aspects in the engineering literature can be observed.

On the managerial side, the front end model of Khurana and Rosenthal [KHURANA, ROSENTHAL 1998, p. 59ff] which is frequently cited [For example KOEN, AJAMIAN et al. 2001, p. 5; ZHANG, DOLL 2001, p. 95; KIM, WILEMON 2002, p. 270ff; HERSTATT, STOCKSTROM et al. 2005, p. 250] sees the new product development phase as a successor to the more strategic portfolio, product and product strategy phase as illustrated in Figure 1-6.

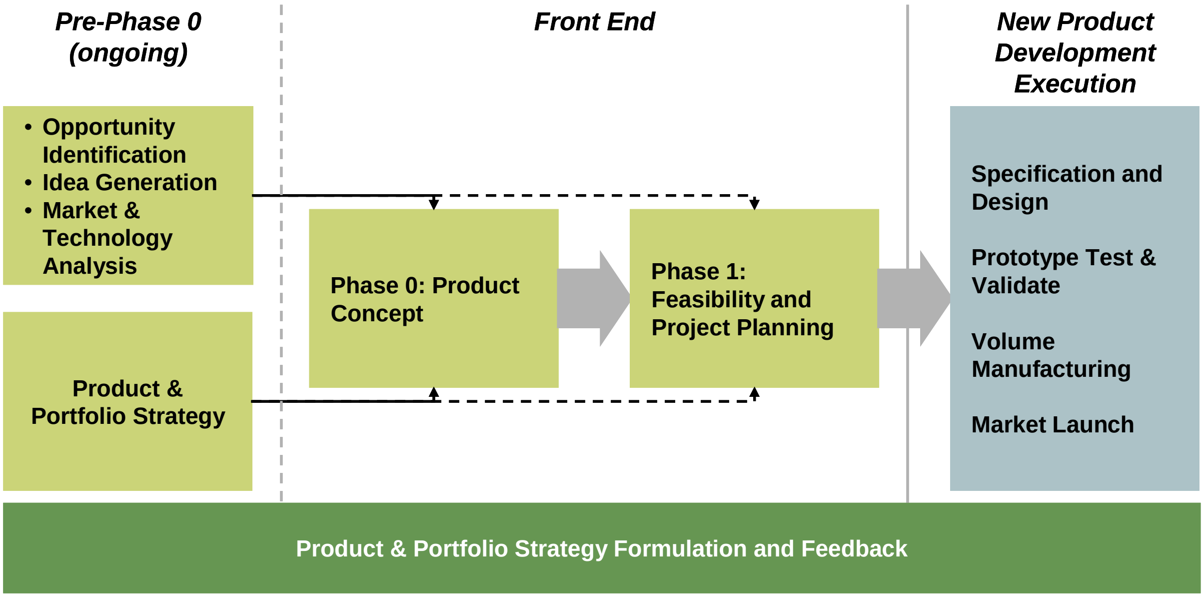

Figure 1-6: Front end model by Khurana and Rosenthal [KHURANA, ROSENTHAL 1998, p. 59]

Within this framework, creative and innovative activities occur mostly in the pre-phase and the front end. The new product development is merely seen as the execution of a pre-defined frame, which takes place in a rather linear and consecutive mode on the technical side.

On the engineering side, however, the focus of the product development problem often lies on the solution process of a pre-defined problem and is hence to a great extent reduced to a technical design problem. As an example, Gerhard [GERHARD 1998, p. 17] divides the engineering task into three basic components: the analysis of the problem, the search and evaluation of solutions and, finally, the selection of an optimal solution. Figure 1-7 illustrates the corresponding procedure model.

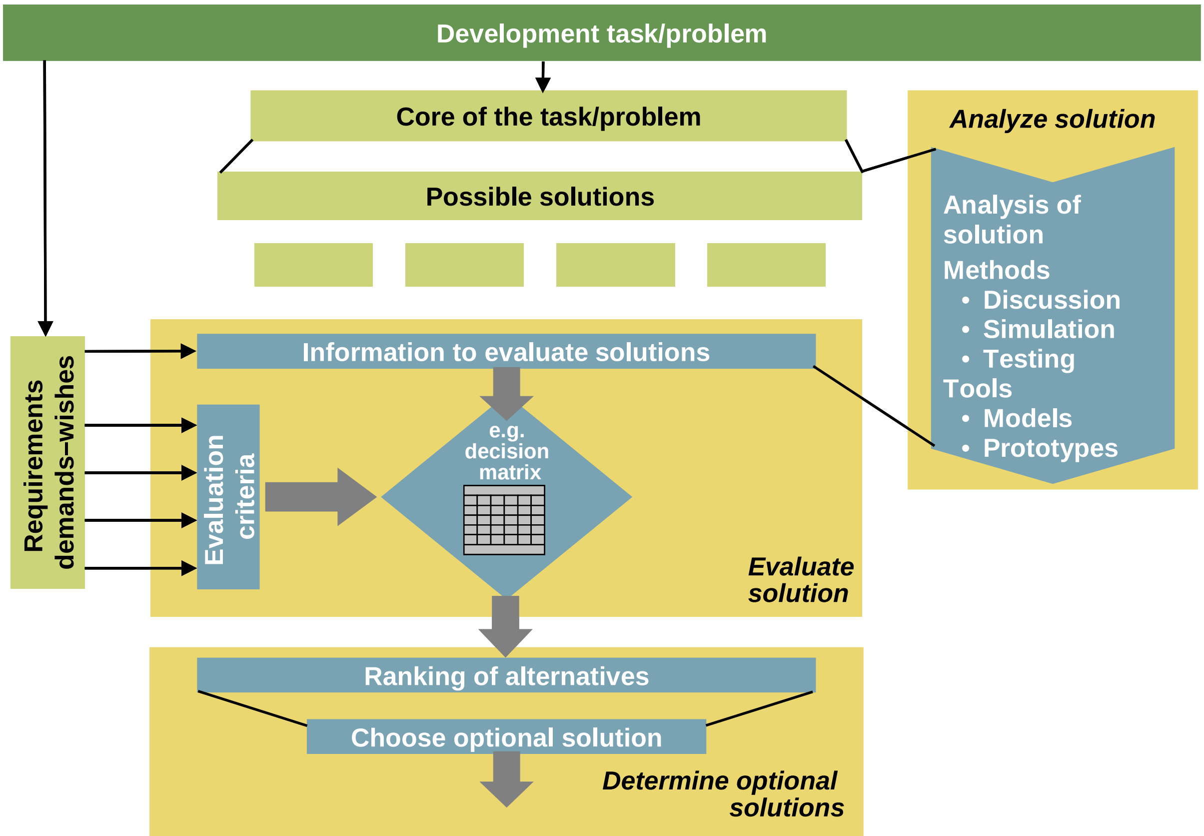

Figure 1-7: Engineering product development approach [GERHARD 1998, p. 17]

From an analysis of the prevailing literature it can be concluded that the material stemming from the managerial side highlights the strategic and organizational aspects of product development in the context of radical innovations. On the contrary, the engineering-oriented sources tend to focus on the embedding of methods (e.g. decision matrix, morphological box) in the new product development process.[5] The research question of this work is centered on radical innovations and the handling of their implied uncertainty in the product development process. Hence, the scope of this thesis will include strategic and market-oriented aspects as well as technical and engineering-driven issues. The methods and procedures for an

[5] Chapter 3 analyzes the existing approaches to product development under uncertainty in more detail.

integrated handling of uncertainty are developed within the context of product development for engineered goods.

Following Marxt's and Hacklin's [MARXT, HACKLIN 2005, p. 420] discussion about the terminology in design studies, the notion of "design" is used in a broader sense here, since the term does not only relate to the specific task of sketching and drawing but is also seen as a core function of a product development process [EHRLENSPIEL 2007, p.1]. In this sense, designing and developing a product contain tasks that may lie outside the historical scope of a mechanical designer (such as defining a target market and aligning the product to a market approach). Yet, such tasks are undisputedly necessary for the realization of successful new products, especially when both the technology and market are new.. This perspective corresponds to Andreasen's [ANDREASEN 1991, p. 321] description of design tasks that compromise problem solving, product synthesis, product development, and product planning.

1.2.3 Scientific Approach

The scientific approach for this thesis is twofold as it consists of an analysis of the existing literature and follows case study research based on a methodology proposed by Yin [YIN 2003]. Case studies are increasingly seen as an effective means of gathering information and understanding real conditions that occur in organizations and could otherwise not be generated [MCCUTCHEON, MEREDITH 1993, p. 251f]. Siggelkow [SIGGELKOW 2007, p. 21] claims that "*cases can help sharpen existing theory by pointing to gaps and beginning to fill them*" and states motivation, inspiration, and illustration as the three most important drivers of case study research.

The empirical study is broadly oriented towards a design research framework presented by Blessing et al. [BLESSING, CHAKRABARTI et al. 1998, p. 44ff].

Herein, observations and analysis in a real case are the source for the derivation of methods which are then applied in a real case setting. The results of this application are thereupon compared to the initial setting. Figure 1-8 illustrates this framework.

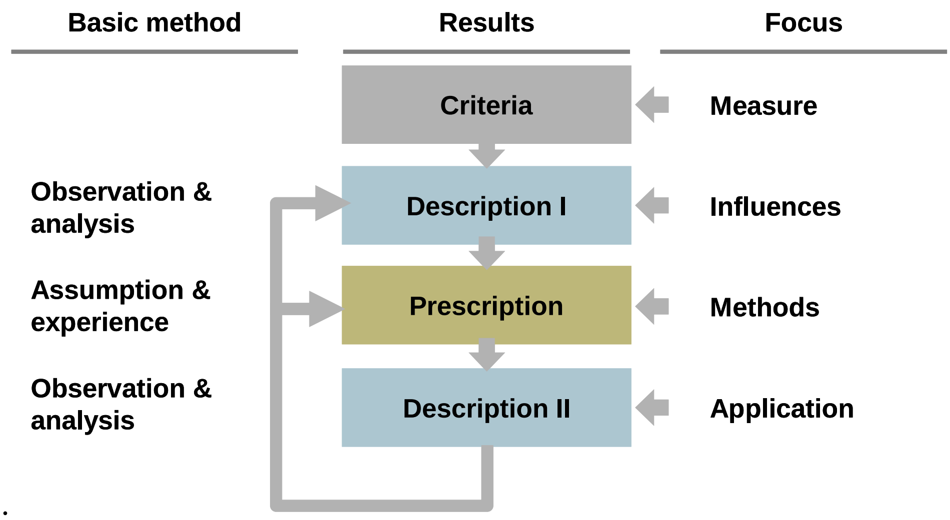

Figure 1-8: Design research methodology [BLESSING, CHAKRABARTI et al. 1998, p. 44]

The analysis of the existing literature and the author's experience create the awareness that the problem of product development under uncertainty is not yet fully resolved. The observation of industrial product development processes forms the first description phase while as the analysis of existing models and the combination of proven methods in the engineering design research lay the foundation for the method of integrated product development under uncertainty. This prescription is then tested during the second description phase, which focuses on the same entities as the initial description phase. The framework is applied in an industrial environment in order to draw conclusions about the initial theory and proposition. Finally, the results are validated with third party industrial experts who did not participate in the case studies but have to cope with similar design problems. This procedure aims at ensuring the robustness and general applicability of the proposed methods and tools derived in this thesis.

In order to the maintain the explanatory power of the conclusions drawn from the case studies the research setup adheres to the prerequisites towards effective case study research according to Benbasat, Goldstein et al. [BENBASAT, GOLDSTEIN et al. 1987, p. 371] and Yin [YIN 2003]):

- One or few entities are examined in a natural setting.
- Case studies are especially suitable for the exploration, classification and hypothesis development stages of the knowledge building process.

- The investigator should have a receptive attitude towards exploration.
- No experimental controls or manipulations are involved.

Furthermore, the chosen methodology is characterized as action research since a collaboration with the industrial partners is conducted with the original purpose of affecting change and learning from it [SUSMAN, EVERED 1978, p.589ff]. Björk and Ottosson [BJÖRK, OTTOSSON 2007] argue that researchers studying the design process should deploy an insider action research approach as opposed to the traditional quantitative outsider perspective. Thus, the researcher can be present and can intervene in the design process in order to get a deeper understanding of the drivers of the design process, which also yields great opportunities for a direct implementation of research findings.

Align with Siggelkow's [SIGGELKOW 2007, p. 21] line of argumentation on the deliberate choice of cases in such research projects, the companies studied were chosen specifically to offer insight into the problems of radical and uncertain product development projects and to provide feedback on the effectiveness of the implemented models: The company dealt with in the first case study, PrintCo experiences exogenous market and technology shocks making its existing technology obsolete and stipulating the need for radical innovation. Thus the innovation strategy and its associated product development procedures are of key importance to the company and bring the problem of uncertainty handling in product development to the surface. The second case of PackagingCo illustrates the handling of radical innovation projects in a company exhibiting a strong track record in its core market and technologies and with no ultimate need to innovate in more distant technologies. It thus provides an important counterpart to the case of PrintCo. Finally, the practices of W.L. Gore & Associates which is frequently mentioned in the context of successful product innovation and product development in industrial markets [for example ANDREW, SIRKIN 2007, p. 64f; HAMEL 2007, p. 87ff] are studied in order to gain more insight into the general applicability of the model postulated.

Specifically in the examined case studies, the management, marketing and design team were accompanied over the course of one to two years. During that period, the role of the author has evolved from an observing and investigating towards a participating and contributing position in the implementation phase of the developed methodology.

The main sources of information for the in-depth case studies were:

- Analysis of documented material on the company's strategy, documentation of development projects and external market material;
- workshops to assess the initial situation in the company as well as the experienced problems on the market and technology side;
- workshops with the management team and the marketing and R&D leadership to derive a new innovation methodology;
- semi-structured and open interviews with the senior management, the relevant designers and the marketing experts;
- a series of workshops with the marketing and design team aiming at a radical innovation in order to refine, implement and evaluate the new methodology;
- the pilot development project, which represents a major radical innovation for the examined company and its associated materials, discussions and decisions.

Some restrictions of the research design setup need to be considered: The uniqueness of each design project and the active involvement of the researcher represent a limitation especially to the general applicability of the methods developed in this work. To counterbalance this, interviews with experts of companies in similar situations outside the case study context are attached so that the respective results complement the insights gained from the case study and provide support in the validation of the propositions [BLESSING, CHAKRABARTI et al. 1998, p. 53; EISENHARDT, GRAEBNER 2007, p. 27].

1.3 Structure of the Thesis

The structure of this thesis is oriented towards the aims outlined in the previous chapter and takes into account the case study based approach chosen for the research problem.

Based on the description of the starting point for the case study in the digital printing industry, the need for an integrated uncertainty handling on the market and technology side is derived in *Chapter 2* which at the same time gives an introduction to the technical and commercial background of one case study. It furthermore stresses the relevance of this topic for the current state of the product development research.

Chapter 3 examines the present state of the literature on the topic of uncertainty handling both from a managerial and a technical perspective and thereby yields a representation of the current state-of-the-art in the product development science with respect to this topic. Simultaneously, relevant methods and tools for the later development of an integrated model are identified.

The observations from the case study as well as the results of theoretical researches are merged in *Chapter 4* in order to get to the formulation of a research and development need in the field of uncertainty handling.

Chapter 5 discusses a model for an integrated handling of market and technical uncertainties. It contains a procedural model, methods and tools, as well as an approach to address the specific challenges of human behavior under uncertainty.

Chapter 6 validates this model and sets up a learning circle that is embedded in the research approach by testing the framework developed in reality on a twofold basis. The methods, processes and tools are applied to the previously described case of the digital printing industry. The impact of the implemented model on the design process and its results are observed and analyzed. At the same time, this yields an important input for the concept developed in Chapter 5. Secondly, the learning from the in-depth case studies are reflected by third party companies, which indicate the general applicability of the development model.

Finally, the results of the thesis are synthesized in *Chapter 7* and possible research goals are discussed. Figure 1-9 summarizes the structure and the main purpose of each chapter.

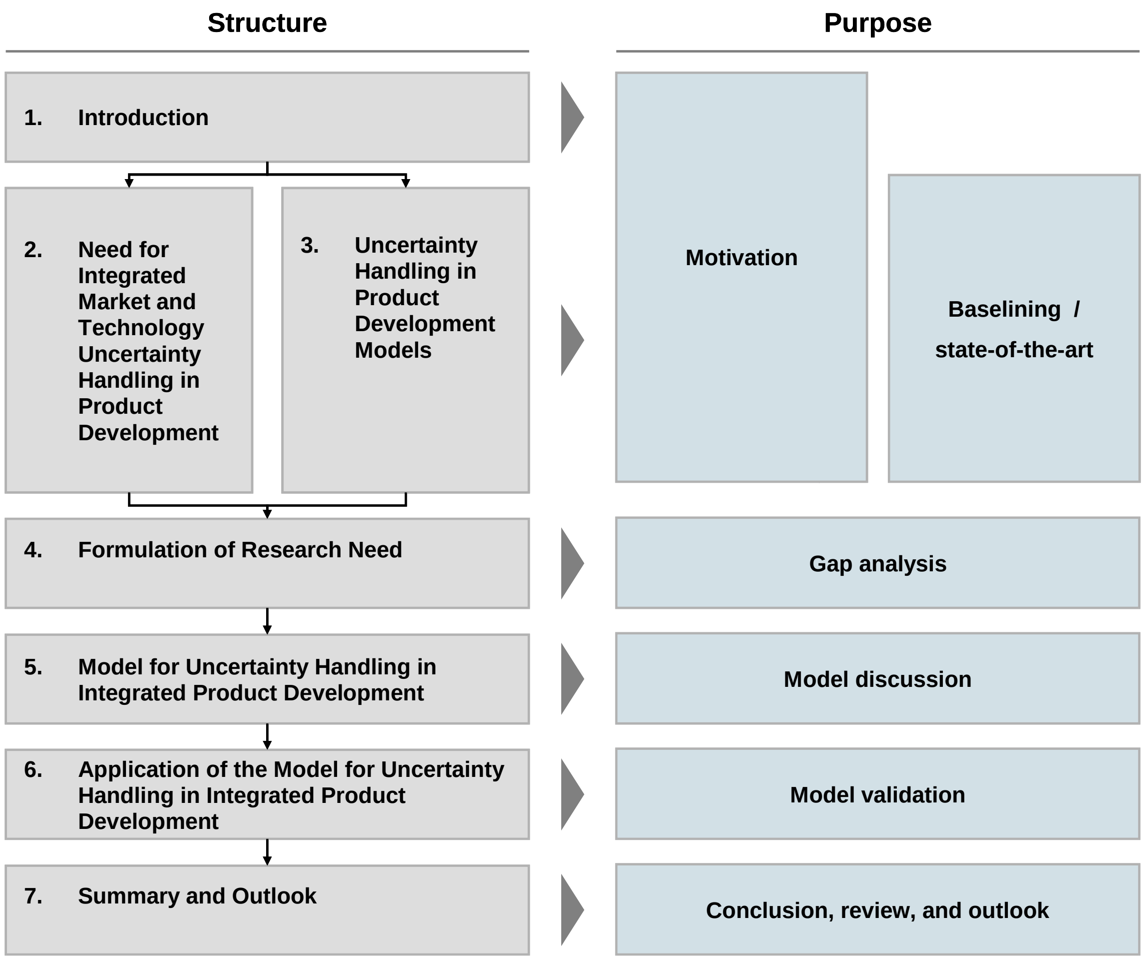

Figure 1-9: Structure of the thesis

2 Need for Integrated Uncertainty Handling in Product Development

2.1 Introduction to Case Study: Development of a New Digital Printing System

2.1.1 Company and Market Background

The model developed within this thesis is strongly motivated by observations of the industrial practice within a medium-sized company active in the photo-technology market. For the remainder of this study, this company shall be called "PrintCo". Despite its comparably small size with revenues of approximately €100 million and 350 employees, PrintCo has developed a worldwide leading position with regard to photomechanical and optical equipments for professional users, for example large format photo enlargers and printers.

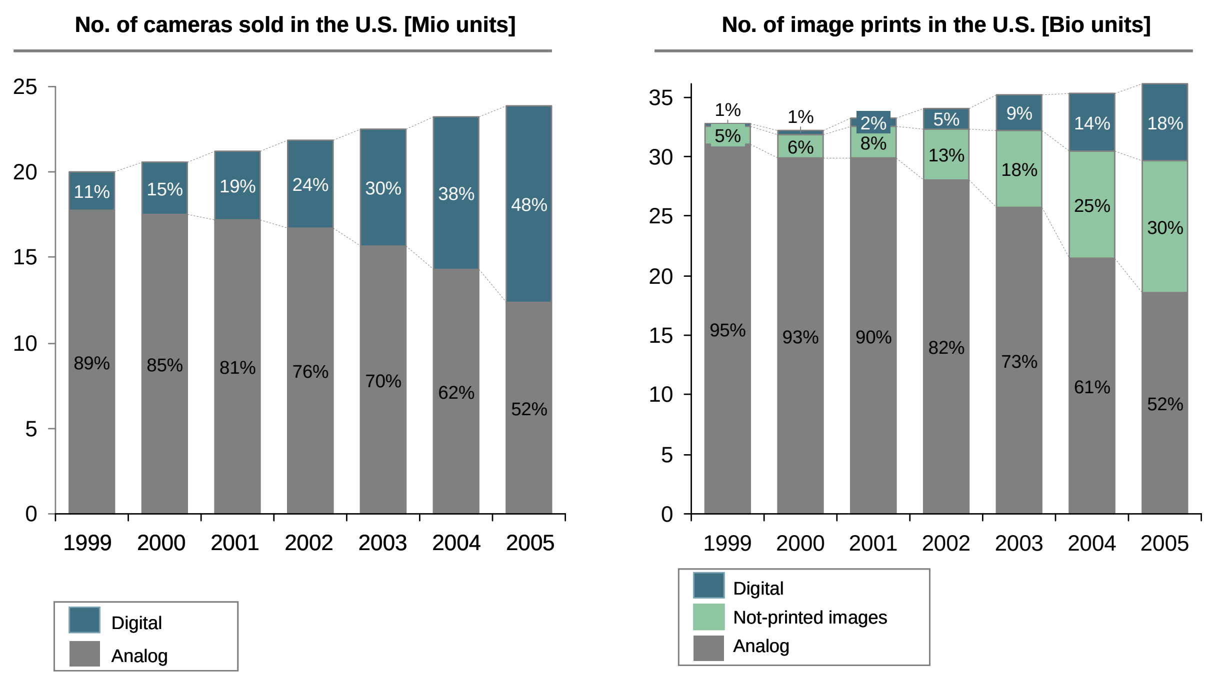

Figure 2-1: US photo cameras sold and images printed between 1999 and 2005 [INTERNATIONAL PHOTO MARKETING ASSOCIATION 2005]

Since the 1990s the traditional photo technology based on the exposure of a light-sensitive film has been replaced by digital imaging technologies, namely the capture, manipulation, storage, transmission and printing of images using digital technologies and media. Figure 2-1 illustrates the continuous substitution of analog photo applications by digital technology between 1995 and 2005.

As a consequence of the fading classical photo market, PrintCo moved into the digital photo-technology market and introduced its first digital exposure unit in 1995. This continued a trend of innovativeness that PrintCo had established since its founding in the 1920s. Figure 2-2 highlights some major innovations as well as the three most significant product generations launched by the company, i.e. analog photo technology, large format inkjet printing and industrial inkjet applications.

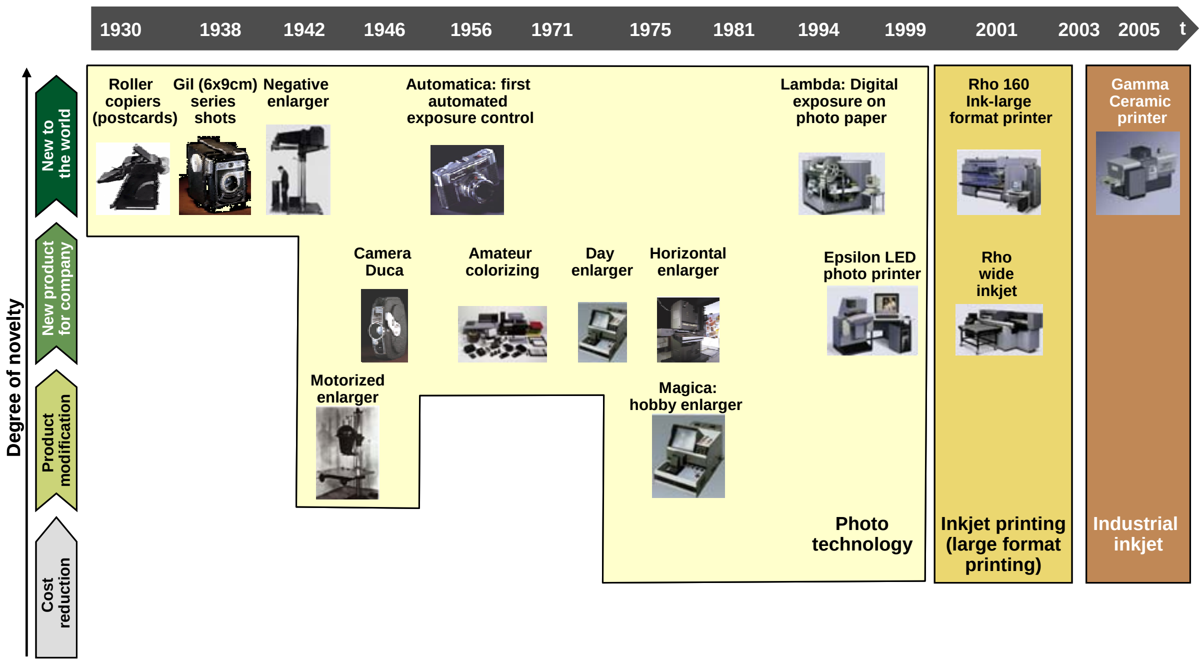

Figure 2-2: Major innovations during PrintCo's history

This case study specifically deals with the third technology shift. It contains the substitution of mechanical impact printing technologies such as offset und rotogravure technology by non-impact inkjet printing in an industrial setting. Exemplary applications are the digital printing of furniture decors, ceramics or packaging, which allow for customized mass-productions in industrial applications.

It is evident that the decay of the analog photo market has an impact on several established photo technology companies like Eastman Kodak, Leica and Agfa. Eastman Kodak and Agfa, for instance, have lost 64%, respectively 20% of their enterprise value, measured in stock market capitalization in the period between January 2002 and January 2007 [THOMSON FINANCIAL DATASTREAM 2007]. In a case study setting, Tripsas and Gavetti [TRIPSAS, GAVETTI 2000] investigate the effects of the transition from analog to digital photo technology on the Polaroid Cooperation. They conclude that apart from the economic and technical challenges faced by Polaroid, the ability of the organization to reframe technology trajectories and to change business beliefs is of key importance [TRIPSAS, GAVETTI 2000 , p. 1157].[6]

In PrintCo's case, several similar phenomena could be observed, which coincided with the transformation of the market focus from photo studies and craftspeople to industrial producers (e.g. in furniture production and assembly). Most importantly, the shift of sales factors from quality and product cost to speed, production cost, and service proved to be a major source of uncertainty and concern. The transformation from a business model with long product lifecycles of about 10 years to innovation cycles of about three to five years also put pressure on the organization and brought uncertainties about target markets, customers, and sales factors to the surface.

The following section introduces the technical background for the case study of PrintCo and highlights some of the initial problems in dealing with radical but uncertain innovation projects.

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[6] A key business belief for Polaroid that needed to be altered was the bundling of the hardware product camera with the consumable instant photo paper that created an attractive “razor/blade” business model.

2.1.2 Technical Background

The case study deals with the application of digital inkjet printing technology in industrial settings. Inkjet printing is a non-impact printing technology where the image information is rebuilt from ink drops that are ejected to a substrate. In contrast to conventional impact printing systems, the inkjet printing technology possesses four key advantages:

- Short run color: Small lot sizes can be printed under economic conditions as no print form is required;
- Printing on demand: Customer orientation and the printing need can be realized at short notice so that storage of finished products becomes obsolete;
- Customized printing: Changes of content can be made even during the printing process;
- Distribute and print: The generation of the image to be printed takes place separately from the actual printing process and the build-up of a print form.

Figure 2-3 sorts digital drop on demand ink printing into Kipphan's general classification of printing technologies, following basic distinctions between impact and non-impact printing technologies [KIPPHAN 2000, p. 43].

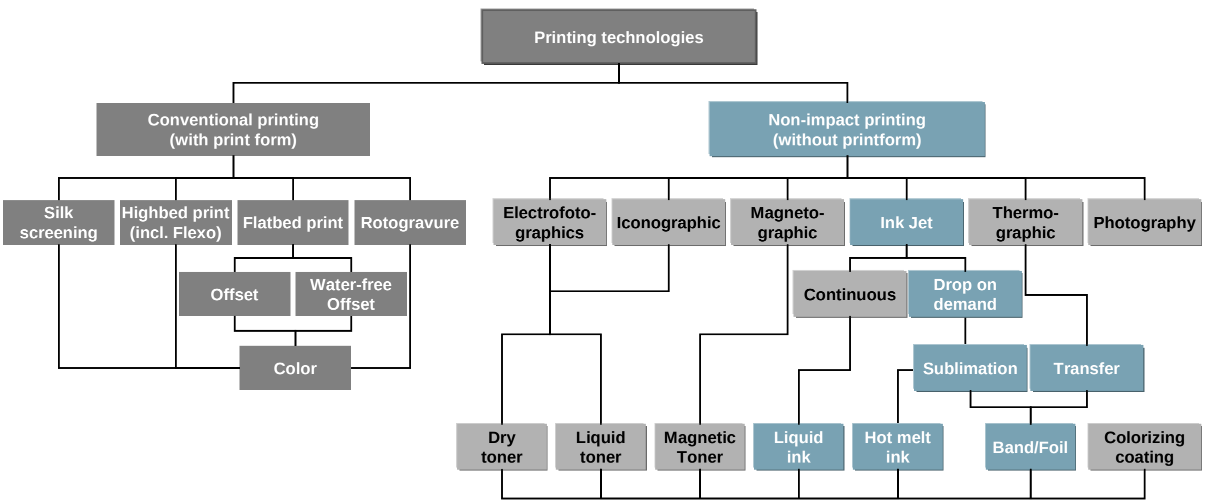

Figure 2-3: Overview of printing technologies [KIPPHAN 2000, p. 43]

Specifically in the targeted solution, a piezo drop on demand inkjet system is utilized, in which a piezo-electric effect compresses the volume of the ink chamber. Thus, a bubble is formed that is then ejected through the nozzle onto the substrate. The ink drop has a volume of approximately 10 picoliters and a diameter of about 30µm. In order to enable high throughput volumes, the print heads containing the nozzle arrays are built repeatedly and positioned stationary: The system is hence called a "single pass" system as opposed to "multi-pass" systems where the print heads are transported orthogonally to the transport direction of the substrate. Figure 2-4 depicts the operating mode of a piezo drop on demand inkjet as well as the basic differences between multi-pass and single-pass inkjet systems.

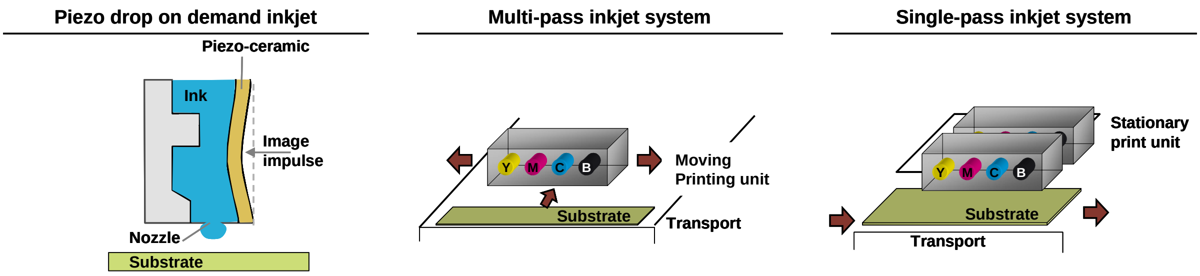

Figure 2-4: Working principle of piezo drop on demand inkjet

In order to embed this technology in an industrial printing system, several technical areas have to intertwine: The accurate transformation represents a key mechanical and control problem, the decomposition of the image information is mainly an information and data transportation problem and, finally, the composition of the ink for processing in the printing machine and for adhesion on the substrate represents a chemical problem. Consequently, there are at least four disciplines, namely mechanics, electronics, computer science and chemistry, which are involved in the development project at any given time. Apart from the inherent uncertainty in dealing with a technology rather new to PrintCo, the interference of several technical areas proved to be a key source for problems on the technical side. Often the interdependencies of the different disciplines were treated with simple "right-of-way-rules". For example, the mechanical designers set the transportation system and thereby also the frame for all other functions to embed their aggregates in. Within an early prototype this caused problems because the steering unit and the ink containers were located underneath the print heads and transportation belt, thus exposing the sensitive steering system as well as the ink containers to a dusty and polluted environment.

Furthermore, the communication between the members of the various disciplines turned out to be difficult when the members of one group were expected to deliver a concrete solution to a certain problem like accurate transportation, but were in fact still searching for an optimal solution within their own technical frame.

To summarize, not only the technical issues und uncertainties faced in the designers' own working area, but especially remote problems in other technical or commercial fields and their second order effect resulted in problems concerning the development project and led to dissatisfaction in the development team.

Thus, the case of PrintCo and the initial consideration on the existing product development literature underline the importance of modeling and handling uncertainties. The following section details the notion of uncertainty with regards to product development.

2.2 Uncertainties in Product Development

As design by definition deals with the creation of new or alternated products, it immanently takes place in some kind of uncertainty that is induced by the degree of "newness" of the product to be developed. Uncertainty occurs at various stages and abstraction levels during the design process: At the beginning of a project, the target direction may be vague, or during the collection of requirements there might be uncertainty about the customers' preferences concerning solution alternatives. During the actual design process, there is uncertainty about static and dynamic forces or about the dimension of its components. Giapoulis [GIAPOULIS 1996, p. 103] argues that constant switching takes place between different activities and result layers in the development process. (See Figure 2-5)

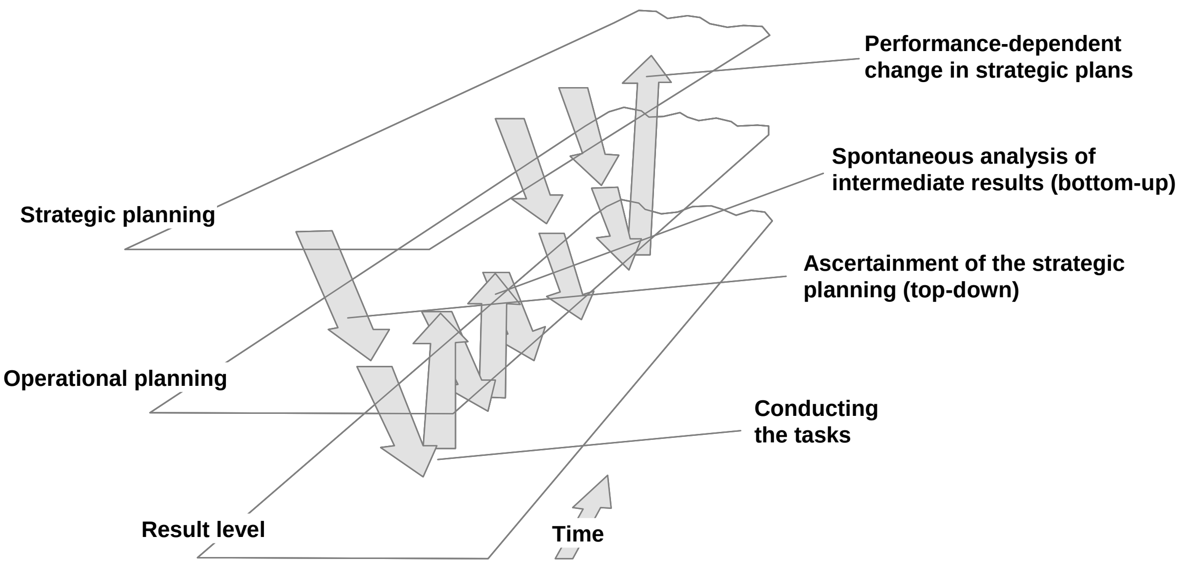

Figure 2-5: Three layer model for development process [GIAPOULIS 1996, p. 103]

Operative uncertainties like those caused by design problems can typically be solved by analysis, references from the designer's experience or codified design guidelines. A similar logic can seldom be applied when considering uncertainty with regard to strategic aspects like market or technology selection. In radical innovations, strategic decisions often have a decisive impact on the overall project and therefore can be regarded as governing issues. Thus, without neglecting the challenging situation of decision-making in product design and its importance, this work predominantly focuses on strategic uncertainties. These can stem from the market or technology side as the two basic sources and typically appear during the business and product development phase of a project. Uncertain issues occurring in the course of later operations, for example sourcing, production or sale and service, are not explicitly modeled. This limitation on strategic aspects arising from market or technological issues in business and product development is illustrated by a cube in Figure 2-6.

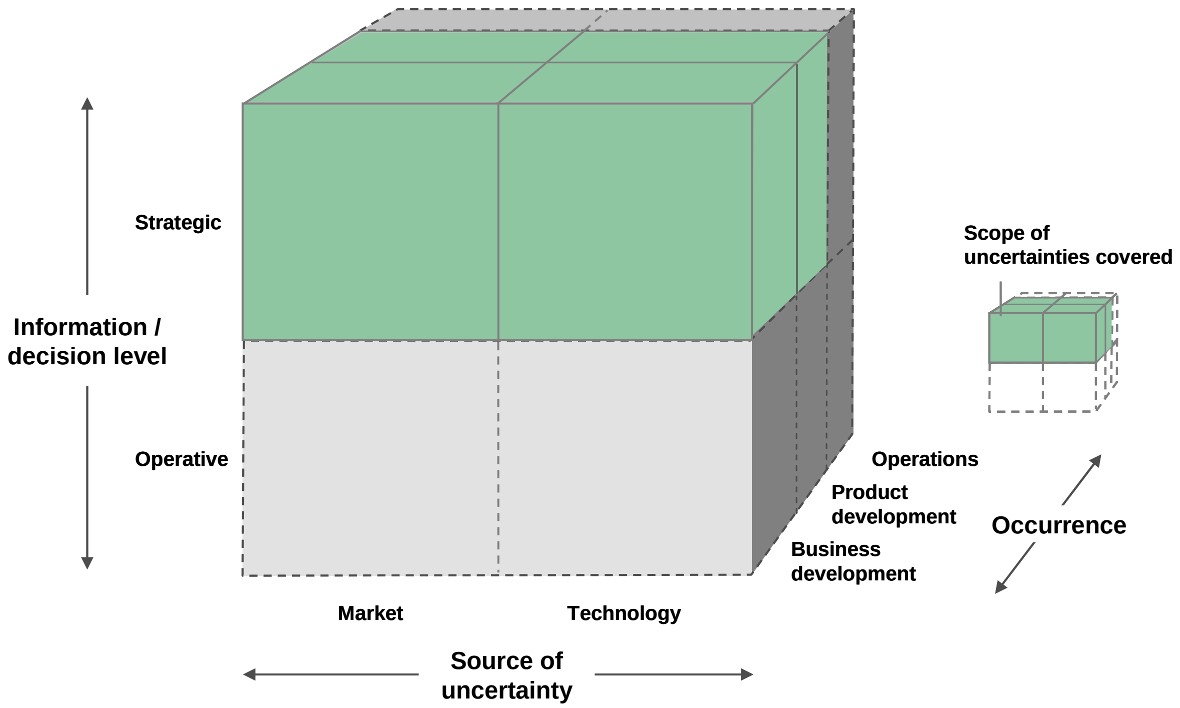

Figure 2-6: Levels, sources, and occurrence of uncertainty

Uncertainty is a multifaceted problem dealt with in psychology, management and engineering. The decision theory differentiates between uncertainty and risk [DUNCAN 1972, p. 315ff]: The former is regarded as a characteristic of situations where the set of possible future outcomes is identified, but where the related probability distributions are unknown. The concept of risk, however, is particular as it describes uncertainty situations with familiar stages and their respective probabilities, comparable to the outcome of rolling a dice or tossing a coin. Schrader, Riggs et al. [SCHRADER, RIGGS et al. 1993, p. 75] claim that in technical problem solving situations with a priori objectively known probability distributions do not exist and hence the usage of the term "uncertainty" is appropriate. Uncertainty can either be defined as objective, i.e. independent from the person subject to the situation, or as subjective, i.e. depending on the person's point of view [WITTMANN 1959, p. 24f]:

$$Degree\,of\ uncertainty_{objective} = \frac{possible\,information}{neccessary\,information}$$
$$Degree\,of\ uncertainty_{subjective} = \frac{available\,information}{information\,considered\ relevant} \tag{2.1}$$

Jetter [JETTER 2005, p. 41] explains the connection between these terms by using the theory of sets as displayed in Figure 2-7.

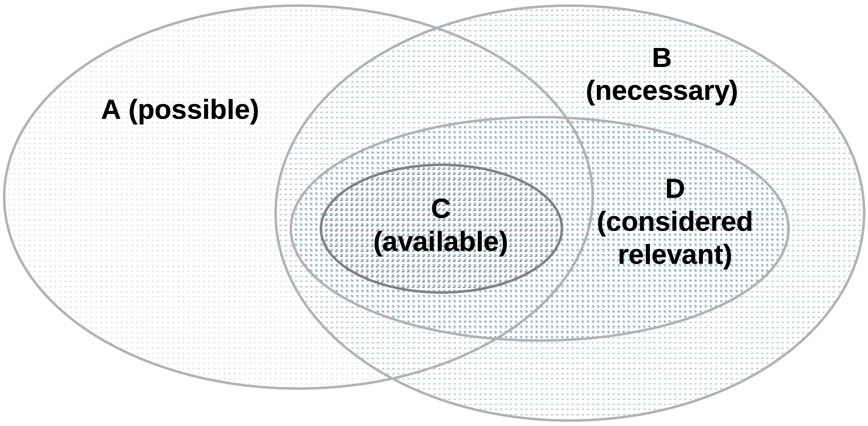

Figure 2-7: Uncertainty and information [JETTER 2005, p. 41]

A denotes all possible information obtainable for a certain decision problem, B the information set necessary to solve the problem. If B is a subset of A, then no uncertainty exists, otherwise there is a remaining set A\B, which is called residual uncertainty and cannot be reduced. C is a subset of A as in practice not all possible information is obtainable. D is the set of information the decider considers relevant. If the decider has collected enough information, D becomes a subset of C and the person will experience no subjective uncertainty even though the objective degree of uncertainty may be significant. Vice versa, the person might try to collect further information despite the fact that B is already a subset of C. This illustration by mathematical sets shows the relevance of personal cognition for the measuring of uncertainty. The implications on the handling of uncertainty in technical problem solving are twofold: The procedures should address objective information acquisition techniques as well as cognitive issues in dealing with uncertainty and information.

In this context, a study of 120 new product development projects by Tatikonda and Rosenthal [TATIKONDA, ROSENTHAL 2000, p. 83] reveals technical novelty and project complexity as the main drivers of uncertainty. They define a shortage of information resulting from a lack of previous experience and a complex decision situation that is difficult to master as task uncertainty.

A further classification of uncertainties that provides important requirements for product development procedures is undertaken by Milliken [MILLIKEN 1987, p. 136f]:

- State uncertainty: Decision makers experience state uncertainty if they consider an external event relevant for their own decision as a problem but cannot predict future states and the corresponding probabilities. Examples include the possibility of deregulation in industry or a union's decision to call for a strike. Furthermore, the interrelationship of environmental incidents is not known;
- Effect uncertainty: Effects of changes in the environment on the very own situation cannot be predicted. Decision makers have to cope with uncertainty about whether state changes could have an impact on their own situation and if so, in which direction and to what extent;
- Response uncertainty: This type of uncertainty is associated with attempts to understand which response options are available in order to react appropriately to stage changes and their effects. Decision makers may be aware of future stages of the environment and their effects, but might not know how to deal with them. This kind of uncertainty is often experienced when an immediate decision must be taken.

The differentiation factor between these types of uncertainties is the lack of information. In the case of state uncertainty, people are not informed about the nature of the environment. With regard to effect uncertainty, a shortage of critical information on the cause-effect relationship between state changes and their impact can be observed. In terms of response uncertainty, there is a considerable lack of information about what the organization's response options are or about the effect of each course of action.

Taking Milliken's model of uncertainty as a base, it is imperative that product development teams investigate future environments and their impact on the own enterprise. Finally, they should be able to derive an estimate of the effect of their actions. A development team should, for instance, aim at understanding which competitors' move can have an influence on the competitiveness of the product to be developed and how the value proposition of the product can be enhanced by technical attributes. In this context, an optimal product development procedure should guide the development team through these steps and provide orientation.

2.3 Conclusion

The product development projects analyzed in the first description phase of the case study are dominated by the above-mentioned market and technical challenges. At the same time, these projects were initiated with a strong drive to introduce new products and continue a trend of innovations at PrintCo.

The resulting development process initially in place at PrintCo can be described by a rather long idea finding and concept generation phase, lasting for about six months, and a quite recursive, pressurized and iterative development process, characterized by several drawbacks and costly changes that had a negative impact on suppliers' operations as well as on the internal production.[7]

Interestingly, little iterations or discussions were initiated at the beginning of the development process when direction-setting issues such as technology or target market choice were up for decision. Some designers and the senior management noted their dissatisfaction with the current procedure and stated that the design teams found themselves optimizing a non-optimal concept in the later development stages.

Summing up, the initial observation phase of the case study highlights several thrusts for an improved development methodology, namely:

- Making uncertainties visible, especially in the front end of the development process;

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[7] Section 6.1 analyses the initial product development procedures in greater detail.

- bringing dependencies among uncertain variables and state to the surface and factoring them into the decision process;
- enabling the development team to deal with these uncertainties and to make solid decisions against this background;
- fostering communication and discussions within commercial and technical teams and across the two main fields market and technology;
- motivating the design and development team as well as the senior management to assess the impact of key technical and commercial decisions and improve their quality;
- shortening the overall time to market and, in particular, reducing costly iterations and reworking activities in the 0-series and series development stages.

Thus, not only the analysis of the status quo but also the strategic goal of PrintCo calls for a holistic approach including commercial and technical areas. This approach should support the development teams with processes, methods and tools to cope with the challenges inherent to the innovation processes of the company. Such an approach will be developed in the following chapters while the findings from the implementation are described in chapter 6.1.

3 Uncertainty Handling in Product Development Models

Various approaches towards an effective innovation and product development methodology have evolved over the past 40 years. They mainly stem from industrial applications, expanding the collective experience to a more universal framework. In the following chapter the state-of-the art of these approaches with regard to uncertainty handling will be analyzed. Product development processes originating from the managerial as well as the engineering domain will be discussed. In order to investigate the specific handling of uncertainties in these models, the analysis focuses on operative tasks and phase models in product development. As illustrated in Figure 3-1, these description levels are nested between micro levels that explain the basic thoughts and action approaches of designers, and macro levels that describe a whole project.

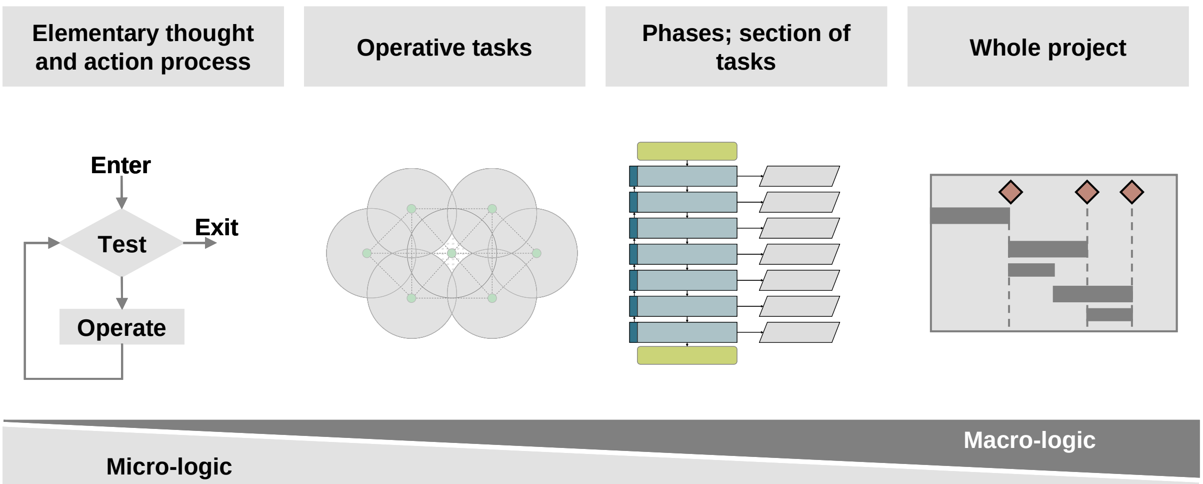

Figure 3-1: Description levels of procedure models [LINDEMANN 2006, p. 13]

Special relevance is laid on their ability to support highly innovative breakthrough development projects. However, successful method implementation requires repeated switching between these steps of process granularity.

3.1 Managerial and Economic Approaches

3.1.1 Stage-Gate Models

The first models describing staged development processes can be found in the 1960s when the NASA applied a so-called "phase review process" containing a scheme for a collaboration with contractors and suppliers during the development phase for several space projects. The basic idea was to break a long development process into discrete phases with dedicated reviews and decision points after each phase. The progress and content delivered at these decision points determined the continuation and funding of the project. The process methodology is often called first generation process model and was adopted outside the government sector by companies like Hewlett-Packard [COOPER 1994, p. 4ff].

The second generation process models result from an analysis of success factors of new product ventures conducted in the NewProd project in the 1970s and 1980s [COOPER 1979, p. 93ff; KLEINSCHMIDT, GESCHKA et al. 1996, p.9ff]. The results of the studies were transformed into general guidelines for the product development process, which led to the notion of a series of process steps ("stages") and corresponding milestone and decision points ("gates"). The development project is thus maneuvered through a series of discrete and consecutive steps and decisions from idea to product launch.[8] The intermediate phases include scoping, definition of a business case, development, testing, prototyping and launching. At the end of each phase is a gate at which one of the following decisions is taken by the committee the project is reporting to: go, kill, hold or recycle. If the project status is reviewed positively, work proceeds with a go decision to the next phase. If not, the work iterates within that phase until it can successfully pass the hurdle put up in the gate meeting. The project may also be set on hold or killed at any stage. Figure 3-2 shows a common representation of the stage-gate process.

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[8] The process models are also often called “waterfall” or “phase-gate” process models.

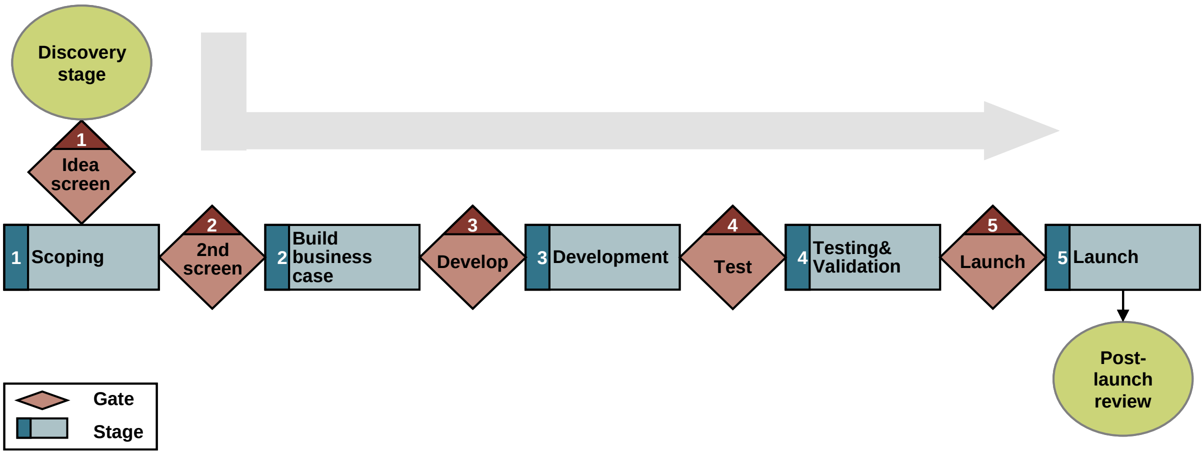

Figure 3-2: Stage-gate process model [COOPER 2001, p. 130]

Such stage-gate processes are implemented in several large - predominantly U.S. - corporations like IBM, 3M, GM, Procter&Gamble, DuPont, Corning, Polaroid, Dow Chemical and Black&Decker [COOPER, KLEINSCHMIDT 1991, p.137; COOPER 1994, p. 4],

Phased development systems are designed to control the technical risk and to linearize an otherwise more iterative and recursive process. Hence, they are set up to improve the manageability of product development ventures, which is especially relevant to companies with dispersed research and development operations running several development projects in parallel. Thus, the early adoption of stage-gate models by large multinational corporations like the above-mentioned HP, 3M or DuPont can be explained. On the contrary, stage-gate processes are less suitable for companies for which speed and time-to-market are more important aspects than process control and technical risk reduction: The documentation of stage-gate processes can be burdensome. In addition, traditional stage-gate processes cause difficulties incorporating cross-phase processes as they do not support parallel tasks within single stages. As a result, the length of each stage depends on the slowest task within that stage, thus lengthening the overall development process [SMITH, REINERTSEN 1992, p. 46; VERWORN, HERSTATT 2003, p. 201].

As a reaction to the criticism brought forward to the model, Cooper [COOPER 1994] proposes a stage-gate process of the third generation relaxing some of the postulations towards a rigid linear and sequential process flow. The modifications are partially derived from individually adopted stage-gate processes in corporations such as 3M, IBM and Northern Telecom. The third generation models should allow for overlapping gates, conditional go decisions, portfolio perspectives and a flexible setup. As a result, several alternative stage-gate models evolve, which range from a two-phase compressed stage-gate model to a fuzzy-gate process. Figure 3-3 illustrates some of these diversified process models.

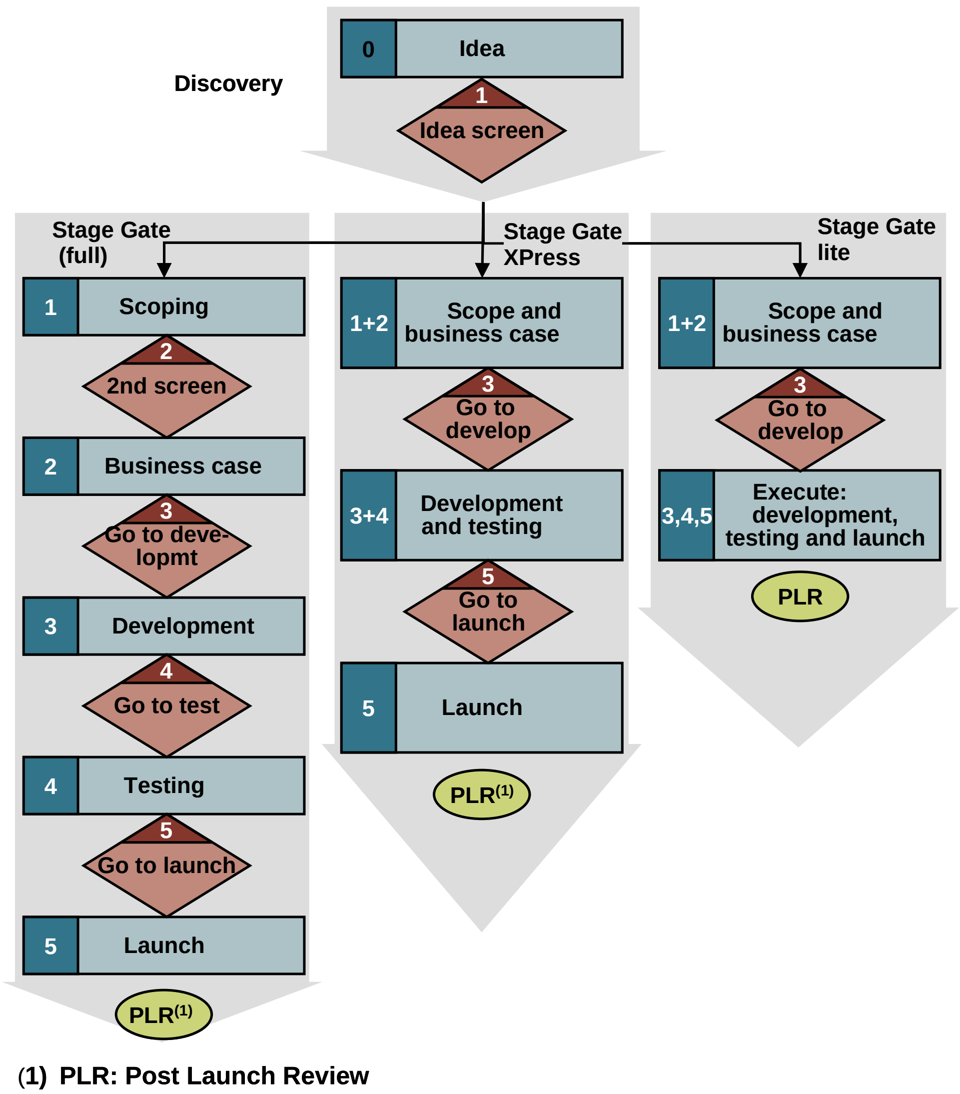

Figure 3-3: Variation of third generation stage-gate frameworks [COOPER 2001, p. 147]

Still, several authors criticize the adverse effect stage-gate processes can have on radical technology development projects [SMITH, REINERTSEN 1992, p. 46ff; KOEN, AJAMIAN et al. 2002, p. 6ff; KOEN 2003, p. 2ff]. Cooper, Edgett et al. [COOPER, EDGETT et al. 2002a; COOPER 2007, p. 68ff] argue that radical technology developments require less rigid and less financially based decision criteria and processes than those offered by typical stage-gate models in order to have a chance to survive in corporate environments. This is due to their nature as hardly to predict ventures, where neither a competitive environment nor a solid customer base is known in the beginning and therefore classical business case projections are not applicable. Cooper claims that *"much damage is done by applying traditional management techniques to non-traditional projects"* [COOPER 2007, p. 6]. Instead, he proposes a technology stage-gate process consisting of three gates and four stages, where mainly qualitative or estimated probability metrics are taken as a base for go or kill decisions. He assumes that after running through such more broadly managed development processes, technology projects can enter a traditional rigid stage-gate process at an intermediate stage.

According to Cooper [COOPER 1994, p. 6], third generation stage-gate models are to generate more room for the "*upfront homework*" through a scoping and an investigation stage. Tasks like market research, competitive analysis, concept tests, and manufacturing assessments can occur here, thus providing a stronger guidance for the remainder of the project. From the observation and analysis of radical innovation projects the author concludes that the front-loading approach adds more clarity to the beginning of the project. However, especially radical innovations also call for flexibility in the actual development phase where unforeseen problems and questions might occur more often than in incremental development projects.

In a review of implemented stage-gate processes mainly in the U.S. industry, Cooper, Edgett et al. [COOPER, EDGETT et al. 2002b, p. 46] infer that gate meetings are often merely meetings to check the progress of the project towards launch and to confirm the completeness of the deliverables required at each gate. This takes place at the expense of actual discussion on the content of projects. Thus, in radical innovations with a high uncertainty that is typically conveyed throughout the development process, gate meetings and the respective decisions alone are not fully capable of addressing the technical and marketing complexity and richness of options. From their empirical survey of 72 automotive engineering managers Ettlie and Elsenbach [ETTLIE, ELSENBACH 2007, p. 27f] conclude that companies alter their stage-gate processes when radical innovations as opposed to incremental technology projects are pursued.

3.1.2 Probe and Learn Process

Based on a historical review of four successful radical innovations, Lynn, Morone et al. [LYNN, MORONE et al. 1996] derive a process model that aims at supporting the specific challenges of radical innovation projects. In Lynn's and Morone's longitudinal studies, some heterogeneous and successful innovation projects – Corning's optical fibers, GE's computer axial tomography (CT), Motorola's cellular phones and Searle's NutraSweet – are examined with respect to their structural commonalities despite their different backgrounds. Through a structured assessment of the evolution from idea to market entry, several common drivers of success are derived. The authors argue that while phased products development processes such as the stage-gate models presented in chapter 3.1.2 support incremental development projects due to their inherent structure and rigor, they fail in enabling discontinuous or radical innovation projects. Since radical innovations are characterized by long development cycles (sometimes over 10 years), high investments, a high technology and market uncertainty (customers may not even be known at the beginning of the development), they require a more flexible approach. Hence, in contrast to the linear proceedings in stage-gate models, Lynn, Morone, et al. propose an iterative procedure: Early products are introduced in test markets, then modified according to the learning gained and, as a last step, again tested on the market. Such iterative experimenting and loops are repeated until the necessary information is generated and the product is modified in order to reach its final market. In the probe and learn model the first development stage – the 'probe' phase gains special relevance as this experiment often sets the track for further iterations. In the subsequent learning phase, companies gain a better understanding of the market for innovation, the technology behind the product as well as the interaction between market and technology.

The case of Corning's development of optical fibers illustrates this iterative and even recursive procedure: The idea of using optical fibers as a means of transporting data over short and long distances came up in the 1960s since such a technology promised vast opportunities in data transmission due to its radically enhanced carrying capacity, speed and reduced weight. Today, Corning is the world's largest producer of fiber optics with net sales of $ 877 M for optical fibers and cables in 2006 [FIBEROPTICSWEEKLYUPDATE 2003; CORNING 2006, p. 114].

Corning's success came only after a series of iterations in which the test markets changed several times. Initially, picture phones were seen as the key application field for optical fibers by possible key customers like AT&T and the British Post Office. After problems with the image quality the market focus shifted to long and short haul transmission, cable television and LAN applications. Yet, none of these markets yielded a breakthrough which could not occur until after a decision of the U.S. government to deregulate the telecommunications industry: MCI, a challenger of the established player AT&T, had to build up its own telephone network, and found Corning's single mode optical fibers to be the adequate technology and thus became the first real customer. From then on the market and technology evolved in the direction of local loops and home applications [LYNN 1993]. Figure 3-4 illustrates Corning's probe and learn process towards the market breakthrough in optical fibers.

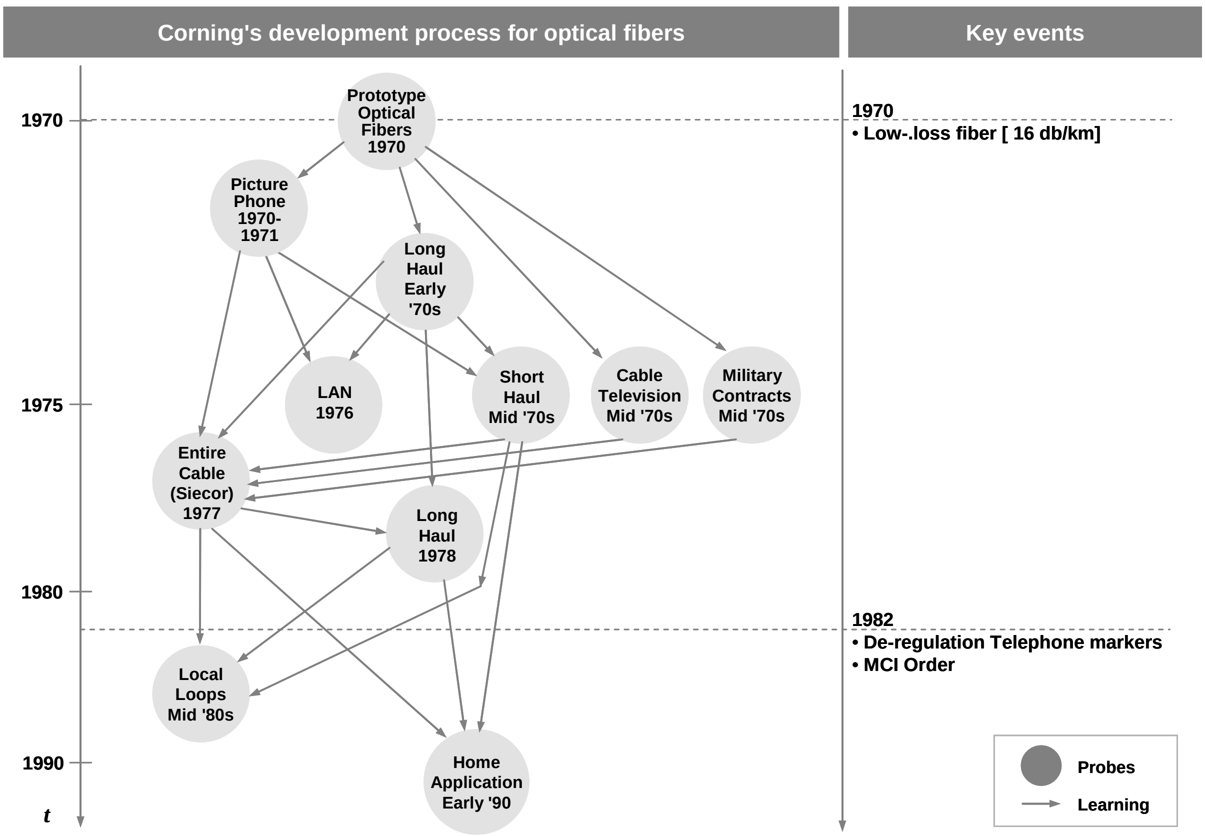

Figure 3-4: Corning's probing and learning process for optical fibers [LYNN, MORONE et al. 1996, p. 24]

By proposing a paradigm for a radical innovation process based on the probe and learn logic, which is visualized in Figure 3-5, Lynn makes generalizations from the above-mentioned case studies. In the field of software development, the notion of "*probing and learning*" finds its equivalent in the spiral model for software development proposed by Boehm [BOEHM 1988, p. 64ff; BOEHM, EGYED et al. 1998, p. 34ff].

None of the successful radical innovation case studies examined by Lynn, Morone et al. could have passed the gates in the early phases of a linear stage-gate process [VERWORN, HERSTATT 2003, p.205]. Lynn and Akgün [LYNN, AKGÜN 1998, p. 13] argue that radical innovations particularly require a more flexible, learning-based approach.

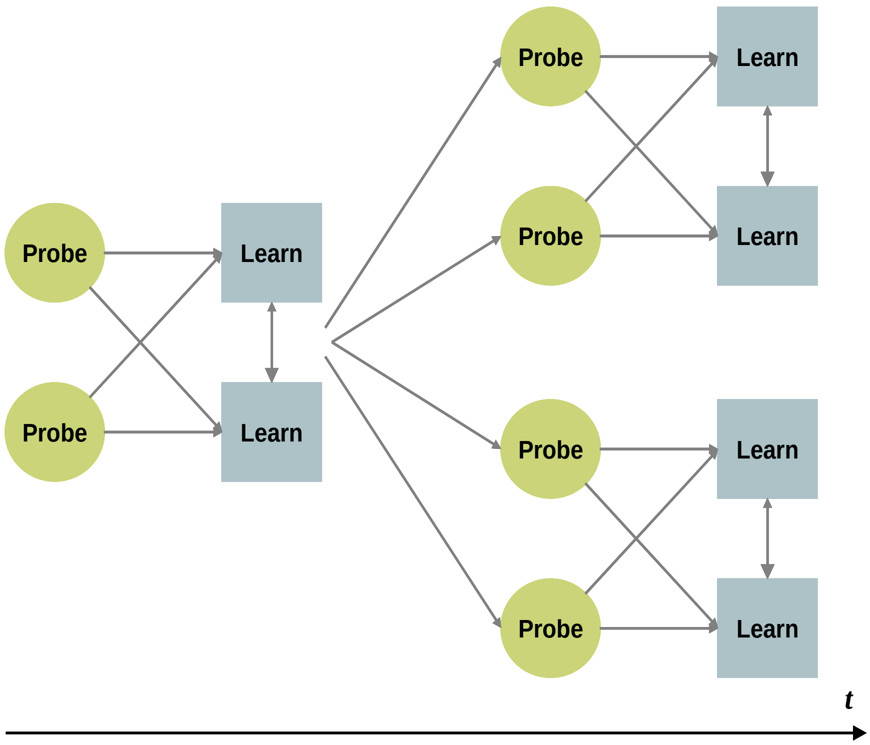

Figure 3-5: Probe and learn paradigm for radical innovation processes [LYNN 1993, p. 288]

While the probe and learn process led to impressive product development results in the ex post perspective, it may seem less attractive or unstructured and "loose" to some managers in an ex ante perspective when significant resources are put against a product idea. A study by Salomo, Weise and Gemünden [SALOMO, WEISE et al. 2007] investigates the effects of new product development planning and structuring on the project's success. The data from 132 new product development projects indicate that project planning, business planning and goal stability throughout the process enhance the performance. The effects of the planning and structuring efforts on the project success are only moderately negatively affected by the degree of innovativeness [SALOMO, WEISE et al. 2007, p. 297]. The engineering design process itself is by nature highly iterative in radical innovations. Lindemann, Kleedörfer et al. [LINDEMANN, KLEEDÖRFER et al. 1998, p. 181] claim that the sequence of iterations appearing in such processes call for a structured process, structural organization, and dedicated IT support.

3.1.3 Real Option Modeling

In the approaches discussed in the previous sections, uncertainty and risk were typically seen as challenges to a product development project. This is align to the most project management guides oriented towards practitioners, which stress on identifying potential risk, assessing, and mitigating their negative impact on a project [For example SMITH, MERRIT 2002, p. 29ff; PROJECT MANAGEMENT INSTITUTE 2004, p. 237ff].[9]

The real option theory, however, offers a different perspective on the inherent uncertainty of such projects, since it emphasizes and values the flexibility that comes along with the liberty to alter projects – for example enhance, modify, put on hold or abandon the venture depending on the actual development of uncertain variables in the project's environment. This corresponds to options and future instruments used in financial markets since the 1970s [HULL 2000, p. 5]. Myers [MYERS 1977, p.155ff] introduced the notion of real options by

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9 To illustrate the proposed risk management procedures and tools, Smith and Merritt use the example of a 50 year old male who is analyzing his risks of having and dying from a heart attack [SMITH, MERRIT 2002, p. 56ff]. While this is merely an illustrative running example throughout the book to apply the concepts in a uniform setting, it also conveys a generally negative perception towards risk.

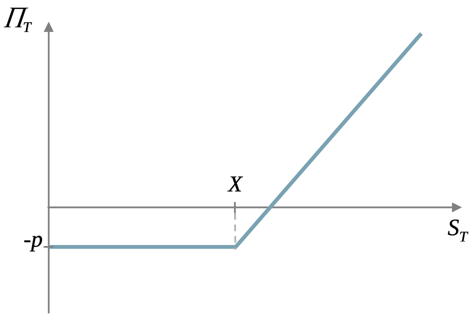
applying this framework to decisions outside financial markets, like decisions to invest in risky assets or to conduct projects. Copeland and Tufano [COPELAND, TUFANO 2004, p. 90] state that every project is a real option, because it gives its managers several choices like pushing ahead or pulling back at certain points.

The core idea of the option and real option framework is that the holder of an option has an asymmetric risk profile, i.e. one would only execute a given option if the environment conditions turn out to be favorable for the option holder. Considering an example of a classical stock option that has been bought at the price *p*, giving the holder the right but not the obligation to buy a unit of the stock at the price *X* and depending on the price of the stock *S* at the time of expiry *T*, the payoff for the option will be as follows:

$$\Pi_T = \begin{cases} S_T - p, & if\ S_T \geq X \\ -p, & if\ S_T < X \end{cases} \tag{3.1}$$

Hence, the option holder is only participating from upwards movements of the stock price, which leads to the above-mentioned asymmetric risk profile. The application of these derivative instruments gained significance in the financial market, especially after Fisher, Black and Scholes [BLACK, SCHOLES 1973, p. 644] developed a closed formula for which Scholes and Merton received the Nobel prize for economics in 1997. Several authors have transferred the idea of financial options to settings in a business context that do not draw back on tradable assets but take general forward-orientated decisions under uncertainty as a base [For example BOWMAN, HURRY 1993; PENNINGS, LINT 1995; COPELAND, KOLLER et al. 2000; LESLIE, MICHAELS 2000; COPELAND, ANTIKAROV 2003; COPELAND, TUFANO 2004; NEWTON, PAXSON et al. 2004; FORD, SOBEK 2005]).

In this context, a product development project is seen as an option to constantly alter the product based on new information and to continue with the project in the given state only if the expected returns are larger than the remaining development costs. Figure 3-6 demonstrates the basic option logic as well as the analogy between financial and real options.



Symbol	Stock option (call on stock)	Real option (PD project)
Π	Pay-off from option exercise	Pay-off from PD project
p	Price of option	Occurred development cost
T	Expiry date	Date for decision
X	Strike price	Remaining development cost
S	Value of underlying stock	Value of product introduction (discounted)

Figure 3-6 Pay-off diagram from basic call option and analogy from stock option to real option [adopted from NEWTON, PAXSON *et al. 2004, p. 116]*

Traditional valuation methods such as net present value calculation do not capture the flexibility a project team has to react depending on changes in the environment and on generated learning. The implicit assumption in these models is that an entity remains passive once it has decided to undertake an investment. Thus they underestimate the value of a project in which the outcome is depending on uncertain variables. Christensen, Kaufman et al. [CHRISTENSEN, KAUFMAN et al. 2008, p. 100ff] call the pure application of financial instruments like discounted cash models or earnings per share ratios "*innovation killers*" as they apply a myopic and isolated perspective on innovation projects. Using these methods, especially the impact of radical innovation projects tends to be underestimated. On the contrary, the real options perspective can positively affect the valuation and decision of risky ventures. All other things equal, the value of the options increases with the uncertainty of the developments and the time to expiry [LESLIE, MICHAELS 2000, p. 99]. Hence, the real options framework gains relevance for long lasting radical product developments. Nevertheless, the derivation of concrete process models or recommendations is vastly lacking behind the financial and real options theory. Newton, Paxson et al. [NEWTON, PAXSON et al. 2004, p. 119] propose several situations in a product development process where real options thinking can enhance insights and decisions. They refer to a model of planning product development in discrete stages where at each step several options have to be considered. Examples are exit and abandonment decisions, waiting to invest or introduce, or decisions on the utilization of a potential first mover advantage.

There are several applications of the real options framework on the problem of major investment decisions [SMIT, ANKUM 1993, p. 241]. Smit and Trigeorgis [SMIT, TRIGEORGIS

2007, p. 87ff] discuss several investment scenarios where the application of a real options lens provides a recommended course of action that may differ from the one generated in a classical new present value perspective. The scenarios comprise the valuation of a first mover advantage for new products, the valuation of investing into new technologies, or joint research and development projects. Here, the real options perspective provides essential input as it increases the value of uncertain options. All other things being equal, more risky investments will be undertaken and will be accompanied more actively in order to exploit the real options value of an investment. For example, Smit and Trigeorgis investigate investments into large-scale technologies like UMTS licenses in the mobile telecommunications industry or the exploration of natural resources and show that the option to wait or to defer investments gains special relevance in uncertain and volatile businesses [SMIT, TRIGEORGIS 2007, p. 89ff]. In a more technical oriented context, Sudhoff [SUDHOFF 2007, p. 89ff] shows the benefit of considering and evaluating options in the question of optimal location choice in industrial production. Specifically, the value of mobility in a production system as a degree of freedom against an uncertain environment is explained and quantified using a numerical multinomial tree approach. In a similar production-oriented problem, Möller [MÖLLER 2008, p. 73ff] assesses the value of mutability in production systems depending on external factors. In theses production settings external uncertainty may be reside in the development of average units cost, wages, or number of required expatriates. Thus, a model that can draw comparisons between mobile and static production concepts in the mid- to long-term investment planning is derived.

Using such models and applying the options theory allows for a detailed valuation of investment vehicles which embed an options character. The real options value compared to the deterministic net present value can be expressed as a function of the value of the underlying, its volatility, and the remaining time to act.

While the implementation of real options in the valuation of mid to long-term investment problems can be characterized as profound, there are only a few implementations of the basic real options idea in a single product development processes. The real options models discussed in the abovementioned case assign a monetary value to the options to stop, abandon, or alter an entire investment, but there is little evidence for applications of the real options framework for the variants within a single project.

A notable purveyor of the application of real options thinking in the proceedings can be found in the concept of set-based concurrent engineering. Here, an option space of design sets is subsequently narrowed down until an optimal solution is found. Concurrent engineering integrates the product development process in order to allow designers to make upstream decisions on the product to downstream and external requirements [Gerwin, Susman 1996, p. 118], [Ehrlenspiel 2007, p. 218ff]. Typical downstream activities are defined by the shape and composition of the product and include sourcing, production and assembly. The methodology of concurrent and simultaneous engineering is dealt with in more detail in section 3.2.3 of this thesis. Based on the concurrent engineering logic, the set-based concurrent engineering approach resulted from studies of Toyota's development system. Toyota's ability to develop products in shorter development times compared to the western automotive industry while considering several solutions in parallel and relatively independently from each other in the design and engineering process is sometimes called the "*Second Toyota paradox*" [Ward, Liker et al. 1995, p.43][10]. Initially, all participants of the design process define broad sets of feasible solutions from their respective area of expertise – for example body engineering, chassis engineering or powertrain development. During the design process, the sets of solutions are narrowed down to the target solution using the information generated and the cross-functional input [Sobek, Ward et al. 1999, p. 70]. The methodology supports the team members to eliminate inappropriate solutions and hinders them from revisiting them in later stages. The process is thus attributed to generate more solid results in a short time frame compared to the alternative of working with only one idea at a time [Sobek, Ward et al. 1999, p. 71].

Figure 3-7 illustrates the logic of narrowing the results down to a number of possible sets and the associated process logic during the development process.

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[10] In this context, the term "*First Toyota Paradox*" is used for Toyota's well-studied production system, integrating the aspects of just-in-time production, worker enablement and kaizen in Toyota's operations and thereby improving productivity and quality [OHNO 1988].

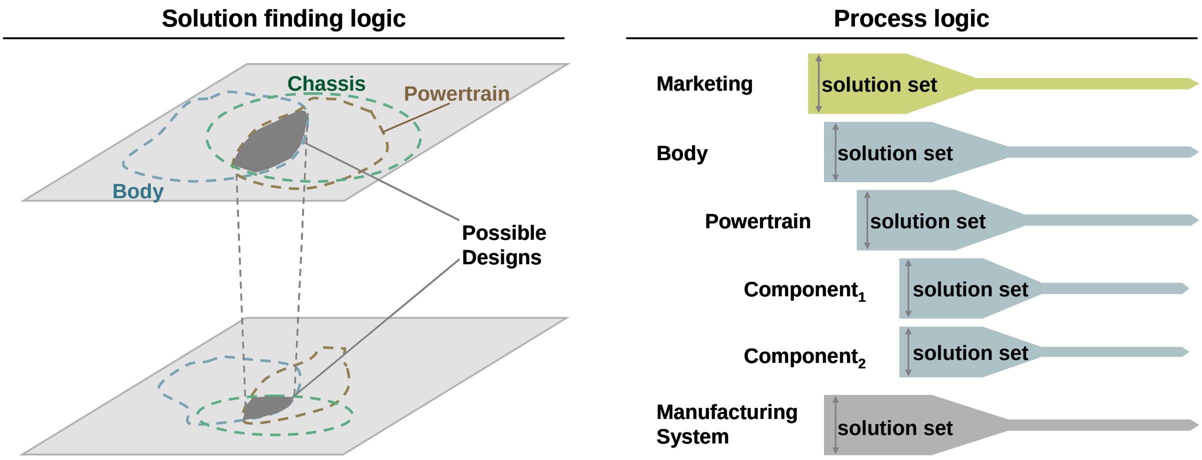

Figure 3-7: Solution finding and process logic in set-based design [FINCH 2006, p. 7]

In a basic simulation, Ford and Sobek [FORD, SOBEK 2005, p. 178ff] show that the real options approach can explain the flexibility obtained in Toyota's set-based concurrent engineering approach over a point-based development approach with early design freezes. The delayed convergence enhances the value of the real options and contributes to an explanation of Toyota's success. In a real options model built from secondary data, Sörensen [SÖRENSEN 2006, p. 175] proves that in the absence of dominating design alternatives it is optimal for a company to invest in larger sets of design alternatives as the options value can cover additional costs.

Pennings and Lint [PENNINGS, LINT 1995] present a similar real options consideration for Philips' more radical innovation of optical tape records showing that projects can be profitable even though their net present value has been negative.

Despite the intuitive logic of real option modeling and the existence of case studies showing its benefits in product development, the implementation of this framework in the industrial product development is still marginal. In a survey of 451 senior executives on management tools and techniques, Rigby [RIGBY 2001, p.143ff] reports that only 6,5% use real options analysis, and of all respondents who had employed the tool, 46,2% had given up using the methodology. From a theoretical perspective these results have multifaceted reasons [BOWMAN, HURRY 1993; SANTIAGO, BIFANO 2005]: finding the right model, determining the input model and solving the algorithm in order to obtain actionable recommendations.

Specifically, the transition of the real option methodology towards a product development methodology offering structural support to a development team is not yet fully accomplished.

In contrast to financial options that can be traced back to a rich set of historical and current market data such as stock prices, return rates or volatilities, real options merely rely on internally generated information, which is more difficult to acquire and to calibrate. Financial options can well be modeled and calculated in cases of risky environments, i.e. known probabilities of outcomes, but suffer from situations of state and effect uncertainty in Milliken's sense which are frequently experienced in the early phases of product development [MILLIKEN 1987, p. 136f].[11]

[11] See chapter 2.2 of this thesis for an illustration of uncertainty and risk in the context of product development.

3.2 Technical and Engineering Approaches

3.2.1 Engineering Design Process according to Pahl and Beitz

The work of Pahl, Beitz et al. [PAHL, BEITZ et al. 2007] has led to a common view of engineering design processes. While there is a great variety of different development processes due to various degrees of novelty (new vs. adaptive designs), several types of production (batch vs. mass production) and further determining characteristics such as company goals and stage in product lifecycle, the proposed engineering design approach offers a structured support to a generic development process. It has been embedded in the VDI guideline 2221 containing process steps and results that promote the process of acquiring, compiling, generating and documenting information [VDI RICHTLINIE 2221 1993, p. 4ff]. The proceedings comprehend a definition of requirements to detail the tasks, the search for possible solutions as well as the development and optimization of solutions up to the documentation of the product. The basic logic of this process is displayed in Figure 3-8.

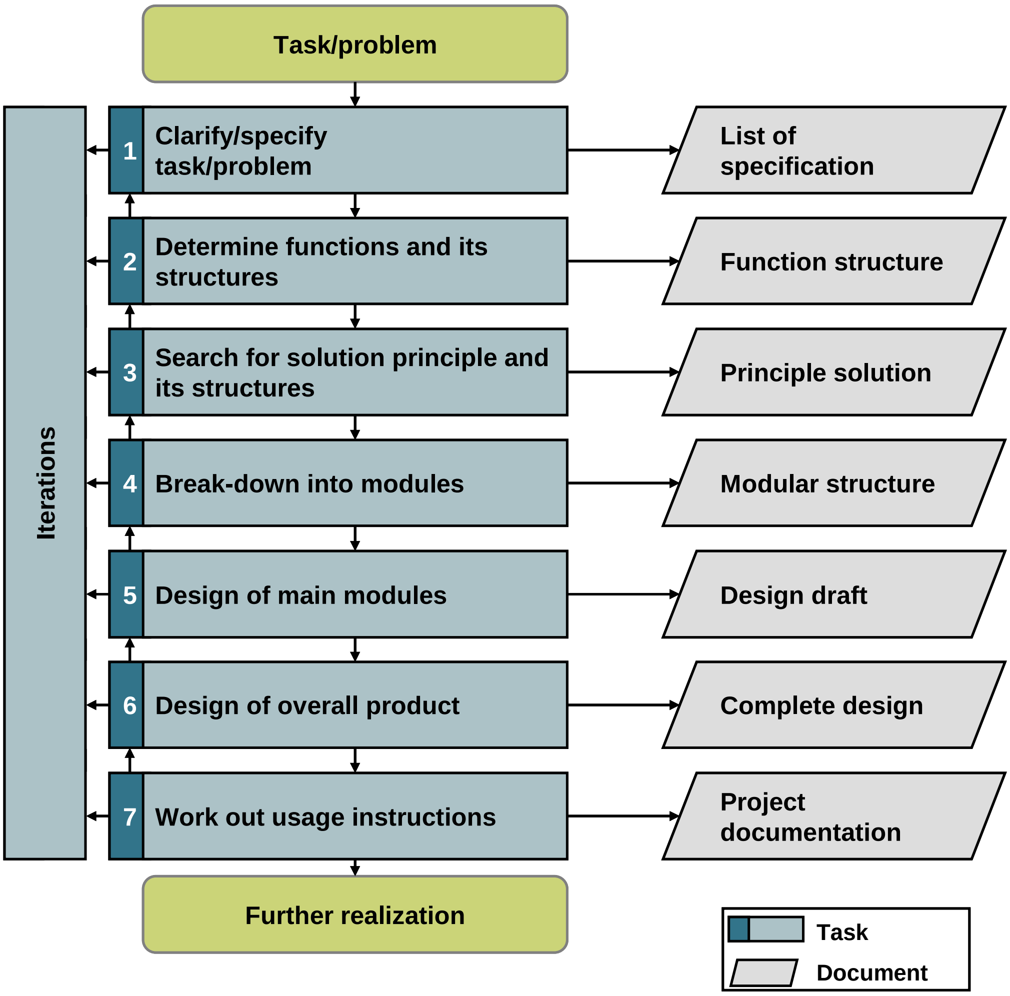

Figure 3-8: Proceedings according to VDI Guideline 2221 [VDI RICHTLINIE 2221 1993, p. 9]

Despite the designated iterations, the process aims at a single solution that is detailed from a basic functional structure to its completed design. The early phases where most of the direction-setting analyses are conducted and the corresponding decisions are taken, receive a stronger emphasis in the original model by Pahl and Beitz. This four-phase procedure logic starts with planning and clarifying the development task, consisting of the following tasks:

- analyzing the market and company situation,
- finding and selecting product ideas,
- formulating a product proposal,
- clarifying the task,
- and elaborating a requirements list.

During the subsequent conceptual phase, a concept for the product is developed through the search for functions and appropriate solution principles, which describes a more iterative process of searching, creating, combining, evaluation and selection of solutions. It leads to the embodiment phase where the design becomes more concrete and design decisions for later value-added steps such as manufacturing and purchasing are taken into consideration. In the final detail design phase, all arrangements of the product and its components are defined. Figure 3-9 summarizes the engineering design methodology.

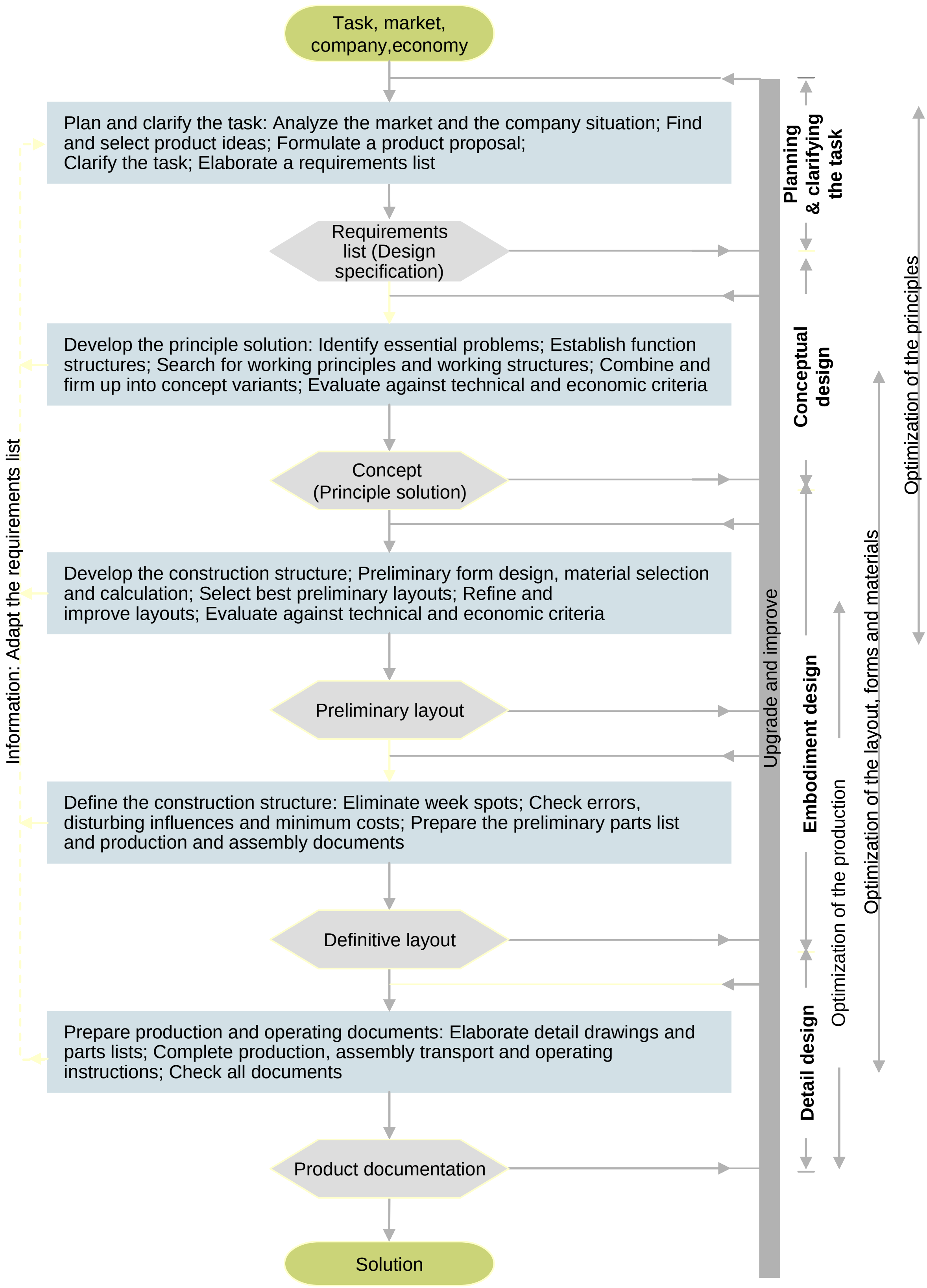

Figure 3-9: Engineering design process [PAHL, BEITZ et al. 2007, p. 130]

Thereupon iterations are planned in two main ways: First, during the search for solutions there is a natural iteration loop since possible solutions will be found, analyzed, revisited and modified as part of the typical design process. Second, the VDI guideline provides a stepwise progress from a single prototype product to a pre-series and a series-ready product with intermediate design and engineering phases. This proceeding is illustrated in Figure 3-10.

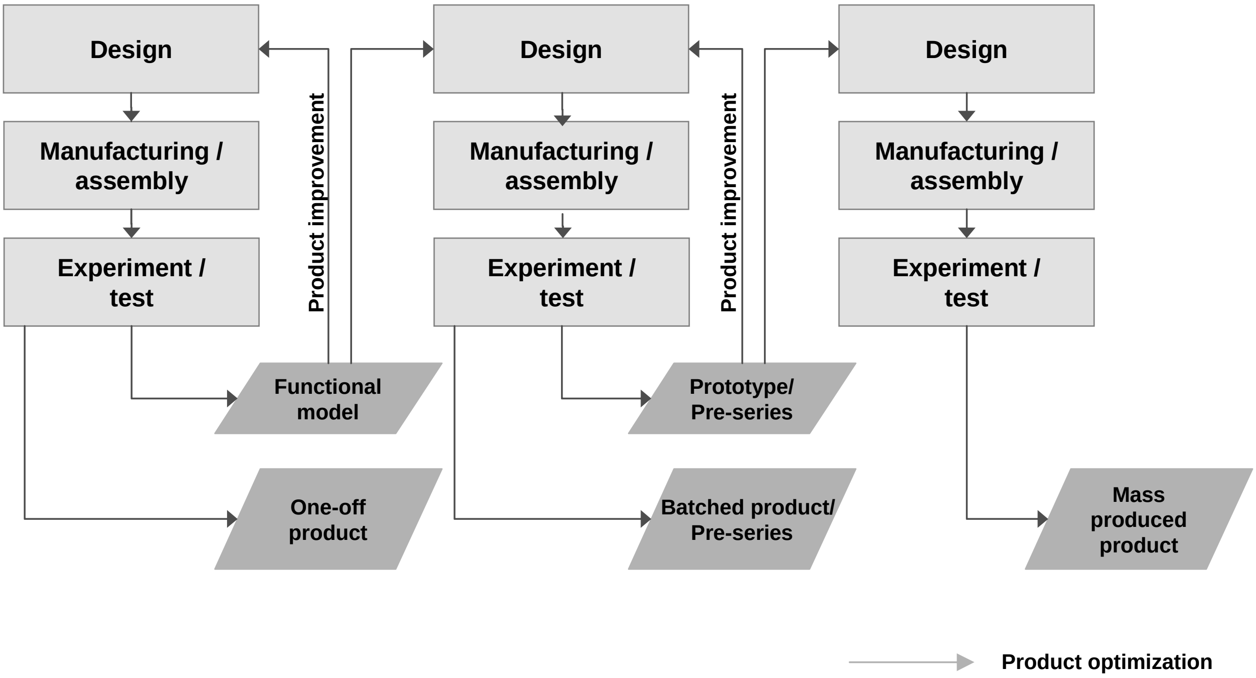

Figure 3-10: Cycles in product generation [VDI RICHTLINIE 2221 1993, p. 10ff]

However, the process in general and the two iteration loops in particular aim at developing and optimizing a previously defined and specified product. This feature poses a significant challenge for radical innovations where the "right" product concept typically does not exist in the first phase [COOPER 2007, p. 6]. A later reset modifying the project goal is not anticipated in the discussed process. Hence, the iterative but linear methodology offers a strong structural support that is at the same time "too linear" for radical developments [LINDEMANN 2005, p. 39]. Ehrlenspiel [EHRLENSPIEL 2007, p. 309] claims that the ambition to bring clarity and order into a development process that appears to be messy is understandable. Additionally, the linear fashion of the VDI 2221 logic creates a situation that is neither realistic nor one which results in a rigid frame for the product development team. Thus, the VDI logic generally seems inappropriate for the support of a radical innovation project due to the rigidity and linearity it imposes on development projects.

3.2.2 Mechanical Design Process according to Ullman

The design process proposed by Ullman [ULLMAN 2003] offers a generic set of activities and decisions suited for redesigns as well as for radical new products where the exact market demand may initially not be known. Ullman stresses the need for quality in the product by achieving quality in the process which consists of five phases, namely project definition and planning, specification definition, conceptual design, product development and product. (See Figure 3-11)

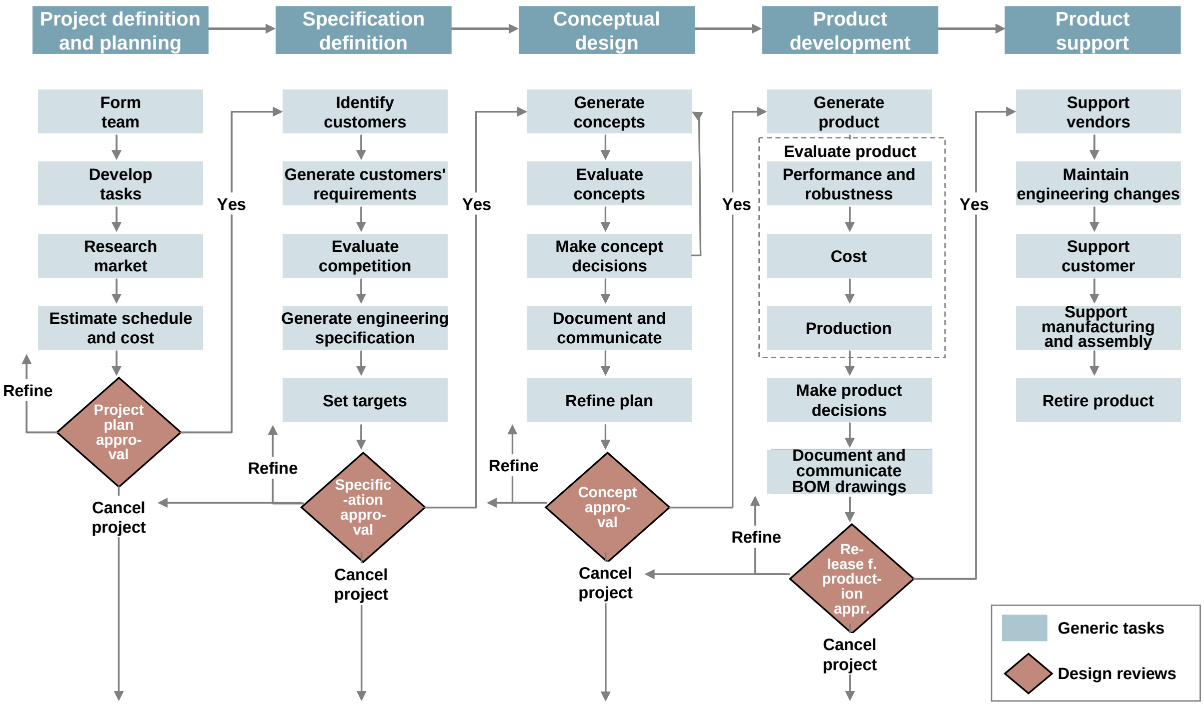

Figure 3-11: Mechanical design process [ULLMAN 2003, p. 86]

Ulrich and Eppinger [ULRICH, EPPINGER 2007, p. 14] propose a similar five step logic for the product development process with comparable, yet rather generic tasks compared to Ullman's process description. (See Figure 3-12)

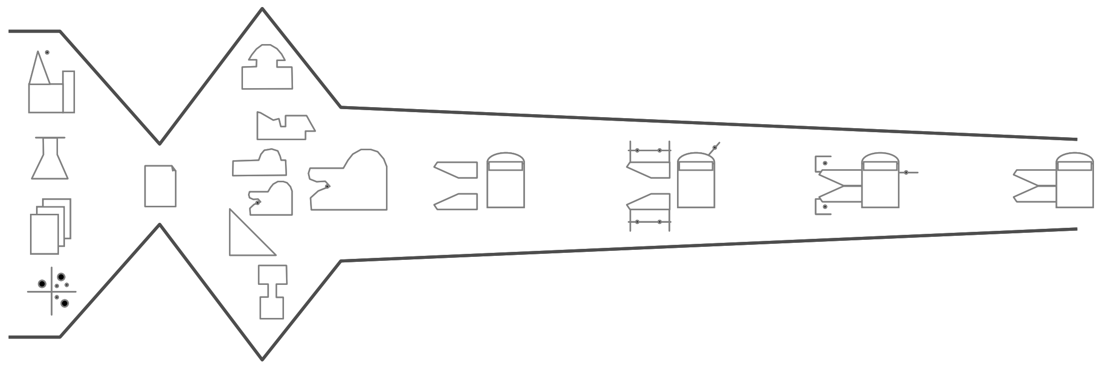

Figure 3-12: Product development process [ULRICH, EPPINGER 2007, p. 14]

It is noteworthy that compared to the process models discussed in the previous chapters special stress is laid on deriving specifications and generating concepts prior to the actual product development. Ullman regards the product development phase as a step where the best generated and evaluated concepts are refined into products. He states that unfortunately many design products begin only with the product development phase: "*Starting a project with a single conceptual design in mind, without concern for the early phases, is poor design practice.*" [ULLMAN 2003, p.73]. This emphasis on target definition and working on several concepts in principle supports radical innovation projects, where a high share of the work is necessary to define the requirements of the target product and several ways to design it. The dominating method to derive these requirements is called Quality Function Development, which is typically implemented in the house of quality that logically guides designers through the following eight questions:

- 1) Who are the customers?
- 2) What do the customers want?
- 3) What is the relative importance of requirements?
- 4) How satisfied is the customer with the competitors' solutions?
- 5) How will the customers' requirements be met?
- 6) How do customers' specifications relate to engineering specifications?

- 7) Which target level should be assigned to each engineering requirement?
- 8) Which interrelationships do exist in target requirements?

The house of quality that translates customer requirements ("what?") into technical specifications ("how?") and links the two dimensions by a relationship matrix in the middle of the house is displayed in Figure 3-13. The roof indicates whether technical requirements interrelate with each other and also the strength of their relationship if they do so. Weighting factors can be added to customers' requirements as well as an estimation of competing products from the customers' viewpoint.

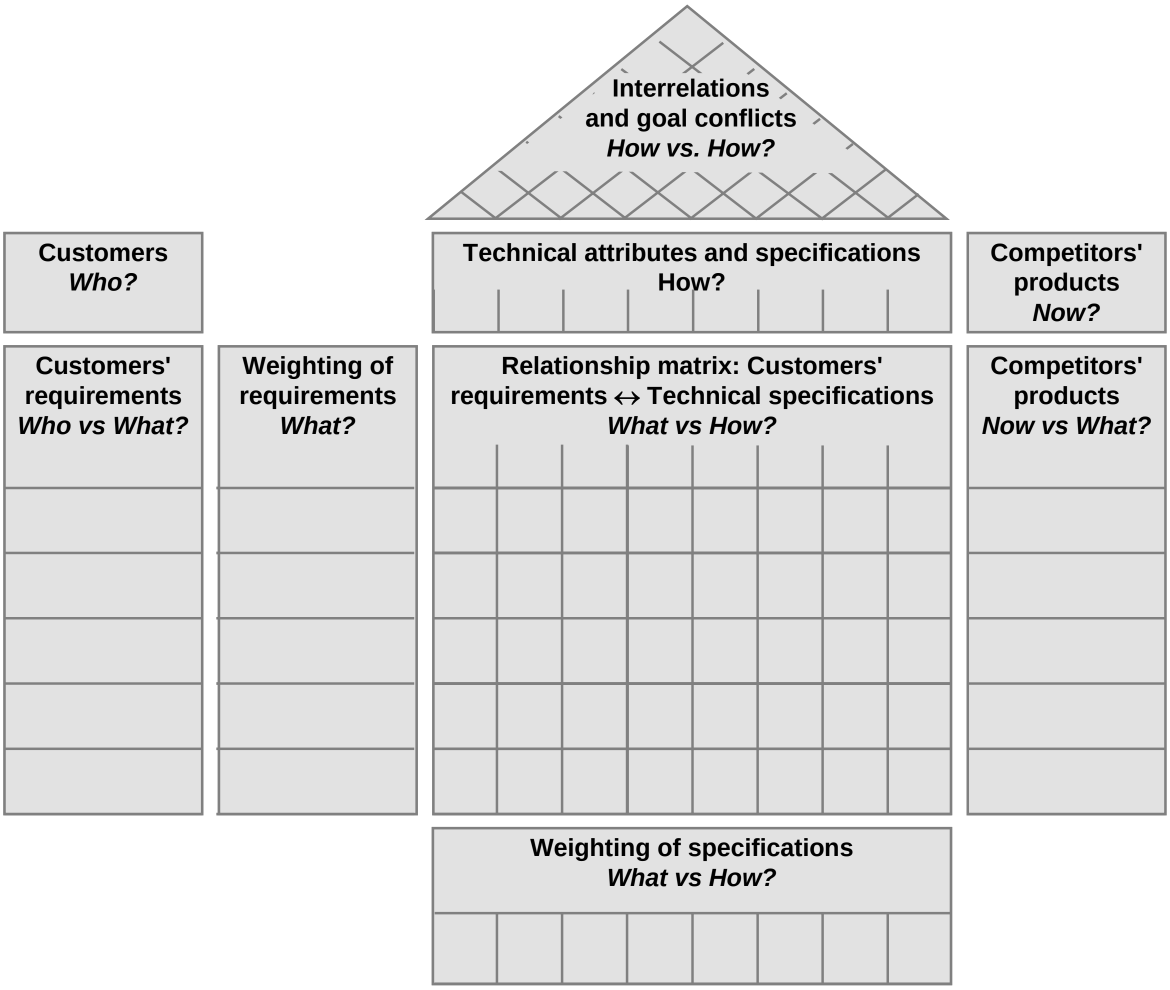

Figure 3-13: Quality function development - the house of quality [AKAO 2004, p.20ff]

The house of quality and thereby the mechanical product development process proposed by Ullman will thus demand for an already solid understanding of the customers and their respective requirements and wishes. This represents a problem when applying the method to radical innovations, as customers' specifications are only vaguely known in the early phases of such innovation ventures. Radical innovations are often based on latent needs, which are not yet clearly articulated by the customers or the marketing department. Brunner [BRUNNER 2001, p. 49] even argues that in such cases marketing might deliver information stemming from existing customers. This information can then circumvent radical innovations, as existing customers tend to extrapolate the known presence rather than to predict the future. A similar problem applies to competitors' products that cannot be utilized as a base to derive and weigh customers' requirements and technical specifications.

3.2.3 Concurrent and Simultaneous Engineering

Concurrent or simultaneous engineering are prominent purveyors of integrated procedure models where multiple functions that are involved in the product development or that are executing operations for the new product are integrated early in the product development process. Ehrlenspiel [EHRLENSPIEL 2007, p.218] defines simultaneous engineering as "*target-oriented, interdisciplinary, parallel and joint work in product, production and sales development*". The tasks are directed at the whole product lifecycle and guided by a firm project management. The goals that are pursued with concurrent engineering approaches are threefold [EVERSHEIM, BOCHTLER et al. 1995, p. 2]:

- Reduction of time to market,
- product cost reduction,
- and quality improvement.

The most notable difference to classical linear and sequential development models is the parallelization of activities during the development and industrialization process in order to speed up the process and the integration of several functional parties as well as suppliers and customers. Swink [SWINK 1998, p. 114] distinguishes between three types of concurrency that can be applied to product development: In a first step different products, for example different variants, can be developed in parallel. Furthermore, different phases of the development process and of the actual design can be parallelized as shown in Figure 3-14.[12]

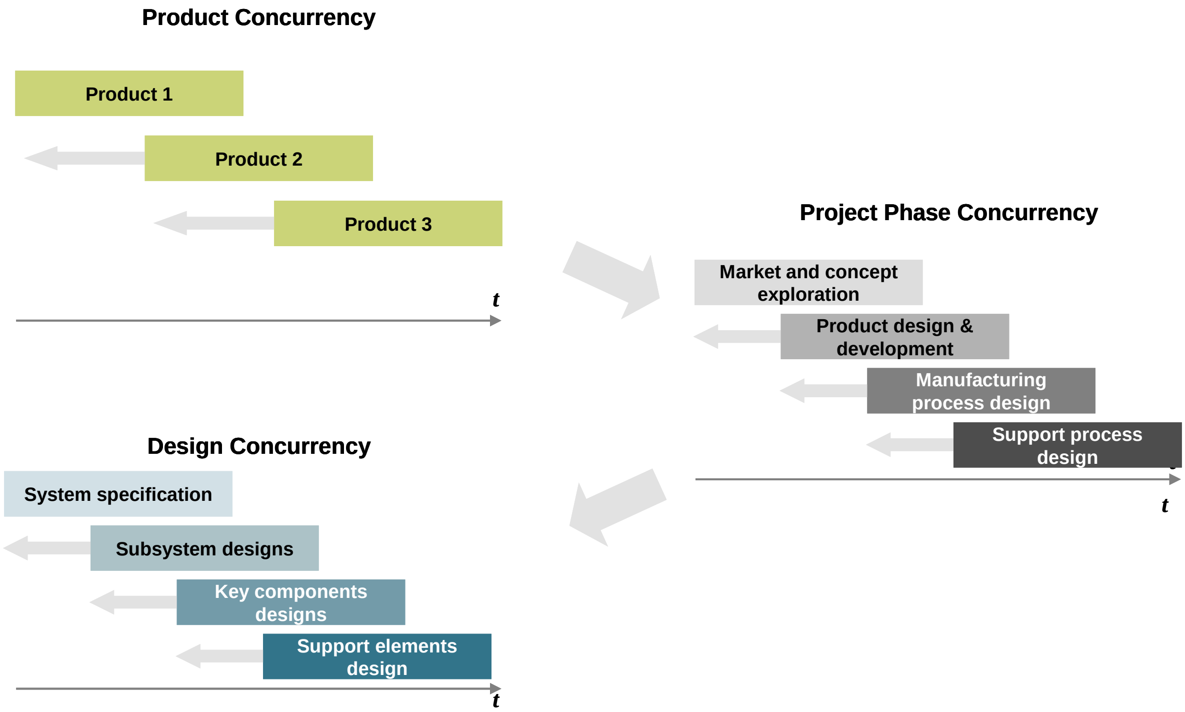

Figure 3-14: Different types of design concurrency [SWINK 1998]

Several case studies illustrate some beneficial aspects of concurrent engineering in design [KRISHNAN 1996; SOBEK, WARD et al. 1999; DITZER 2005]. Haddad [HADDAD 1996, p. 125ff] analyzes how a U.S. automotive company was able to turnaround comparably long development times and low profitability. The respective company cut development times for a new car model from four-and-a-half years to three-and-a-half years and thus could save more than €260 million in direct costs. The author attributes the success of the concurrent engineering implementation to organizational aspects, technology enablers, but also strongly to a senior management commitment to fundamental change.

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[12] In a broader perspective, Andreasen [ANDREASEN 1991, p. 331] defines concurrency as simultaneity of procedures, integration of various parts of the company ("*design for x*") and farsighted thinking.

Gerwin and Susman [GERWIN, SUSMAN 1996, p. 118] note that while the concept and benefits of concurrent engineering can be easily understood, its implementation often represents a radical change compared to existing practices. The new simultaneous engineering model breaks the traditional sequential new product development processes, functionally based organization structures and reward systems as well as the concentration of decision-making authority in management. These arrangements, which may have worked adequately and successfully, can generate a certain "stickiness" to the old mechanism. Yet, an effective change towards simultaneous engineering principles implies a change in process mode, calls for team work and hence represents a challenging task.

In the context of radical product development programs, concurrent engineering approaches do not fulfill special requirements towards uncertainty management and step-wise learning. The parallel development process forces a development team to forward unsecured information to downstream functions so that the impact of wrong decisions is even strengthened.

A strong overlap in development tasks can lead to a situation where the risk is continuously carried forward and multiplied which might cause a high number of changes in the back-end of the process. Hence Verworn and Herstatt [VERWORN, HERSTATT 2003, p. 206] expect the time to market to increase again. They conclude, that concurrent engineering is better suited for incremental than for radical development projects. Furthermore, Gerwin and Susman [GERWIN, SUSMAN 1996, p. 121] report that there is little evidence of companies using concurrent engineering approaches in the front end development phases of a project. This is due to the fact that concurrent engineering techniques offer little structural support to the early direction-setting phases, which gain special relevance in radical development projects.

3.2.4 Integrated Product Development according to Andreasen and Ehrlenspiel

Andreasen and Hein's considerations [ANDREASEN, HEIN 1987, p. 1] are generally seen as precursors of an integrated product development approach. They argue that while the division of work into single seemingly remote tasks like strategy, operations marketing, product or production might be tempting for efficiency reasons, severe problems arise from this division of labor which can only be solved by using an integrated approach in the development process. It is important to note that integrated development in Andreasen and Hein's sense is not aiming at an integration of departments, functions and management tasks, but at the introduction of integrated procedures, goals and attitudes. Following this logic, integrated product development constitutes an idealized model for the integration of project and management tasks and the embedding of the functional tasks involved in product development. The latter are grouped into market, product and production which are being executed in parallel during an innovation project from the need towards the execution [ANDREASEN, HEIN 1987, p. 21ff]. In more focused projects like product modifications only one stream of activities is active, whereas highly innovative projects require all three streams to be executed in parallel. (See Figure 3-15)

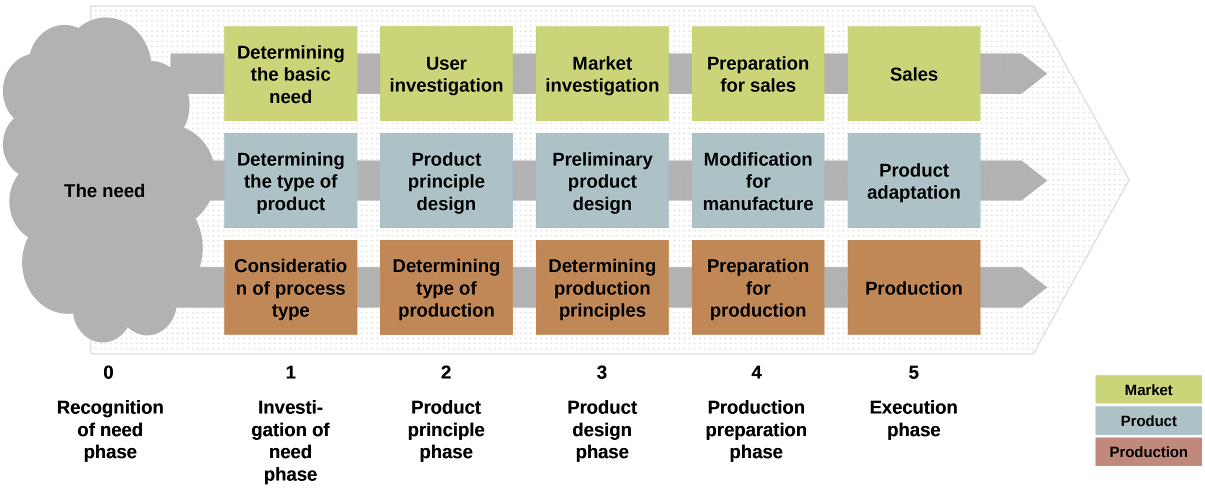


Figure 3-15: Integrated product development process [ANDREASEN, HEIN 1987, p. 27]

Following the logic of integrated product development, Ehrlenspiel [EHRLENSPIEL 2007, p. 82ff] derives a respective process from a series of structured and goal-oriented "trial and error" activities. The procedure model is assembled from combinations of self-similar test-operate-test-exit (TOTE) loops as illustrated in Figure 3-16.

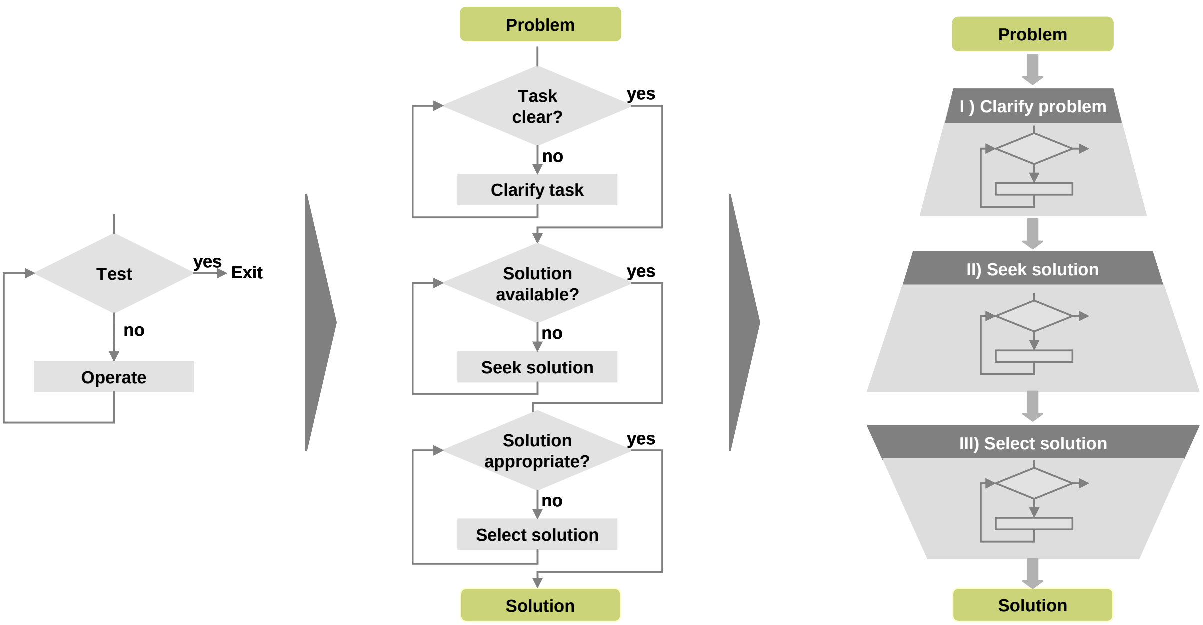


Figure 3-16: Derivation of development proceeding from TOTE-scheme [EHRLENSPIEL 2007, p. 87]

The procedure cycle of the integrated product development consists of the following three basic steps: I) problem clarification, II) search for solutions and III) selection of a solution that can be further segmented in three sub-steps each as illustrated in Figure 3-17.

The procedure partially also contains a fourth step: IV) realization of a solution. Herein, the results of the planning process are implemented and a performance review is conducted.

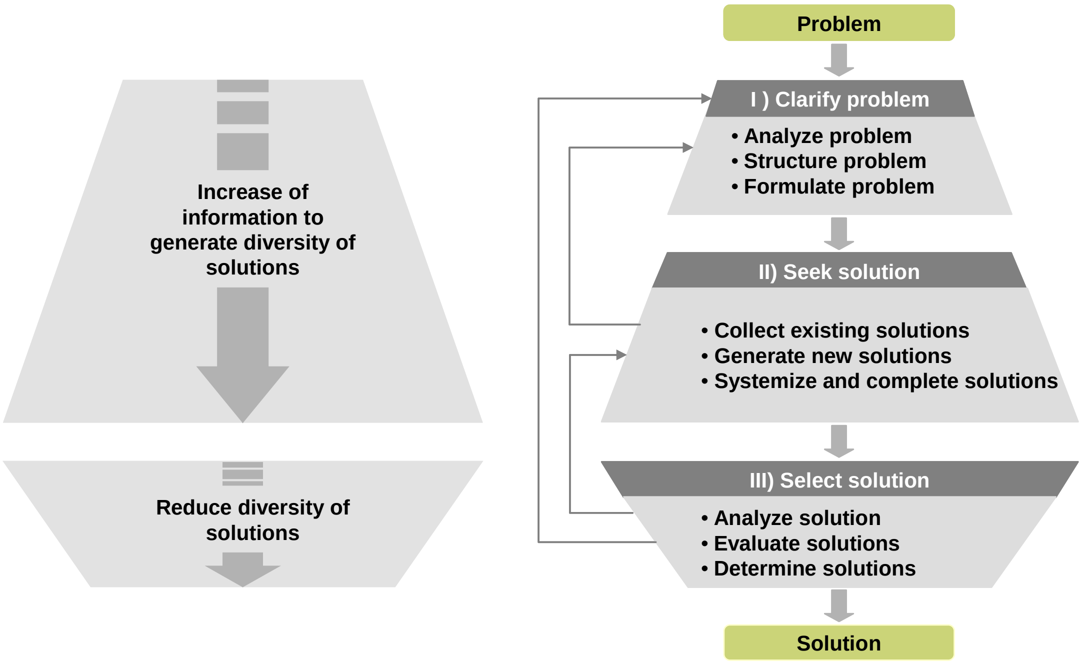


Figure 3-17: Procedure cycle derived from problem solution cycle in systems analysis [EHRLENSPIEL 2007, p. 88]

In the first step, the problem is analyzed, structured and formulated, hence generating a deeper understanding and clarification of the actual problem. Ehrlenspiel assigns highest priority to this step of the cycle as no other process step or phase is more decisive for the success or failure of the product development venture [EHRLENSPIEL 2007, p. 364]. He sees the basic dilemma of the clarification task in the customers' ignorance of the requirements important to the designers and also in the designers' ignorance of the costumers' explicit and implicit demands. Yet, as the requirements are significant for the design and dimensioning of the product, Ehrlenspiel concludes that the above-mentioned information asymmetry and barrier need to be resolved and the customers' requirements have to be integrated in the clarification of the task. If direct customer statements are unavailable, intermediate agents such as traders, retailers or service engineers may serve as sources of information. The clarification of the problem and hence the derivation of requirements is supported by a series of organizational and technical measures which include

- deployment of cross-functional teams and the reduction of communication barriers between departments,
- application of question lists and check-lists,

- interviews with potential customers and users,
- setting of the scope of the product, varying this scope,
- and abstraction of the problem.

By applying this logic to the type of radical innovation described in chapter 1.2, the crucial importance of the clarification task becomes apparent as the problem is typically weakly structured and little references can be drawn to past development projects. At the same time, the customers' real requirements can hardly be met due to the newness of the product to be developed. In some occasions, the actual later user of a product may not even be known yet in these steps of the development process.

During the further problem solving cycle, Ehrlenspiel stresses the importance of thinking in options and the necessity to generate a variety of them. The cycle itself aims at increasing the amount of available information to create a diversity of solutions in the first two phases. In the third one, i.e. the selection of solutions, the number of possible solutions is finally reduced to the chosen one. This procedure supports radical innovation ventures where a chronic lack of information is common in the early phases. The generation of several possible solutions thus also aids to explore an option space that can eventually lead to an optimal solution.

Based on this procedure cycle, Lindemann and Kleedörfer [LINDEMANN, KLEEDÖRFER 1997, p. 118ff] built up an integrated product development system that consists of processes, project management, individuals and organizations, problem solving strategies and methods, cost management, and tools.

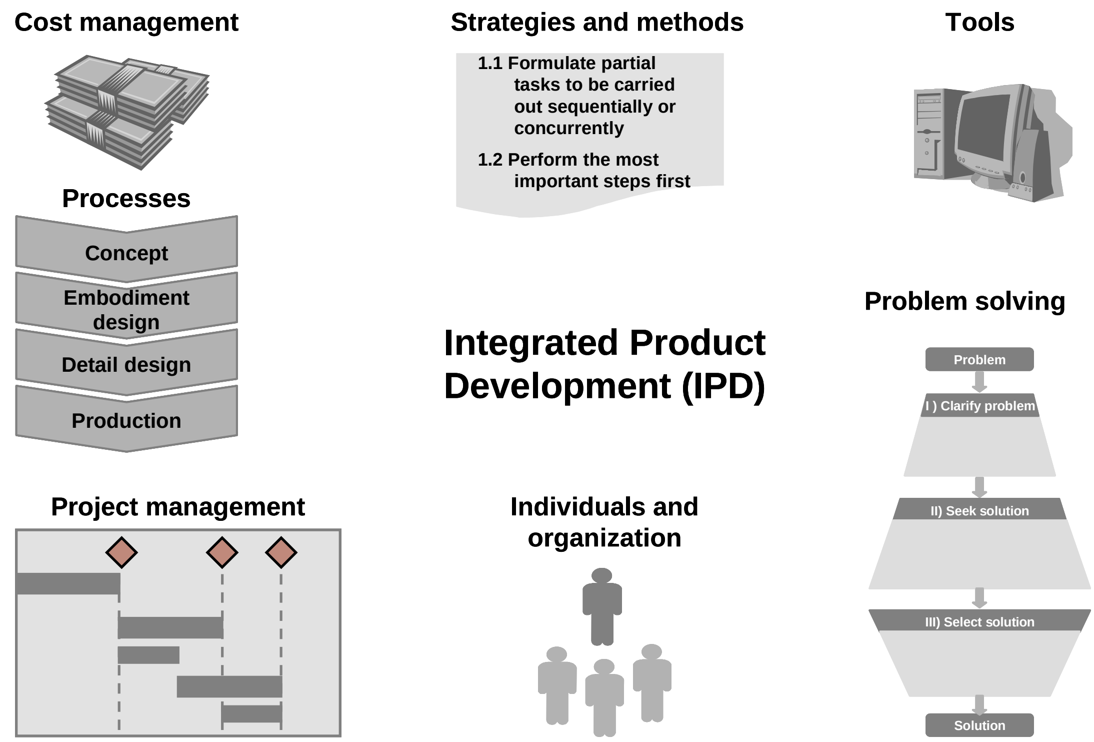


Figure 3-18: Subsystems of Integrated Product Development [LINDEMANN, KLEEDÖRFER 1997, p. 128]

This system underlines the continuous collaboration of various commercial and technical functions of an enterprise during the entire development process. In contrast to classical simultaneous or concurrent engineering approaches, the integrated product development does not only stress the role of functional experts as consultants to the product development process, but also emphasizes their role as experts who take over parts of the development work in a close interplay with all involved parties [DUFFY, ANDREASEN et al. 1999, p. 114; LINDEMANN, BICHLMAIER et al. 1999, p. 31].

According to Bichlmaier [BICHLMAIER 2000, p.118] the implementation of integrated product development requires strong methodological support and specific adoption to company, product and project conditions. In this context the above-mentioned system and its components provide support to product development ventures. Especially radical innovations with a high degree of inherent uncertainty are likely to benefit from tools that are both robust and scalable to specific project requirements.

3.2.5 Munich Procedural Model according to Lindemann

Lindemann [LINDEMANN 2005] proposes the Munich Procedural Model (MPM) which structurally differs from the approaches discussed in the previous sections, as this model does not interpret the development process as a largely linear path from problem to solution with iterations in between. Rather, the development process consists of seven equipollent elements joint via several network connections.(Figure 3-19)

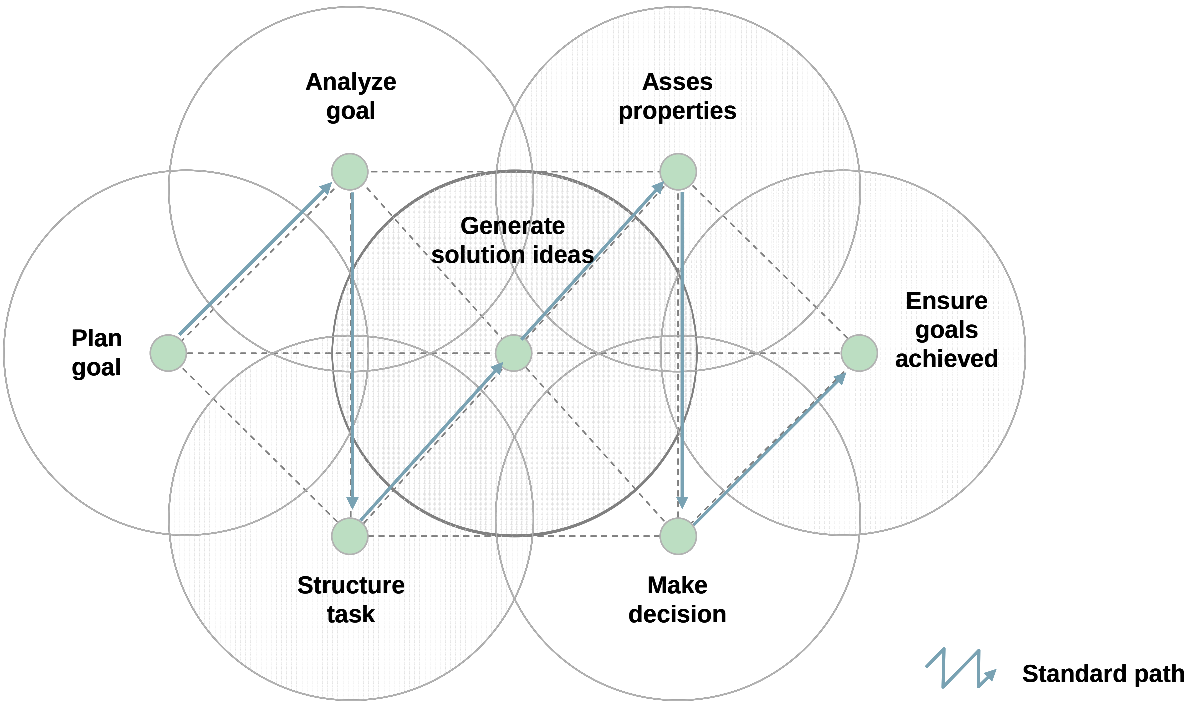


Figure 3-19: Munich Procedural Model (MPM) [LINDEMANN 2005, p.40]

A standard linear path through the network is possible. However, the actual flexibility is shown through non-standard paths allowing jumps between different levels of completion and detail. The MPM aims at supporting planning and direction-setting in the development process as well as providing a basis for a structured analysis and reflection of the proceeding. The following elements with their corresponding tasks are summarized in the MPM:

Plan goal:

- analysis of company situation as well as deduction of specific measures;

- influence of market, customer, competition and other external influences on product development.

Analyze goal:

- formulation of specific and detailed requirements for the new product;
- analysis of interdependencies between various requirements, including goal conflicts.

Structure tasks:

- structuring the system, resolving its subsystems and determining core actions;
- formulating the goal and defining degrees of freedom.

Generate solution ideas:

- search for a solution by applying engineering design methods like TRIZ or morphological boxes;
- aiming at a structured and concise representation of alternative solutions.

Assess properties:

- analysis of available alternatives for their relevant and assessable properties;
- evaluation of single alternatives and combined systems.

Make decisions:

- interpretation of assessment results;
- choice of optimal solution.

Ensure goals achieved:

- reconfirming goals to minimize risks;
- if necessary, initiation of preventive measures.

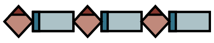
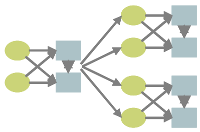
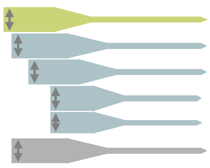
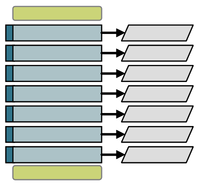
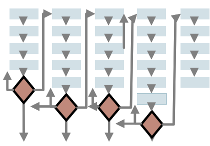
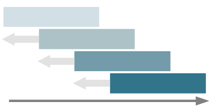
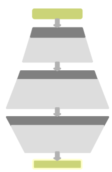
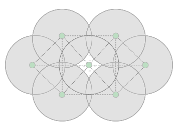
The model does not only support backward and forward iterations along a defined path like the VDI model discussed in section 3.2.1, but it facilities switches between the different levels of abstraction. Thus, an already tackled problem may be revisited and thereby modified and optimized. From the observation of the thought and project progress in radical innovation projects like those discussed in chapter 3.1.2 with the probing and learning approach that had to undergo several breakthrough innovations, this procedure seems to support this type of innovation activities. Furthermore, in contrast to the previously discussed engineering design process models starting with a task and ending with a solution, the network layout of the MPM allows for various entry and exit points. This seems to support the typical tasks in radical innovations where the partial testing and not necessarily the full completion of a development cycle yields valuable information on the feasibility of options on hand. Taken as a whole, the MPM offers a flexible set up that does not only support engineering-driven modification designs, but also provides a structure for the necessary clarification of requirements and successive resolving of uncertainties which is essential to more radical and hence uncertain innovation tasks. At the same time, the flexible set-up of the Munich Procedural Model may challenge users who are looking for firmer guidance throughout the development process. In this context, the MPM requires some experience and comfort in detailing with the adoption of methods and proceeding to the respective company and project background.

4 Formulation of Research Need

4.1 Synthesis of Existing Approaches and Derived Gap

The discussion of existing product development models as well as their ability to support decision-making in uncertainty and hence radical innovation projects at large points out some common characteristics of these models. At the same time, their respective shortcomings in supporting innovation projects under uncertainty become evident and indicate an area for development and research. Figure 4-1 summarizes the discussed models and their respective core ideas, their different approaches to the handling of uncertainty and finally their suitability for the support of radical and uncertain design projects.

A common point of several models is the ambition to picture and execute the design process in a strongly linear fashion. The discussed stage-gate, real options and set-based concurrent engineering the engineering design process according to Pahl and Beitz, the mechanical engineering design process according to Ullman, simultaneous and concurrent engineering, and the integrated product development according to Ehrlenspiel follow this paradigm with varying degrees of strictness. The most stringent purveyor is the stage-gate logic where progress towards the ultimate goal is only possible if all necessary tasks for each phase are completed and their respective results have been evaluated positively. In this sense, stage-gate does only allow movements directly targeted towards the project end, and planning occurs merely in a forward planning mode, i.e. the gate meeting *i* sets the targets for meeting *i+1*. Reverse planning from the goal, which is seen is vital for a successful planning and solution mechanism from a behavioral perspective is not supported by the stage-gate logic [DÖRNER 2007, p. 238f]. All other discussed linear process models deliberately allow for jumps backward and partially even jumps forward, i.e. leapfrogging single steps. With regard to more radical innovation projects, the linearity typical of the discussed process models seems like a major stumbling block. The ambition to handle also more radical and innovative product development processes in a linear mode is understandable. However, from an empirical point of view, especially these types of innovation require jumps not only along one dimension but will also call for jumps to the side

Process Model	Main source	Process illustration	Basic principle	Uncertainty handling	Suitability for radical innovations
Stage-Gate	[COOPER, 1994] [COOPER, 2003]		Linear series of stages (process steps) and gates (decisions)	Discussion within gate meetings	◔ • Rigid linear proceedings • Lack of knowledge prolongs phases
Probe and learn	[LYNN, 1993] [LYNN, MORONE et al., 1996]		Early products 'probed' in test markets, optimized in learning phase	Testing uncertain (market) hypotheses in probing phases	◑ • Supports iterative nature of radical innovations • Little ex ante process support
Real options modeling	[NEWTON, PAXSON et al., 2004] [SOBEK, WARD et al., 1999]		Option space of design sets subsequently narrowed down to optimal solution	Laying out option space with possible variants	◑ • Supports flexible approach • Modeling and derivation of conclusion cumbersome
Engineering design, VDI 2221	[PAHL, BEITZ et al., 2007] [VDI-RICHTLINIE2221, 1993]		Structured subsequent steps in engineering design with respective output	Linear iteration along process (backwards and forwards jumps)	◔ • Little support for handling of uncertainty in development process • Rigidity allowing for little flexibility
Mechanical design process	[ULLMAN, 2003] [AKAO, 2004]		Five phase model with intermediate decision points	Special relevance on early phase to define specifications and generate ideas	◑ • Already advanced understanding of customers and products in early phase required
Simultaneous / concurrent engineering	[SWINK, 1998] [GERWIN, SUSMAN, 1996]		Parallelization of activities during development and industrialization	Dispersion of decision making authority in design	◔ • Little support to early phases • Possible negative impact of risky decisions
Integrated product development [IPE]	[EHRLENSPIEL, 2007] [LINDEMANN,KLEEDÖRFER, 1997]		Three-step process, recurring application of TOTE-principle	Early integration of customers' requirements and thinking in options	◑ • General linear mode • Tools and methods to support radical innovations in context with IPE
Munich procedural model	[LINDEMANN, 2005]		Seven equipollent elements in network setup	Jumps between levels of completion and detail. Analysis and reflection of the proceeding	◕ • Flexible set-up allowing for jumps • Requires skills in navigating through loose network

○ low ◑ middle ● high

Figure 4-1: Overview of design processes and their respective uncertainty handling (for example, testing several realization concepts at the same time) or between different levels of concreteness [EHRLENSPIEL 2007, p. 309].

From the analysis of experiments of individuals and groups that are being confronted with complex and uncertain decision problems, Dörner [DÖRNER 2007, p. 55ff] derives the main sources of failure and suboptimal decisions. He sees linear thinking, unawareness of side-effects and goal conflicts, and pure orientation on tools and methods as key behavioral elements leading to weak decisions and negative results. In this perspective, linear processes applied to complex systems with uncertain variables result in vague connections between actions and effects, which are inclined to lead to suboptimal solutions due to the limitations they put on the information processing and decision process. While linear, process and tool-oriented product development regimes like the stage-gate and concurrent engineering approach have helped to improve the understanding of the new product development process and have generate transparency in an innovation project, they have an adverse effect on radical innovations. The PDMA Foundation that promotes structured proceedings in product development conducted a study on product development procedures and results gathering information from over 400 practitioners in North American companies. Interestingly, the percentage of radical, new-to-the-world innovations in the participants' project portfolios dropped from 20,4% in 1990 to 11,5% in 2004, which corresponds to a 43,7% decline of such ventures [ADAMS, BOIKE 2004, p. 26ff]. Referring to this study, Cooper speaks of "*alarming results*" and states that "*businesses are preoccupied with minor modifications, product tweaks and minor responses to salespeople's requests, while true product development has taken a back seat.*" [COOPER 2005, p. 26].

Cohen and Levinthal [COHEN, LEVINTHAL 1990, p. 129] argue that the ability of a firm not only to recognize external information but also to assimilate and apply it is critical to its innovative capabilities. They label this capability a firm's absorptive capacity and see it as a self-energizing property depending on prior knowledge. Following this logic, a process that supports individual and organizational learning is vital for the innovative capabilities of an organization. Linear processes support learning only on a pre-defined track and, hence, do not utilize the full learning potential.

An exception to this linear proceeding is the probe and learn process [LYNN, MORONE et al. 1996] and the Munich procedural model [LINDEMANN 2005]. In the probe and learn process a predominantly highly innovative technology finds its way to the market through a series of market probes which are reflected in learning phases. This enables the absorption of a rich information set and the embedding of the respective conclusions into the subsequent design activities. From a theoretical viewpoint as well as from the observation of successful radical innovations, such an iterative procedure supports radical innovation projects as these ventures are hardly to plan for upfront but require a certain flexibility along the way.

Lindemann's [LINDEMANN 2005] Munich procedural model builds strongly on the logic of enabling a flexible development process. Its network structure allows for flexible iterations and switches between the levels of embodiment during the design phase. Whereas the probe and learn process seems unstructured in an ex ante view as little guidance is given for the set-up of the design process, the MPM transfers this task to the user. A procedural model should provide several ways to reach a desired goal and support the reflection along the process to ensure that the design team maintains control over their actions. From an analysis of cognitive processing during design processes, Ehrlenspiel [EHRLENSPIEL 2003, p. 39] concludes that for highly innovative projects in particular a stronger utilization of structures and methods is supporting the designers. In contrast to the probe and learn process, the Munich procedural model offers a framework to structure and lay out the development upfront without reducing flexibility, as various paths become possible within the MPM.

A further characteristic of the design processes discussed so far can be observed with regard to the handling of market and technology uncertainties. Typically, a model supports the product development team in their discussion of one of these sources of uncertainties and offers the respective tools and methods. The two sources market and technology are often not integrated although they coexist in the company's environment and are interdependent. Due to the nature of test markets and market probes acting as experiments, the probe and learn model mainly addresses the existing uncertainty on the market side. Other procedure models such as the real options approach, the engineering design process and the VDI 2221 guideline [VDI RICHTLINIE 2221 1993] or the integrated product development according to Ehrlenspiel [EHRLENSPIEL 2007] mainly address the technical uncertainty by defining specifications, designing principle solutions and choosing an optimal one among them. Some models handle market and technology uncertainty subsequently in the process model. Cooper's [COOPER 2001] stage-gate process focuses on economic aspects in the stages zero to two, namely idea generation, scoping and business case building. The stages three to five deal with technical aspects as they cover the actual development, testing and validation, and launching. A similar logic is applied in Ullman's [ULLMAN 2003] engineering design process. The first two basic phases consist of strongly market-driven tasks like market research and analysis of the competition, whereas the last three phases concentrate on the technical aspects of the problem. This procedure implicitly assumes a logical order in a sense that market uncertainty can be resolved before technical uncertainty. Furthermore, the underlying assumption is that market uncertainty and technical uncertainty are largely independent from each other and that the corresponding activities a company chooses to undertake in both areas do not interfere. The discussion of an innovative product development process in the area of retort food processing and packaging machinery in chapter 1.2.1 of this work highlights the multidirectional implications of actions in uncertainty. In general, the aspect of uncertainty that receives the highest attention depends on the original domain from which the process models are stemming; Engineering models tend to focus on technical uncertainties, while the economic ones rather focus on market uncertainties. While this is not surprising, authors from both domains underline the importance of collaboration across all function areas within a company in order to successfully realize innovative ventures [For example, COOPER 1994, p. 59; BOUTELLIER, GASSMANN et al. 2000, p. 29ff; SALOMO, GEMÜNDEN et al. 2003, p. 185f; ULLMAN 2003, p. 118ff ; LINDEMANN 2005, p. 12ff; EHRLENSPIEL 2007, p. 219].[13]

The Munich procedural model is capable of handling market and technology uncertainties due to its flexible set-up allowing for various paths through the network. Elements like goal planning, analysis and structuring of the task rather refer to market aspects, whereas the generation of solution ideas, assessment of properties and decision-making relate more to

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[13] The different perspectives on product development depending on the focus of the relevant domain can even be generalized. After an analysis of the prevailing literature on product development in the disciplines of marketing, organizations, engineering design and operations management, Krishnan and Ulrich [KRISHNAN, ULRICH 2001, p. 3ff] conclude that the typical viewpoints on product development, the associated terminology and focus areas differ significantly.

technical aspects. The final maintenance of achieved goals then again bundles the activities on the market and technical side and reviews their effectiveness in relation to the original goal. However, the flexible maneuvering through the MPM in order to resolve market and technical uncertainties requires a high level of comfort with a flexible process set-up and with jumps between market and technology issues.

4.2 Requirements for Procedural Models Handling Uncertainty in Product Development

The discussion of the prevailing process shows that existing models exhibit key weak points when being applied to radical innovations. Specifically the handling of uncertainties and decision-making as well as action planning is not fully supported. The uncertainty inherent to more radical innovation ventures calls for flexibility in the process setup and the actual proceedings through a development project and for an integration of the market and technology uncertainties.

Veryzer [VERYZER 1998, p. 304f] argues that with most product development efforts focusing on incremental innovations, the research on the new-product development process follows the same directions. From a study of eight discontinuous product development projects Veryzer concludes that half of them use a structured process for conducting a radical innovation project. However, these processes differ significantly from those the same companies apply for incremental innovation tasks. This result empirically supports a finding from the theoretical discussion, namely the limited applicability of most process models to breakthrough innovations.

The general requirements towards processes models supporting product development projects such as general applicability, scalability, and expandability or systems are considered as a prerequisite. Furthermore, the specific challenges of radical innovations and their inherent uncertainty are translated into six specific requirements, of which the first four can be seen as balancing forces between two poles.

First, a procedural model supporting such ventures needs to offer the necessary flexibility for iterations, switches, and jumps in the level of embodiment. Giapoulis [GIAPOULIS 1996, p.

98] classifies iterations, recursions, and feedback loops as result-dependent tasks and stresses their importance for the designers' work. At the same time, the procedural model should create a certain stability and orientation in navigating through the development. It is worthwhile to note that this kind of stability and direction should be perceived by the design team also at the start of the project, i.e. in an ex ante perspective. A completely loosely-structured procedural model offers little guidance as it relies purely on a "trial and error" mode. It would be seen as too weak for guiding a design team through a project. Thus, providing guidance and structure is a second requirement.

Third, the model should enable the development team to acquire and compile information early in the process in order to tackle the perceived uncertainty and to derive options for actions. The more information can be gathered, the higher the chances are to find a realizable solution which is illustrated by all breakthrough innovations that were discussed in section 3.1.2. The possible solution space should be broad in order to increase the knowledge generation on uncertain areas and to improve the chances of finding an optimal solution.

However, especially in radical innovation projects the uncertainty will not entirely diminish. The procedural model should encourage the design teams to take decisions even though the information base may not be complete. This idea is reflected in Ullman's design paradox [ULLMAN 2003, p. 13] that illustrates the challenges faced by designers. As the knowledge of the design problems increases with the progress of a project, the design freedom decreases. (See Figure 4-2)

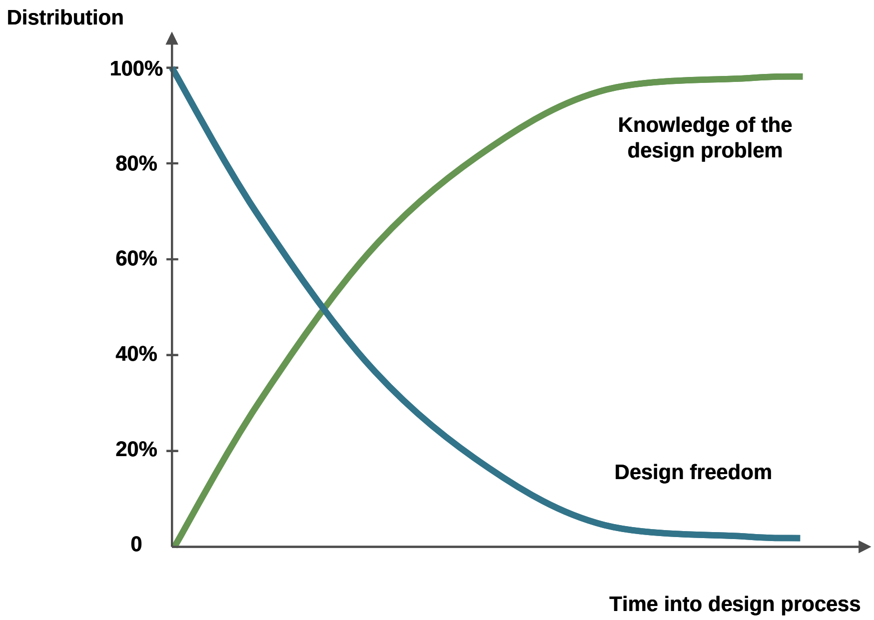

Figure 4-2: The design process paradox [ULLMAN 2003, p. 13]

This logic implies that early decisions have to be taken although individuals and teams would rather refrain from doing so. Hence, as the crucial part takes place in the beginning of the process, the attention and resources allocated on the new product venture need to be front-loaded in order to match the significance of this phase. Thus, a procedural should stipulate decision-making against the background of uncertainty in the front end. This notion is established as a forth requirement acting as a counterweight to the claim of information gathering and option building.

From an organizational standpoint, the model should foster the collaboration of all vital functions in a company. This aspect is regularly stressed in the relevant literature on product development and is generally accepted in academia and industry. Nevertheless, managers from R&D, marketing, and production regularly state that there is an insufficient interplay of the various functions in the product development process [GUPTA, WILEMON 1996, p. 500].

A sixth and final requirement is the backing of the process with tools and methods in order to enhance its stability and traceability. According to Bichlmaier [BICHLMAIER 2000, p.118], the implementation of integrated product development methods requires strong methodological support. Radical innovations with a high degree of perceived uncertainty are likely to benefit from tools providing orientation and guidance. Through established tools and methods the communication and decision-making between different functional units can also be improved as they rely on a solid base.

Figure 4-3 summarizes the requirements for procedural models handling uncertainties in product development and also illustrates the logic of balanced requirements.

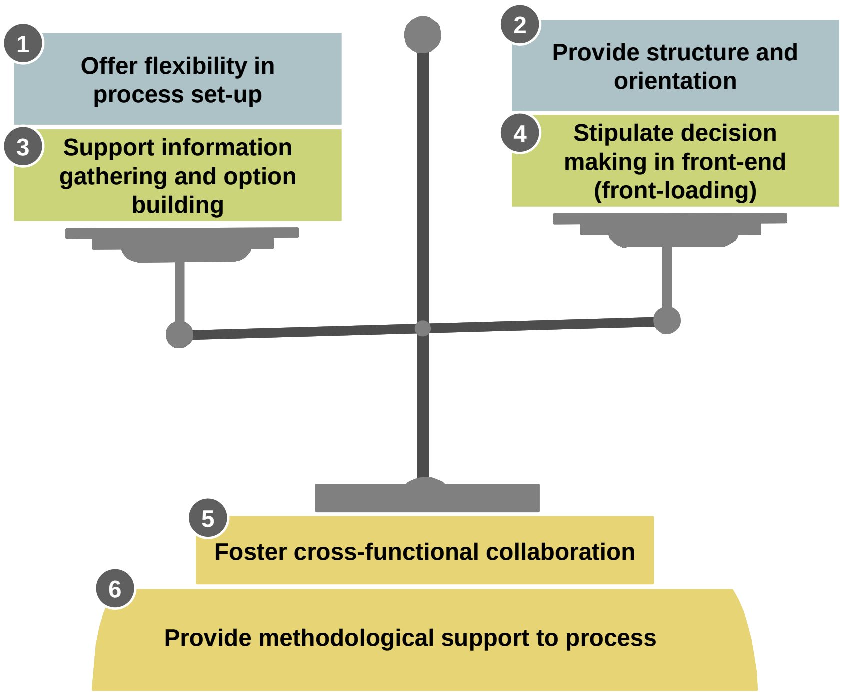

Figure 4-3: Requirements for procedural models handling uncertainties in product development

5 Model for Uncertainty Handling in Integrated Product Development

Following the requirements for procedural models supporting development projects with a high level of inherent uncertainty in chapter 4.2, a corresponding model is developed within the following chapters. The set goal of such a model is the active and holistic handling of uncertainties in the integrated product development process. Chapter 5.1 builds the foundation of the procedural model, which is described in section 5.3 and substantiated with methods and tools in chapter 5.4. Section 5.5 covers the aspects of individuals, teams, and organizations focusing on human behavior under uncertainty and cross-functional collaboration. Finally, section 5.6 reflects on the model and elaborates on its major differences compared to prevailing product development models discussed in chapter 3.

5.1 Founding Principles

5.1.1 Process Orientation

DIN EN ISO 8402 [DIN EN ISO 8402 1995] defines a process as a set of interrelated resources and activities which transform inputs into outputs where resources may include personnel, facilities, equipment, technology and methodology. Procedural models have an impact on the way organizations handle key processes and thus rely on an orientation of processes in a sense that the established ones govern the way organizations work rather than purely hierarchically or opportunistically driven approaches. Products are seen as direct output of processes, which in turn implies that high quality products are driven by the corresponding quality in processes. Following this argumentation, several authors claim that process orientation and stability are key success factors for enterprises [For example BICHLMAIER 2000, p. 34ff; HAMMER, CHAMPY 2003, p. 47ff; BECKER, KAHN 2005, p. 5ff].

Gaitanides et al. [GAITANIDES, SCHOLZ et al. 1994] argue for a radical realignment of enterprises in order to set up flexible, lean, profitable, and efficient processes. They see a consequent orientation at customers' needs as one of the key drivers for process orientation.

For the depiction of models for the product development and design this implies the rationale to focus on design processes that are suitable to describe a range of possible applications. Thus, this approach allows for a generalization from specific design areas to a broader concept. Ullman [ULLMAN 2003, p. 15] illustrates this idea by picturing the design process as a catalyst transforming problems into solutions. In this context, general design process knowledge and domain-specific know-how support this transformation process. (See Figure 5-1)

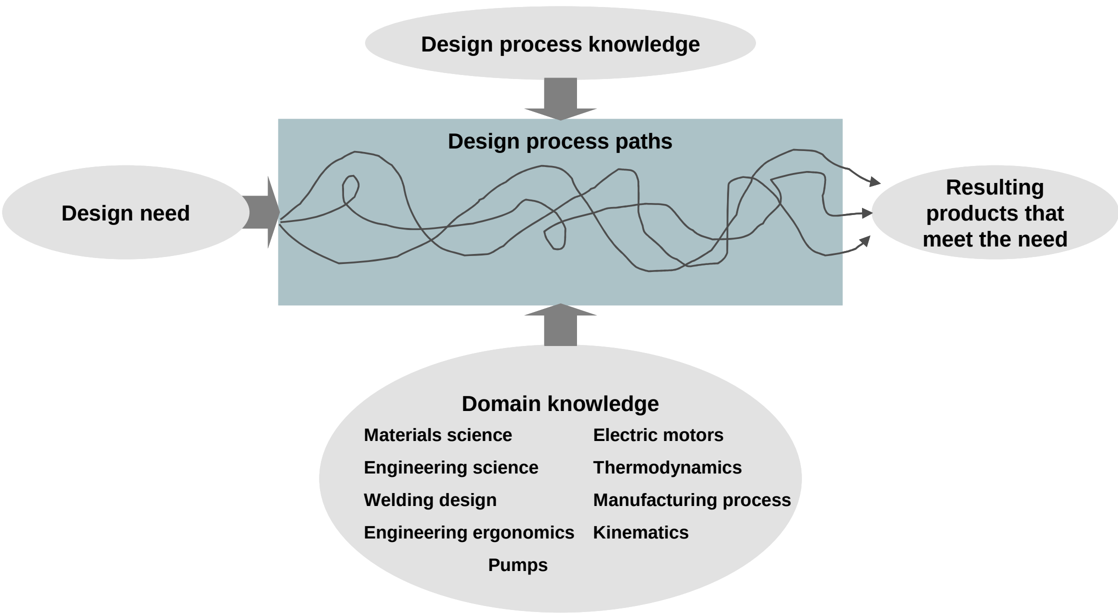

Figure 5-1: Abstract product development process [ULLMAN 2003, p.15]

5.1.2 Front-loading

The early phase is of particular relevance for the design of innovative products. It is characterized by a chronic lack of information and a high level of uncertainty, yet the decisions taken in the early stages have the strongest impact on the final product. Ullman [ULLMAN 2003, p. 13] calls this phenomenon the "*design paradox*" as the design freedom decreases with an increasing knowledge of the problem (See also Figure 4-2). Hence, the early phase gains special relevance for the entire process as decisions are taken during this phase can crucially influence the overall project and its results. According to Meerkamm et al. [MEERKAMM, HEYNEN et al. 1999, p. 103 ff] not enough emphasis can thus be laid on this phase.

Ehrlenspiel et al. argue that in the beginning of the product development work, most notably even before the actual design process starts, a high share of the product properties and costs is fixed. This assigns special importance to this phase even though the direct costs incurred are typically minor in the overall product lifecycle cost [EHRLENSPIEL, KIEWERT et al. 2007, p. 12]. This effect is pointed out by Figure 5-2: The relevance of the early phase is even magnified in projects with a high degree of innovativeness as several direction-setting activities, for example the choice of technology and product positioning, take place here.

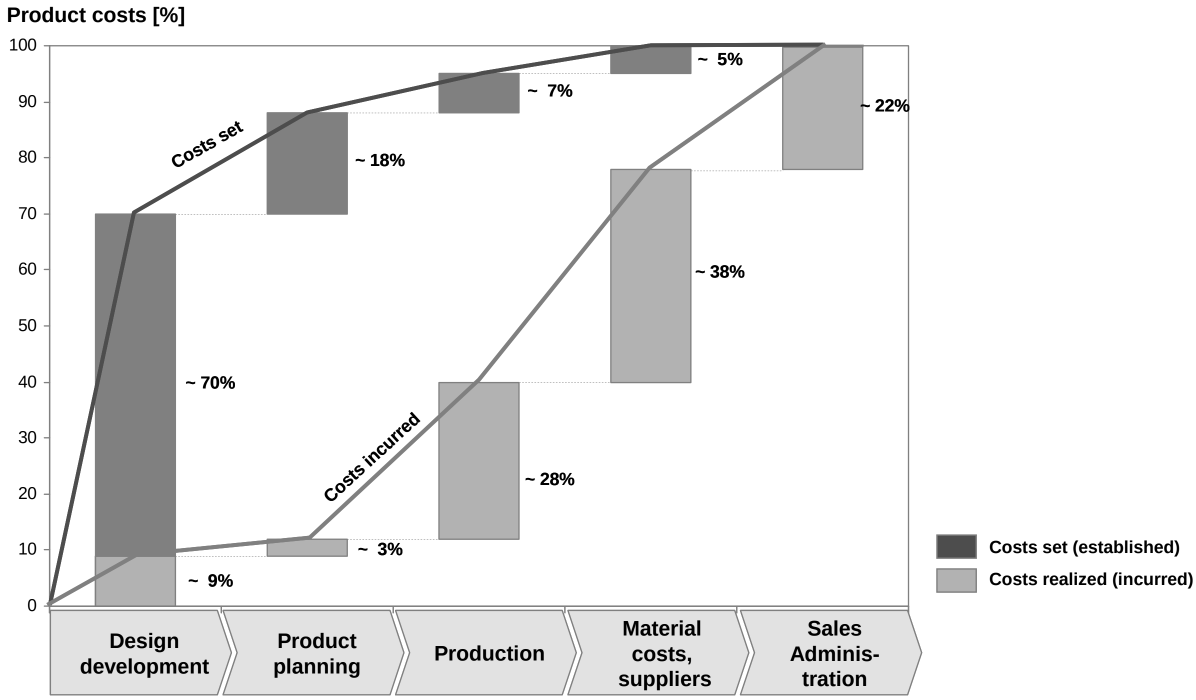

Figure 5-2: Costs sets established and incurred in different departments [EHRLENSPIEL, KIEWERT et al. 2007, p. 12]

Since the 1990s, also the managerial oriented literature has been focusing more on the front end of development activities and the handling of the arising problems herein [For example KHURANA, ROSENTHAL 1997; KHURANA, ROSENTHAL 1998; KIM, WILEMON 2002; KOEN, AJAMIAN et al. 2002; HERSTATT, VERWORN 2003; JETTER 2005]. Herstatt and Verworn [HERSTATT, VERWORN 2003, p. 197] justify this emphasis with the impact the early phases have on the results of the process and the challenges to be tackled in the early phases. They regard uncertainty and "*fuzziness*" of environmental states, internal actions, and their corresponding results as key challenges and thus refer to the term "*fuzzy front end*". This notion of the formative nature is similar to Ullman's design paradox [ULLMAN 2003, p. 13] discussed in section 4.2 in a sense that decisions need to be taken in this state which is largely characterized by information shortage and uncertainty. Figure 5-3 illustrates the gradient of the uncertainty and the resulting challenges in the front end.

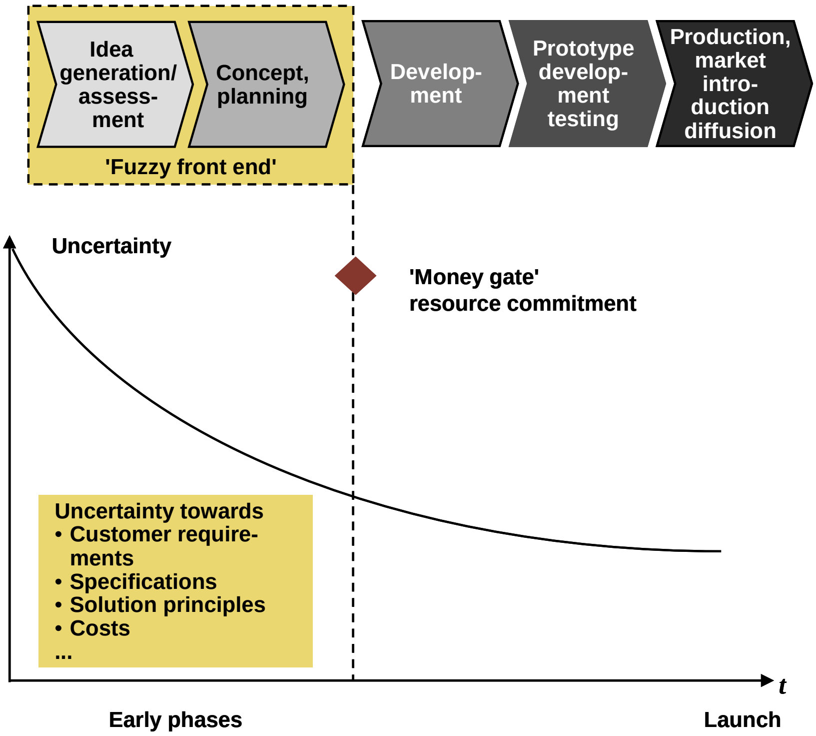

Figure 5-3: Generic innovation process and the "fuzzy front end"

From an empirical point of view there are also several studies showing that the quality of execution in the early phases has a strong impact on the overall project success. Within the NewProd project series, Cooper and Kleinschmidt [COOPER, KLEINSCHMIDT 1994, p. 24] investigate the success factors of 200 new product development projects in 123 firms. They conclude that following the proposition of a unique superior product the quality of pre-development activities is the second most important success factor leading to profitable products. According to their study, 70 percent of the projects characterized by solid work in the early phase were eventually successful, whereas those with little upfront work yielded a success rate of only 30 percent.[14] While possible moderating effects of the innovativeness of the projects are not discussed, the magnitude of the difference shows the importance of the front end.

[14] Cooper and Kleinschmidt [COOPER, KLEINSCHMIDT 1994, p. 24] thus refer to the upfront development activities as "*homework*".

In a further study, Dwyer and Mellor [DWYER, MELLOR 1991, p. 41f] analyze factors of success or failure in a study of 96 product projects in 75 Australian manufacturing firms. Compared to unsuccessful projects, the successful ones show a higher proficiency in the upfront development activities like initial screening, preliminary market and technical assessment, and financial assessment. In a case-based study on the automotive and industrial components industry, Thomke and Fujimoto [THOMKE, FUJIMOTO 2000, p. 140f] analyze the dependence of early problem-solving capabilities and product development performance. They infer that the strategy of shifting the identification and solving of design problems to earlier phases in the process has a beneficial impact on the overall product development performance.

5.1.3 Embedding Options

Thinking in options essentially means the generation of several possible solutions from which an optimal one can be chosen. Most of the procedural models discussed in chapter 3 of this work incorporate the provision of alternatives in one process step. Ullman's mechanical design process [ULLMAN 2003], integrated product development according to Ehrlenspiel [EHRLENSPIEL 2007], and the Munich procedural model [LINDEMANN 2005] explicitly built in process steps supporting the generation of solution options. For the probe and learn process [LYNN 1993] and the real options modeling approach [NEWTON, PAXSON et al. 2004] the generation of options is the key attribute of the procedural model as such. Within the probe and learn framework the path to market entry is generated through a series of probes that can be interpreted as options while set-based concurrent engineering procedures can be regarded as an implementation of a real options approach as an initial set of possible design solutions is subsequently narrowed down to an optimal solution. The embedding of options serves two main purposes:

- Firstly, the solution space is deliberately enlarged in order to seek an optimal solution that might not have been available when following only one initial idea.
- Secondly, through the development of options a solution space is created which strengthens the understanding of the initial problem and independencies within solutions. This idea finds supports in Simon's scholarly piece on the

characteristics of artificial objects and the human behavior in complex systems. He argues that a problem can comprehended within all facets through generation and evaluation of solutions [SIMON 1996, p. 85ff].

Hence, the options generated aid in the overall understanding of the problem and stipulate integrated decision making across the commercial and technical aspects of a problem. They can be classified as real options as they provide alternatives which help the project responsible to take decision in an uncertain environment. As opposed to the real options applications discussed in section 3.1.3 which evaluate this flexibility value, the main focus within this work is to select an optimal combination of market and technology variants of a product. Thus, the aspect of quantifying the value of the options is considered secondary to the aspect of generating options and linking the market and technology perspective through them. This relates to Kester's [KESTER 1984, p. 157ff] argumentation which emphasizes the embedding of flexibility into planning by considering options in the given choices. Thus is does not highlight the actual option value quantification which can be burdensome in corporate environments.

Lindemann [LINDEMANN 2005, p. 58] stresses the need for thinking in alternatives and argues that this approach has proven to be successful in product development. As the actual future cannot be predicted, solution options form the base for the derivation of measures for process and product planning. The importance of the usage of options is reflected in Lindemann’s and Maurer’s [LINDEMANN, MAURER 2006, p. 45ff] approach to the development and product structure planning of individualized products. In this context, the product structure is set up to allow for options of individualization of certain elements while other areas are free, scalable, or fixed. Optional elements and free spaces can be seen as real options where decisions on certain elements of the product are deferred or altered. Figure 5-4 presents this model of a product structure.

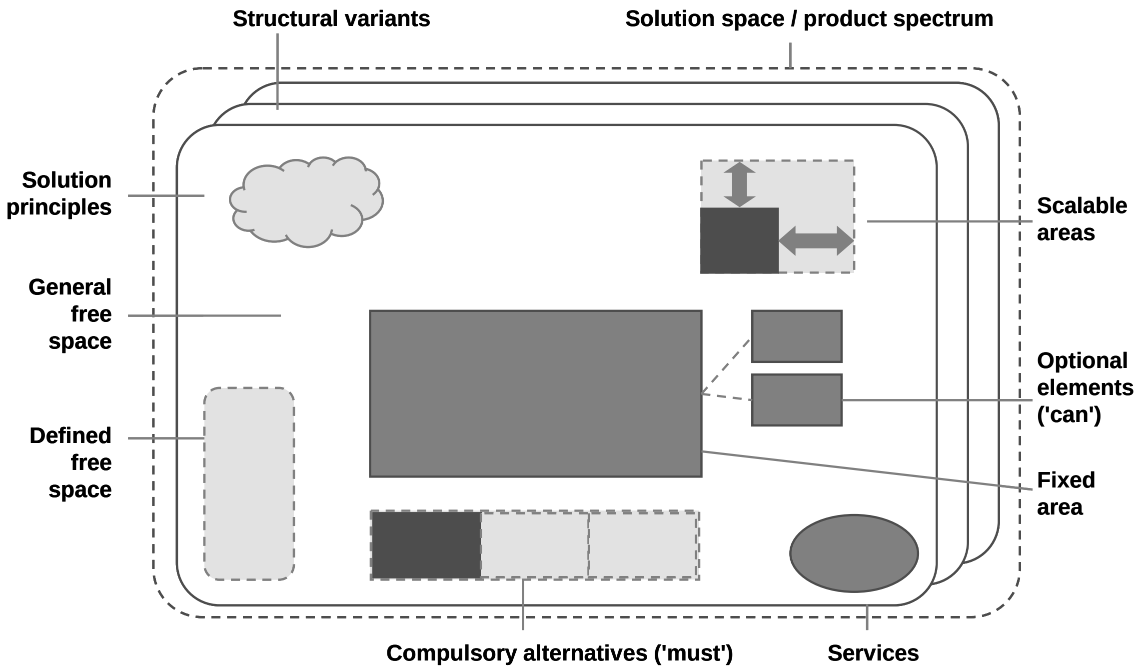

Figure 5-4: Model of the product structure with different degrees of individualization [LINDEMANN, MAURER 2006, p. 46]

In a broader perspective, options can also be regarded as an output of scenario modeling. Gausemeier [GAUSEMEIER 2003, p. 532] emphasizes the need of modeling the future environment in the starting phase of product planning. As the future cannot be forecasted completely, it is described with the help of scenarios created from the analysis of influencing factors and their interrelation. The resulting scenarios can then lead to solution options in the above-mentioned sense. Hence, the option building within the scenario management technique supports the idea of getting more information and describing solutions in an uncertain environment.

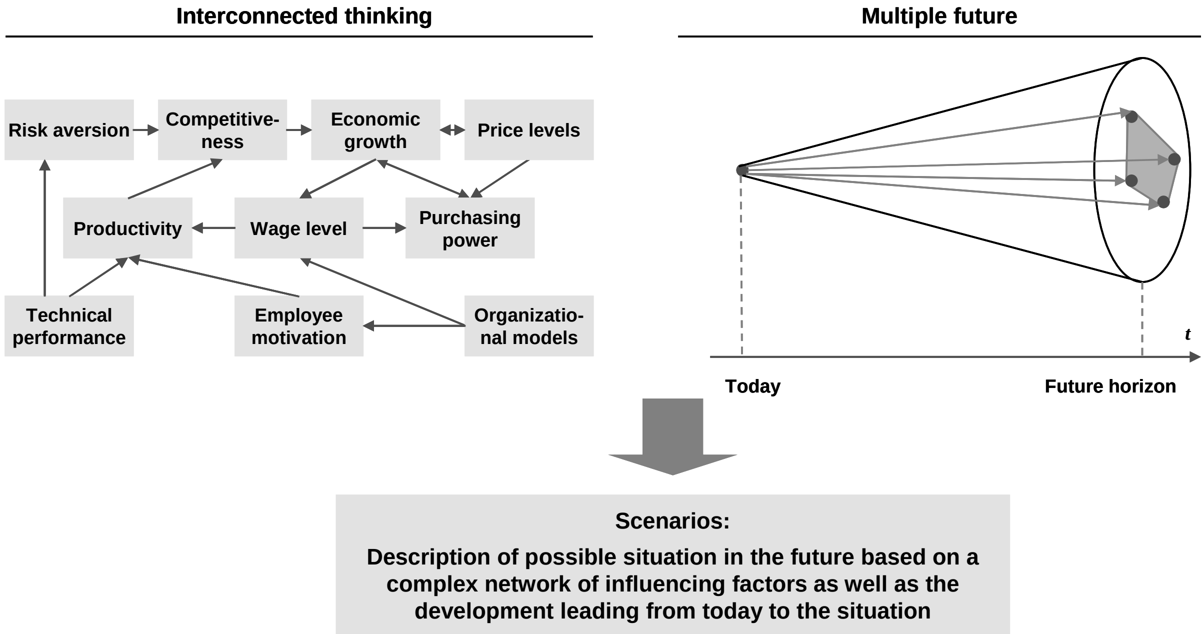

Figure 5-5: Basic principles of scenario techniques [GAUSEMEIER, LINDEMANN et al. 2000, p.139]

From a more psychological perspective Dörner [DÖRNER 2007, p.80f] argues that thinking in intermediate targets can be of advantage when the ultimate purpose and means of being successful in the handling of a certain problem are not clear. A very rigid focus on one goal is likely to have a negative influence the flexibility in a project. In order not to act erratically, intermediate goals can be set to reach a state with a high level of "*efficiency-divergence*". Such a state is characterized by enabling several possible operations ("*divergence*") with a high probability of success ("*efficiency*"). In this sense, the deployment of options can put development teams into a position where they have a greater overview and range of possible measures than in the initial starting situation where the perceived uncertainty and lack of viable alternatives is the strongest.[15] It is thus highly relevant to radical product innovations where the described conditions are highly applicable of the early phase.

5.1.4 Interdisciplinary Work Mode

An integrative and interdisciplinary work mode between all technical functions (e.g. mechanical and electrical engineering) and between the technical and commercial function is a prerequisite for successful radical innovations consisting of a commercial and a technical part as discussed in chapter 2.3. However, today's process organizations are often characterized by a division of labor and a strongly functional specialization that constitutes a structural obstacle for a holistic commercial and technical approach in product development. Ehrlenspiel [EHRLENSPIEL 2007, p. 161ff] explains this division of labor with the increasing complexity in product development which again is driven by the complexity of the respective products and the increasing throughput in development and production. Organizations react with specialization and a division of work along working steps resulting in strongly sequential or parallel procedure in the operations. As a consequence, documents and strict process models are implemented to enable the information flow and coordination between specialized departments. Ehrlenspiel argues that such strict process models yield a certain process orientation but are of little help in solving the problems design teams face. The effects on the working mode of the individuals and groups are often barriers between departments and create local optima: Individuals lose sight of the overall product and the development goal while optimizing and detailing processes and solutions only within the department boarders.

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15 While the generation of intermediate goals is generally beneficial to complex problems under uncertainty, one has to be careful not to degenerate intermediate goals to absolute ones by concentrating the energy to these intermediate goals and thereby to lose sight of the original goal [DÖRNER 2007, p. 96].

Several authors such as Andreasen, Hein [ANDREASEN, HEIN 1987] and Ehrlenspiel [EHRLENSPIEL 2007, p. 188] see integrated product development an effective strategy to overcome these problems associated with the division of labor in the product development process.

In an approach to enhance product structuring in the early phases, Sekolec, Kunz et al. [SEKOLEC, KUNZ et al. 2003] propose a procedure to integrate the market and technical view in designing modular product structures. In a market view the product family is described along its characteristics and parameter values as an initial step. Then, the technical view is reflected in the module structure of the product. Finally, in a deciding step market and technical aspects are combined by a matrix reflecting internal and external views. These process steps represent a key element of the procedure as decisions concerning standardization and re-use of components take place.

Within the concept of front-loading Thomke and Fujimoto [THOMKE, FUJIMOTO 2000, p. 130] point out the importance of early integration and cross functional decision-making in R&D, marketing and production.

5.2 Model Overview

Smith and Morrow [SMITH, MORROW 1999, p. 238f] point out that for a product development process model to have useful predictive value it must satisfy four key technical criteria: It needs to address an important managerial issue, the decision-making should be based on available and accurate information, the assumptions and simplifications of the model must be reasonable and finally the model has to be computationally tractable. Yet, even if a model fulfills all the above-mentioned criteria, it still might not be applicable in industrial practice for several reasons [SMITH, MORROW 1999, p. 260]: Assumptions and simplifications may not meet industrial practice or the required information may not be available at a specific point of time.

The model for structured handling of uncertainties in integrated product development dealt with in this work comprises three main components that address the above-mentioned criteria as well as some concerns towards applicability, namely:

- Process model and procedural logic: The procedural logic describes the development process, displaying the relevant tasks, decisions, relations and iterations in the procedures from idea to market launch. While the procedural model needs to yield some flexibility to account for unpredictable changes that might occur in innovative projects, it should also give guidelines and orientation to the development. Furthermore, a structured development process can relieve a part of the management's anxiety regarding a perceived ambiguity in development projects;
- Methods and tools: The development process is supported by methods stemming from the literature and practice of integrated product development [For example ULLMAN 2003; GAUSEMEIER, LINDEMANN et al. 2004; LINDEMANN 2005; EHRLENSPIEL 2007] as well as tools and methods specifically developed in order to enhance problem solving in radical innovation projects.
- Individuals, teams, and organizations: Individuals represent the most important element in an integrated development process. Bernard [BERNARD 1999, p. 84] calls them the engine and driver of the product development teams. Especially in the case of radical innovations with embedded uncertainties in several functional areas (e.g. market, product, operations) it is vital for a procedural model to enable the collaboration of individuals, teams and functions.

Figure 5-6 illustrates the three building blocks for this approach.

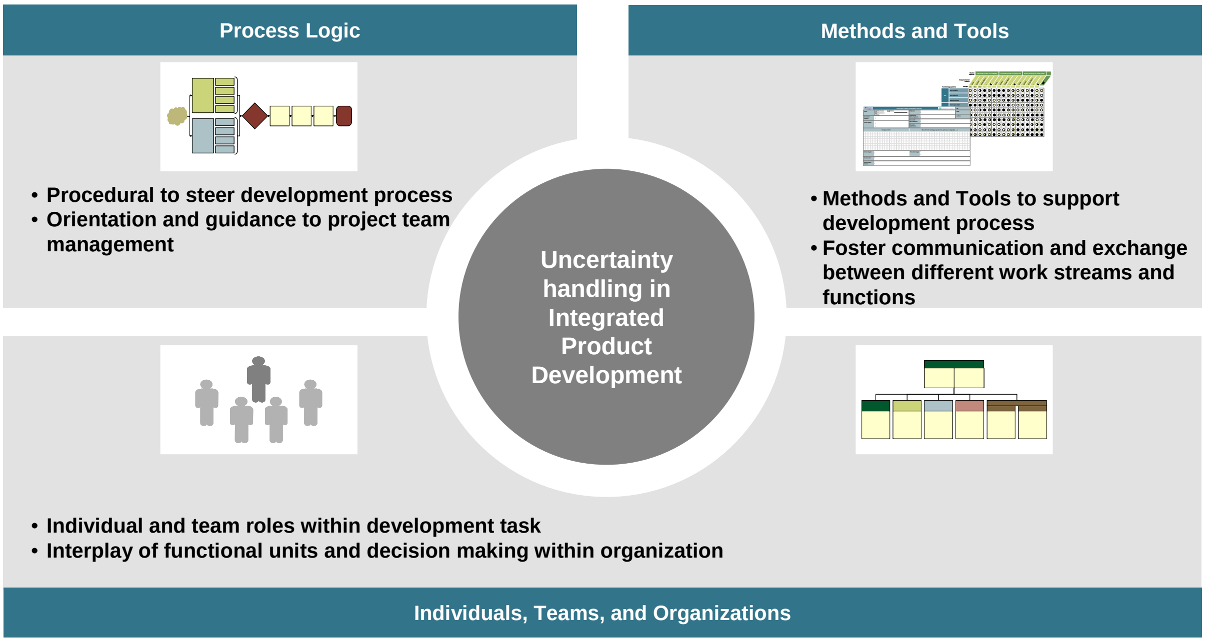

Figure 5-6: Key components for uncertainty handling in integrated product development

5.3 Process Logic

Several authors stress on the importance of depicting the product development process [GIAPOULIS 1996, p. 16f; SMITH, MORROW 1999; ULLMAN 2003, p. 67f; LINDEMANN 2005; EHRLENSPIEL 2007, p. 169f]. Bichlmaier [BICHLMAIER 2000, p. 68f], for instance, argues that process models should support the design with regard to five key aspects: exchanging or creating intermediate results across functional areas, planning and documentation of the development process, transparency of the process, prioritization within the process, and flexibility in implementing the process.

For the modeling of structured uncertainty handling in integrated product development, the early phase gains special relevance as the highest level of perceived uncertainty is experienced here and the most direction-setting decisions are taken. Three specific objectives are pursued during this phase:

- Exploring the main fields of uncertainty by generating options on the market and technology side,
- synchronizing activities on the market and technical side,
- taking integrated decisions.

One important joint result of these objectives is to deliberately shift activities both on the market and technical side to the front end. In the integrated model, fields of uncertainty are defined and subsequently explored by options. Following a structured idea generation phase, possible market approaches and technical solutions are drafted as options in the front end. A key element of the procedural model is the evaluation and decision step during which options from the technical and market side are integrated, evaluated, and finally decided on. It is noteworthy that options need to be considered from commercial and technical perspectives and their implications and interdependencies should be discussed holistically. Following the expanded and multi-option based front end, the development project is funneled down to a single-option process by means of the evaluation and decision step. Hence, the detailed design, prototyping and 0-series ramp-up aim at the solution chosen in the evaluation/decision step. Possibilities for deliberate backward jumps are provided, where the major jump is expected to occur after the evaluation and decision step when the generated solution proves to be unsuitable for the problem. Such jumps are also feasible at later stages in development and testing, yet the intention is to filter out such issues in the evaluation and decision step. The corresponding overall process logic is illustrated in Figure 5-7.

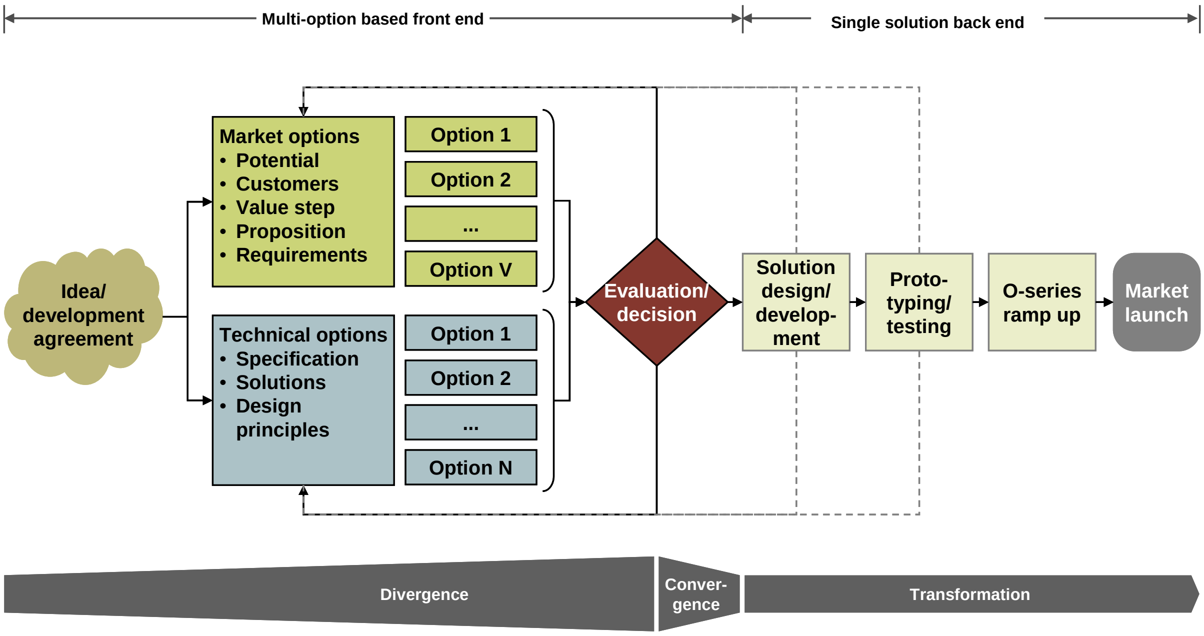

Figure 5-7: Process design for integrated uncertainty handling

The proceedings as an overall process resemble those proposed by Finger and Dixon which follows a divergence, transformation, and convergence logic [FINGER, DIXON 1989b, p. 56]. In the divergence stadium the design boundaries are expanded, whereas in the transformation stadium they are bounded and structured. In the convergence stage decisions are taken in order to lead the design towards a singular solution that is pursued further. These three steps correspond to the option generation, decision-making and subsequent development phases in the discussed model. Tasks and decisions in each stage follow this overall guiding logic and indicate specific steps towards the goal of recognizing and exploring the option space in the early phases and enabling a more stringent development approach in the later phases.

5.3.1 Front End: Idea Phase and Development Agreement

The initial idea stage is particularly significant with respect to the discussed model for uncertainty handling in product development, since it leads to a development agreement describing project goals, resources and the main areas of uncertainty that should be investigated through options.

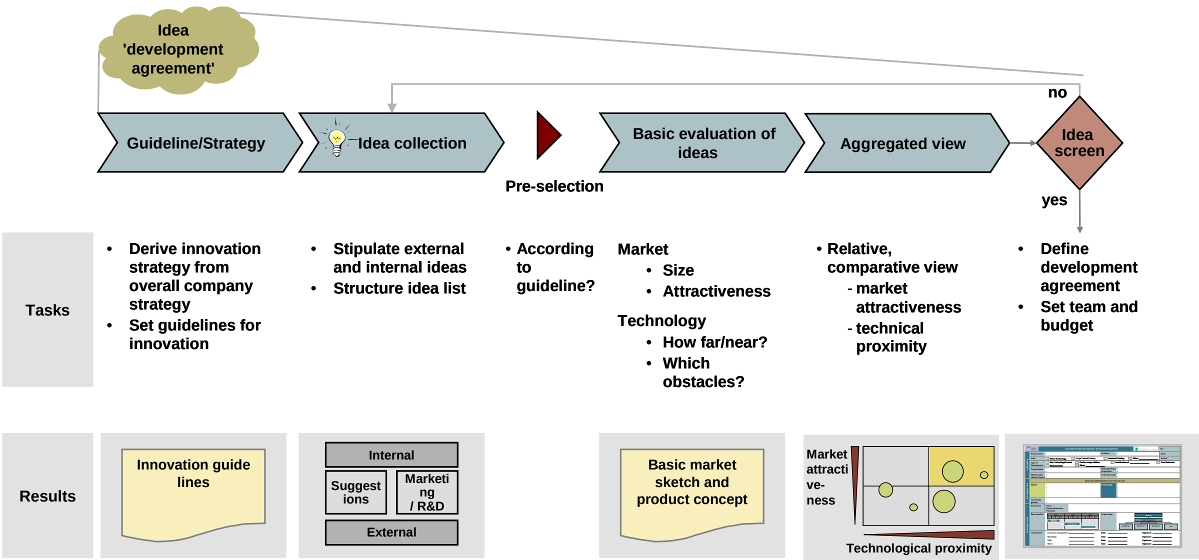

Figure 5-8: Idea stage and development agreement

Initially, the innovation strategy and guidelines for new product ideas are derived from the overall company strategy, and ideas are collected from internal and external sources. Internal sources may comprise R&D and marketing departments, but it is often especially beneficial to activate the idea pool of a whole company by utilizing a structured suggestion scheme. At this point a range of proven tools and methods like brainstorming, brainwriting, morphologic boxes or Delphi analyses [LINDEMANN 2005, p. 217ff] can come into play in order to enrich the idea set. Outside ideas are typically influenced by the observation of competitors' offerings, announcements and the interaction with clients at various levels, for example management, sales or service. Schwankl [SCHWANKL 2002, p. 100f] presents an approach for structuring and storing ideas in an idea pool that can be integrated into the procedural model at this point. Following the idea generation step, ideas are being pre-selected along their compliance with the innovation guidelines and are briefly evaluated along the two main dimensions market attractiveness and technical feasibility. In this context, two main questions are concerned in particular:

- How attractive is the market that is addressed by this idea? A first broad answer to this question will comprise an estimate of the addressable market as well as a differentiation and margin potential.
- How feasible is the realization of the product idea for the company? Technical obstacles as well as the company's prior know-how in the technical field that are being affected by the product idea will represent the input factors to this question.

The results from this broad initial assessment can be represented in a matrix illustration where one axis stands for the market attractiveness and the second for the technical proximity of the idea. Gausemeier, Lindemann et al. [GAUSEMEIER, LINDEMANN et al. 2004, p. 102ff] present similar portfolio-based methods displaying the characteristic trade-off for each idea and assisting in its comparative evaluation. Finally, a certain number of ideas is selected for the development of a corresponding product. At this point, typical procedural models stemming from the engineering background emphasize the importance of having a complete list of specifications at the beginning of the development project [EVERSHEIM, BOCHTLER et al. 1995, p. 21ff; VDI/VDE RICHTLINIE 3694 2005]. From the analysis of setting specifications in interdisciplinary development projects, Jung [JUNG 2006, p.17ff] states that the ambition to set firm specifications in such development environments can cause severe errors as necessary requirements may be neglected, inappropriately formulated or defined, whereas on the other hand unnecessary requirements may be considered as important. Jung hence proposes the implementation of an accompanying and iterative requirements analysis and specification setting throughout the overall development process [JUNG 2006, p. 81ff].[16] Similarly, it has been argued in the sections 3.2.2 and 4.1 that radical innovations also

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[16] Jung's model of iterative clarification of requirements is based on relations between elements of the system that can be modeled and structured in a database supporting the development process [JUNG 2006].

demand for a more flexible approach in setting requirements and specifications. In the early phases where typical engineering procedural models demand the setting of requirements in order to lend direction and clarity to the development project, the level of uncertainty is most elevated. Here, ambiguity on the product’s target properties, its customers and markets is highest, making it hardly possible to define useful requirements in the early phases of such projects. In contrast, the model for uncertainty handling explicitly points out areas of uncertainties and defines these "white spots" as development needs. Hence, three core parameters are set for the development project as an output of the ideation phase:

- The overall project goal is defined which consists of the target market, including a scoping of relevant applications and technologies.
- Human and financial resources are assigned to the project and responsible leaders for the overall project as well as the commercial and technical parts of it are put in charge.
- Finally, open issues are defined and development needs are named, i.e. areas where the current know-how or existent solutions are insufficient. Moreover, among the list of open issues, those for which it is already clear that several options will be required to explore the uncertainty space can be "earmarked".

Figure 5-9 illustrates the components of the development agreement and the proceedings to derive these parameters.

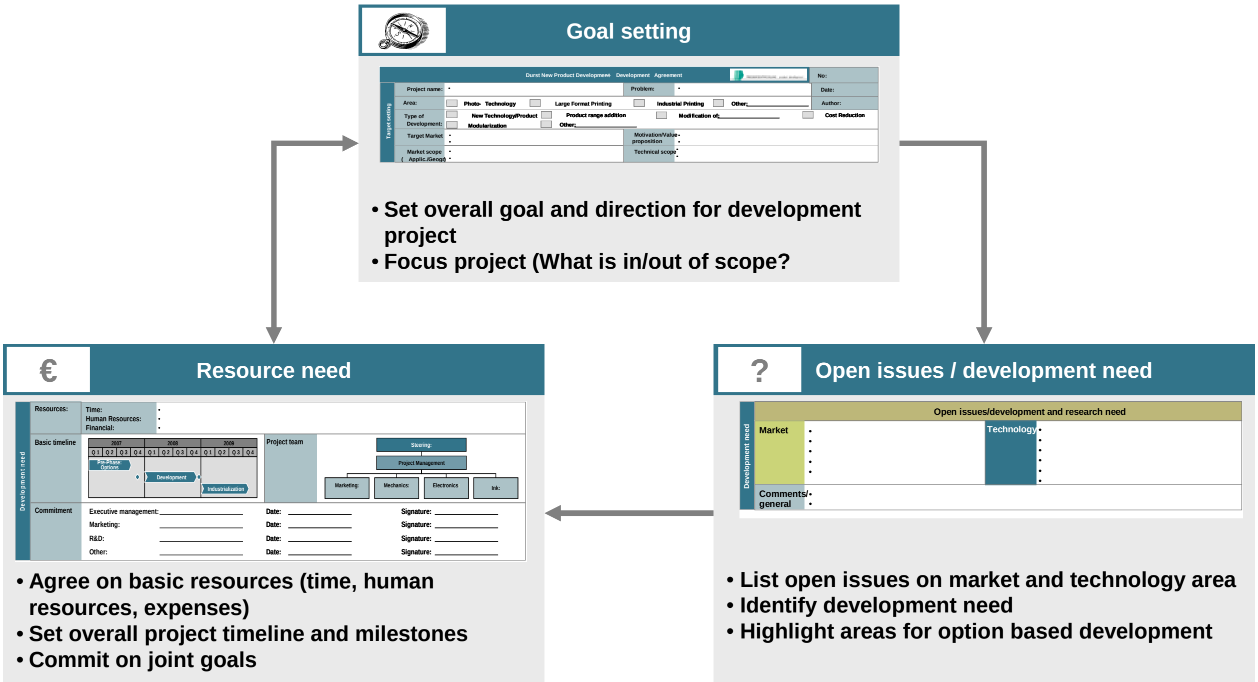

Figure 5-9: Key elements of development agreement

5.3.2 Front End: Option Generation and Assessment Phase

The requirements for explicitly handling implied uncertainties on the market and technology side in order to ensure a synchronistic procedure in both areas govern the set-up of the options generation and assessment phase. Based on the development agreement discussed in section 5.3.1, a structured options generation and an analysis are conducted in this phase. Driven by the different nature of tasks, the proceedings on the market and technology side show a differing content. Nevertheless, the process logic enables the synchronous handling of both work streams and the integration of intermediate results.

As pointed out in the previous section, the technically oriented work stream focuses on the technical option development. Initially, a set of open issues and questions is compiled, from which some areas of further investigation are derived. The key step is then the generation of options for each technical area under investigation. From the perspective of uncertainty handling it is essential to create heterogeneous solution principles for each area. As options are a suitable means to explore an uncertain space and acquire knowledge, this proceeding promotes the implied exploration aspect. The proceedings in the options generation step resemble the logic of a morphological matrix, where for each sub-function displayed in rows different solutions are mapped in columns [PAHL, BEITZ et al. 2007, p. 184]. Apart from supporting option and solution finding tasks, this procedure also adds to the understanding of the initial problem as well as the documentation and knowledge accumulation in the project and in the development department overall [LINDEMANN 2005, p. 251]. Figure 5-10 depicts the proceedings and tasks in the options generations and assessment phase.

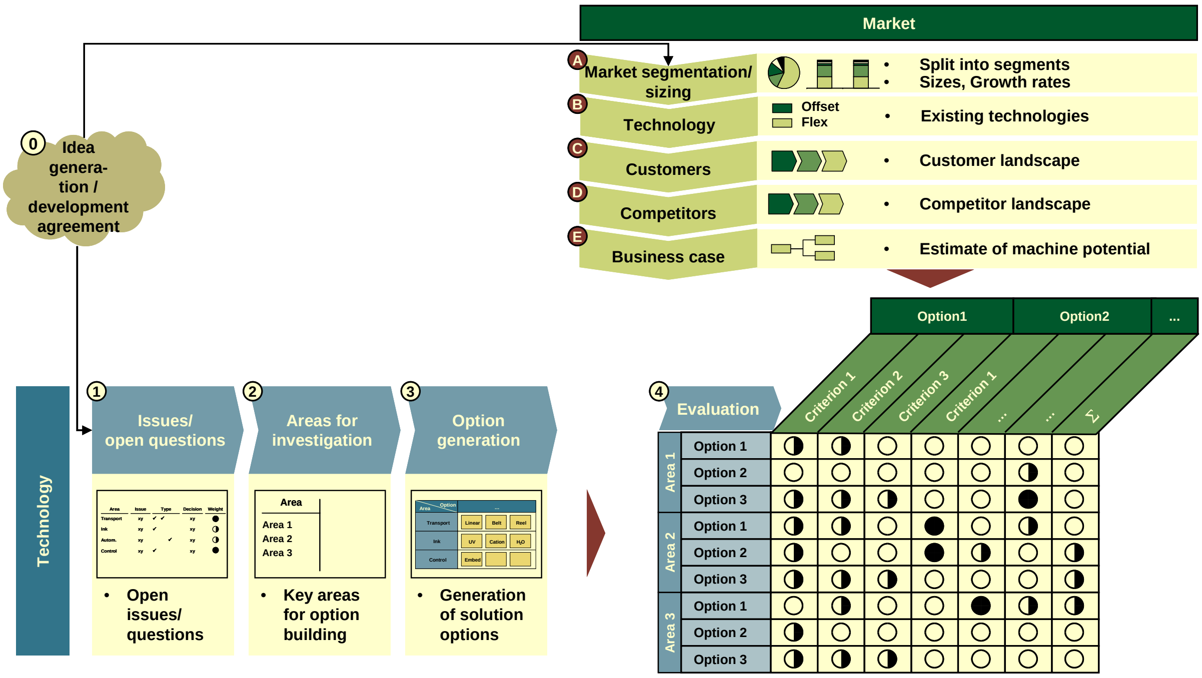

Figure 5-10: Option generation and assessment phase

On the market side two essential tasks with regard to the proceeding of the development project take place: First, through a segmentation of the market that is addressed by the initial product idea, options on market segments are defined. On industrial as well as on consumer markets, different segments of a market often show strongly divergent characteristics. Targeting a very broad market can thus result in very broad specifications and hence costly and costumer-unspecific products. In the marketing literature, a clear market segmentation is seen as a prerequisite for the effective positioning of a product [KOTLER 2000, p. 256ff]. The second objective of the market analysis phase is to derive market-based requirements and specifications. These requirements then serve as criteria for the evaluation of technical options. Due to the dual results of the market-oriented work stream, the proceeding consists of five steps answering one key question each:

- Market segmentation: Which are the main segments in the target market and how do they differ from each other in terms of size, growth and characteristics?
- Technology: What is the prevailing technology on the market and which are its segments that the new product has to compete with?
- Customers: Which type of customers can be found in the target market and what are their main requirements?
- Competitors: Which competitors will the product face and what are the differentiating factors between them?
- Business case: What is the economic outlook of the project considering volume, pricing and cost insights gained in the previous analyses?

These key questions on the market side will typicall require some form of secondary research on the target markets, modeling and analyses as well as partially primary research with potential market participants. Like in the technical work stream, most questions will most likely not receive final and fully confident answers. However, investigations of these areas as well as the analysis of results and joint discussions add considerably to the exploration of an uncertain space and the generation of valuable direction-setting in the development project.

As a final step of the options generations and assessment phase the results of the technical and commercial work streams are integrated into a matrix. The areas or functions of the product including the analyzed options form the rows, whereas market options along with key requirements form the columns. Within the resulting market and technology matrix an integrated view on all options and an evaluation can take place. For each function and option, the fulfillment of criteria in each market option is assessed and expressed in an ordinal scaling system. Representing its fit with the market, requirements can be derived. This score then forms an analytical base for the selection of options.

By definition ordinal scales describe relations of equivalence and order that can typically be found when classifying the hardness of minerals or ranks in a hierarchical organization [STEVENS 1964, p. 679]. As opposed to interval or ratio scales measuring temperatures or velocities, ordinal scales formally only allow monotonic transformation. Being strict, ordinal variables are not suited for additions or the building of means as the original data contain information on classes and ranks but not on the distance between these classes. Nevertheless, additions, multiplications and the building of averages are common in management. Stevens [STEVENS 1964, p. 679] states that "*On the other hand, for this 'illegal' statisticizing there can be invoked a kind of pragmatic sanction: In numerous instances it leads to fruitful results. While the outlawing of this procedure would probably serve no good purpose, it is proper to point out that means and standard deviations computed on an ordinal scale are in error to the extent that the successive intervals on the scale are unequal in size.*"

In the case of ordinal scores which are drawn from a normally distributed population, the manipulating effect of additions and means is limited [SIEGEL 1957, p. 14]. When assigning scores to technical and market options, a structural bias should thus be avoided. Having the formal limitations of mathematical operations on ordinal scales and of their conclusions in mind, one can nevertheless gain a valuable input for a decision problem under uncertainty:

Applying a formal description from linear algebra, the scoring logic can be expressed in matrix operations: Let $T_i,\ i = 1,2,...,N$ be the function *i* of the product, and let $T_{ij},\ i = 1,2,...,N, j = 1,2,...,K$ be the option *j* for the function *i*. In order to enhance the model’s lucidity, the number of options per function is uniformly limited by *K*. *K* can be a set as the maximum number of options occurring in a function. In case that one function has less then *K* options, the remaining options are left empty. On the market side, there are *V* market options, denoted with $M_p,\ p = 1,2,...,V$. The market requirements derived are denoted by $c_q,\ q = 1,2,...,L$. Using these definitions, the scoring logic indicating the fulfillments for market requirements can be expressed as a function *f* assigning a score $s_{ij,pq}$ to indicate the fit of the technical option T_{ij} the criteria c_q in the market option M_p:

$$f:\ (T_{ij}, M_p, c_q) \rightarrow f(T_{ij}, M_p, c_q), \tag{5.1}$$

where $$f(T_{ij}, M_p, c_q) = \begin{cases} s_{ij,pq}, & \text{if function } i \text{ has an option } j \\ 0, & \text{otherwise} \end{cases}, \quad s_{ij,pq} \in \{1,2,3,4\} \tag{5.2}$$

The scores 1 to 4 can be understood as low, middle, high and full compliance of the technical options with the market requirements. The resulting matrix, assigning a score to every function and option and indicating the fit to the market requirements set up in the market options phase is illustrated in (5.3):

$$
\begin{array}{cc|ccccc:ccccc:c:ccccc|}
 & & & & M_1 & & & & & M_2 & & & \cdots & & & M_V & & \\
 & & c_1 & c_2 & c_3 & \cdots & c_L & c_1 & c_2 & c_3 & \cdots & c_L & & c_1 & c_2 & c_3 & \cdots & c_L \\
 & T_{11} & s_{11,11} & s_{11,12} & s_{11,13} & \cdots & s_{11,1L} & s_{11,21} & s_{11,22} & s_{11,23} & \cdots & s_{11,2L} & \cdots & s_{11,V1} & s_{11,V2} & s_{11,V3} & \cdots & s_{11,VL} \\
 & T_{12} & s_{12,11} & s_{12,12} & s_{12,13} & \cdots & s_{12,1L} & s_{12,21} & s_{12,22} & s_{12,23} & \cdots & s_{12,2L} & & s_{12,V1} & s_{12,V2} & s_{12,V3} & & s_{12,VL} \\
T_1 & T_{13} & s_{13,11} & s_{13,12} & s_{13,13} & \cdots & s_{13,1L} & s_{13,21} & s_{13,22} & s_{13,23} & \cdots & s_{13,2L} & & s_{13,V1} & s_{13,V2} & s_{13,V3} & & s_{13,VL} \\
 & \vdots & \vdots & & & & \vdots & \vdots & & & & \vdots & & \vdots & & & & \vdots \\
 & T_{1K} & s_{1K,11} & s_{1K,12} & s_{1K,13} & \cdots & s_{1K,1L} & s_{1K,21} & s_{1K,22} & s_{1K,23} & \cdots & s_{1K,2L} & & s_{1K,V1} & s_{1K,V2} & s_{1K,V3} & \cdots & s_{1K,VL} \\ \hdashline
 & T_{21} & s_{21,11} & s_{21,12} & \cdots & & s_{21,1L} & s_{21,21} & s_{21,22} & \cdots & & s_{21,2L} & & s_{21,V1} & s_{21,V2} & & & s_{21,VL} \\
 & T_{22} & s_{22,12} & \ddots & & & \vdots & s_{22,21} & \ddots & & & \vdots & & s_{22,V1} & \ddots & & & \vdots \\
T_2 & T_{23} & \vdots & & & & & \vdots & & & & & & \vdots & & & & \\
 & \vdots & & & & & & & & & & & & & & & & \\
 & T_{2K} & s_{2K,11} & \cdots & & & s_{2K,1L} & s_{2K,21} & \cdots & & & s_{2K,1L} & & s_{2K,V1} & \cdots & & & s_{2K,VL} \\ \hdashline
\vdots & & & & & & & & & & & & & & & & & \\ \hdashline
 & T_{N1} & s_{N1,11} & s_{N1,12} & \cdots & & s_{N1,1L} & s_{N1,21} & s_{N1,22} & \cdots & & s_{N1,2L} & & s_{N1,V1} & s_{N1,V2} & \cdots & & s_{N1,VL} \\
 & T_{N2} & s_{N2,11} & \ddots & & & \vdots & s_{N2,21} & \ddots & & & \vdots & & s_{N2,V1} & \ddots & & & \vdots \\
T_N & T_{N3} & \vdots & & & & & \vdots & & & & & & \vdots & & & & \\
 & \vdots & & & & & & & & & & & & & & & & \\
 & T_{NK} & s_{NK,11} & \cdots & & & s_{NK,1L} & s_{NK,21} & \cdots & & & s_{NK,2L} & & s_{NK,V1} & \cdots & & & s_{NK,VL}
\end{array}
\tag{5.3}
$$

Introducing a weighting factor $w_q,\ q = 1,2,...,L,$ for the criteria c_p, where $w_q \in [0,1]\ \forall q,$ and $\sum_{q=1}^{L} w_q = 1$, the overall fit of the technical option *j* within function *i* for the market option *p* becomes:

$$y_{ij,p} = y(T_{ij}, M_p) = \sum_{q=1}^{L} w_q \cdot s_{ij,pq} \tag{5.4}$$

Hence, the optimal technical option j^* within the function *i* can be identified as the one receiving a maximum score across the weighted criteria:

$$ij^*, p = ij^*(i), p = \{ij, p \mid y_{ij,p} = \max_j \{y_{ij,p}\}\} \tag{5.5}$$

Using the same model but applying a different perspective yields further information on the interrelations between technical and commercial options. Summing up, the scores of the optimal technical options for each market option provide an analytical answer to the question which market option is best supported by the developed options. Let x_p be this sum:

$$x_p = \sum_{i=1}^{N} y_{ij^*,p} \tag{5.6}$$

Then the market option that is best substantiated by the available technical solution alternatives can be identified as

$$p^* = \{p \mid x_p = \max_p \{x_p\}\} \tag{5.7}$$

While the selection of new products should not be merely internally driven, this analysis can indicate situations where no market option is sufficiently supported by technical options. This can lead to decisions to stop or re-iterate the project in the evaluation step. In the case of a successfully passed evaluation and decision step, the project will pursue with one market option and a set of selected options for each function of the product. It can also be inferred from this analysis that one may decide to split up the options into several single projects resulting from various market options.

5.3.3 Back End: Detailed Design, Testing, Prototyping, and Launching

The working mode in the front end deliberately widens the range of solutions and thus creates a multitude of options on the technical and commercial side. The evaluation and decision steps at the end of the front end gain special relevance as they represent focal points where the generated knowledge is processed and key decisions on further projects are taken. In a sense, the highly iterative and broad front end can be seen as an investment in the later development stages, as these are expected to run rather linear and narrowly focused. This resembles the proceedings found in several procedural models [For example COOPER 2001, p. 130; ULLMAN 2003, p. 86; PAHL, BEITZ et al. 2007, p. 130]. Nevertheless, the back end of the development process contains important tasks such as detail design, prototyping, testing and launching. In the context of uncertainty handling in integrated product development two aspects are of great importance: Firstly, the execution of these back-end tasks is often decisive for the success of the overall project. A timely production and sales ramp-up is crucial to capture a first-mover advantage that highly innovative technologies can provide. Additionally, the initial quality and costs levels of the final product are elaborated by the execution of the detailed design and decision phase. A further aspect attributing special relevance to the back-end phase addresses the uncertainty encountered in the front end. While the decisions taken under uncertainty mainly depend on option-based assumptions, analyses and the collective experience of the project team, the back end provides insights on the actual outcome of uncertain decisions. These insights can be generated as results from prototypes, pre-series as well as feedbacks from pilot customers. The ex-post analysis of uncertain decisions against the background of newly generated information provides fruitful learning loops. In a direct loop, the learning from the execution phase can be reflected by the decisions made under a higher level of uncertainty in the front end. A second learning loop targets the transfer of experience and know-how across projects. The effectiveness of this loop implies that learning occurs when individuals and teams are repeatedly exposed to decision problems in uncertain environments. This claim is affirmed in the psychological literature as long as there is not a saturation effect from being over-exposed to uncertain situations [ZIMBARDO, GERRIG 2004, p. 243 ff]. In the case of innovative product developments where the content typically changes strongly from project to project, it is sound to assume that the learning and exchange between projects is beneficial to an organization. Figure 5-11 illustrates the learning process within and across projects.

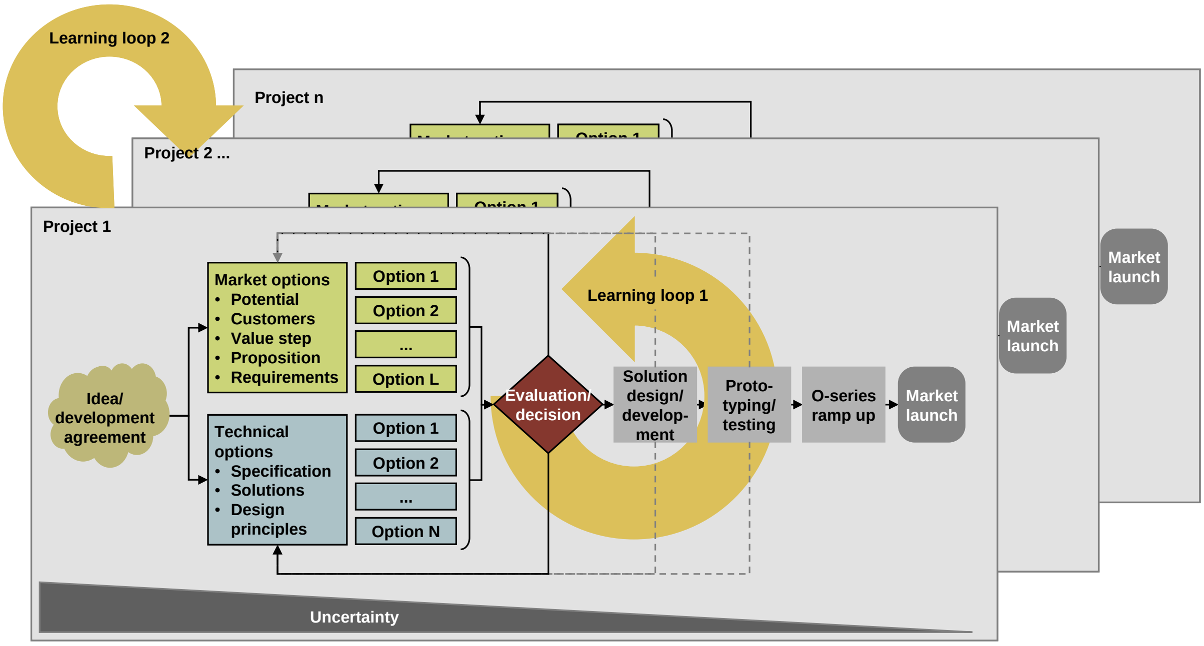

Figure 5-11: Learning loops in product development under uncertainty

While the working mode changes from a broad multi-option based mode to a narrower single-option mode with a switch from the front to the back end, the integrative work mode should be kept throughout the project. The interdisciplinary project team set up also supports integrative design methods such as design for manufacture and assembly which should consequently be implemented during the solution development phase [ULLMAN 2003, p. 286].

5.4 Embedded Methods and Tools

In the procedural model, methods and tools are used for multiple purposes: They support and stabilize the process, they document key analyses and decisions during the process, and they thus contribute to the documentation of a project. As laid out in Figure 5-12, the process is supported by tools, and an emphasis is laid on the three focal points development agreement, options generation and evaluation and decision. The key methods and tools are discussed below. As pointed out in section 5.3.1 the generation of ideas and solutions can be stipulated by a range of proven tools and methods like brainstorming, morphologic boxes, or Delphi analyses [LINDEMANN 2005, p. 217ff].

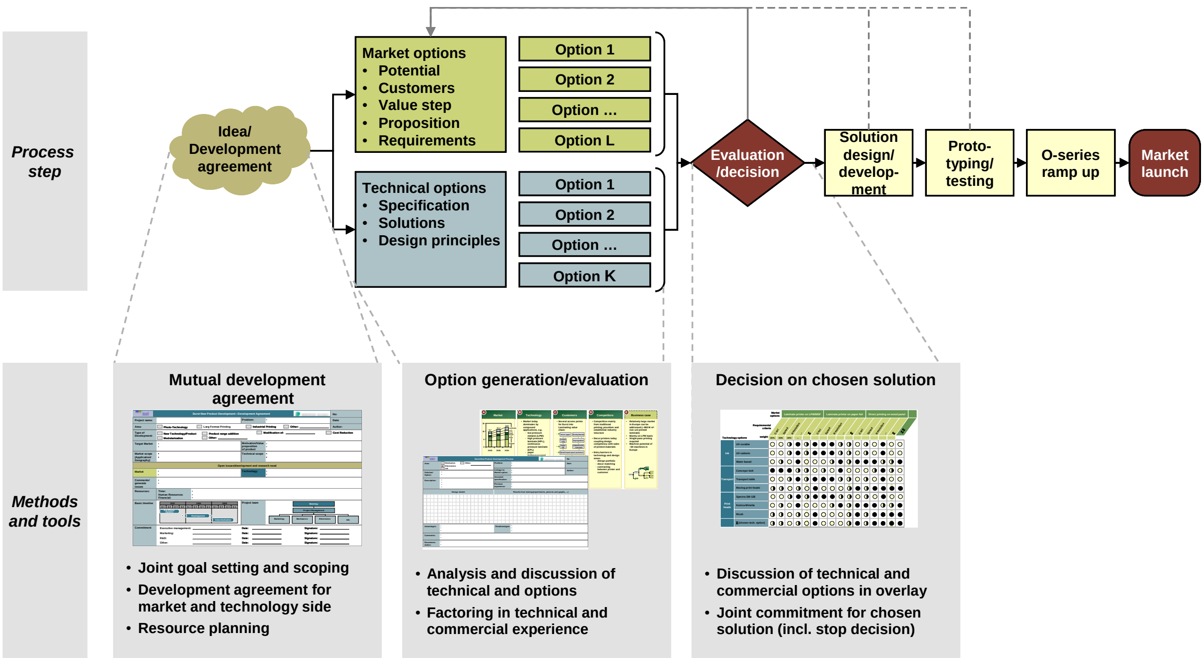

Figure 5-12: Process support by methods and tools

The mutual development agreement between management, marketing and the R&D discussed in chapter 5.3.1 should be regarded as an essential component of the integrated product development model under uncertainty. Herein, important parameters of the targeted product, the development process and the team are defined. In an iterative working mode the overall goal and scope as well as the development need and the required resource need are set and receive a commitment from all participating parties. While defining goals and planning resources is a common element of several development processes, the explicit naming of open issues and the definition of development needs is specifically targeted at handling uncertainties. Rather than setting specifications, the unknown areas are made explicit. Thereby questions are raised with respect to the product's market and technology that have to be answered during the options generation and assessment phase. Moreover, the areas where multiple solutions should be generated in the form of options can be listed. These analyses, directions settings, and commitments are codified in a mutual development that acts as a project script. Figure 5-13 illustrates the content and possible structure of such a mutual development agreement.

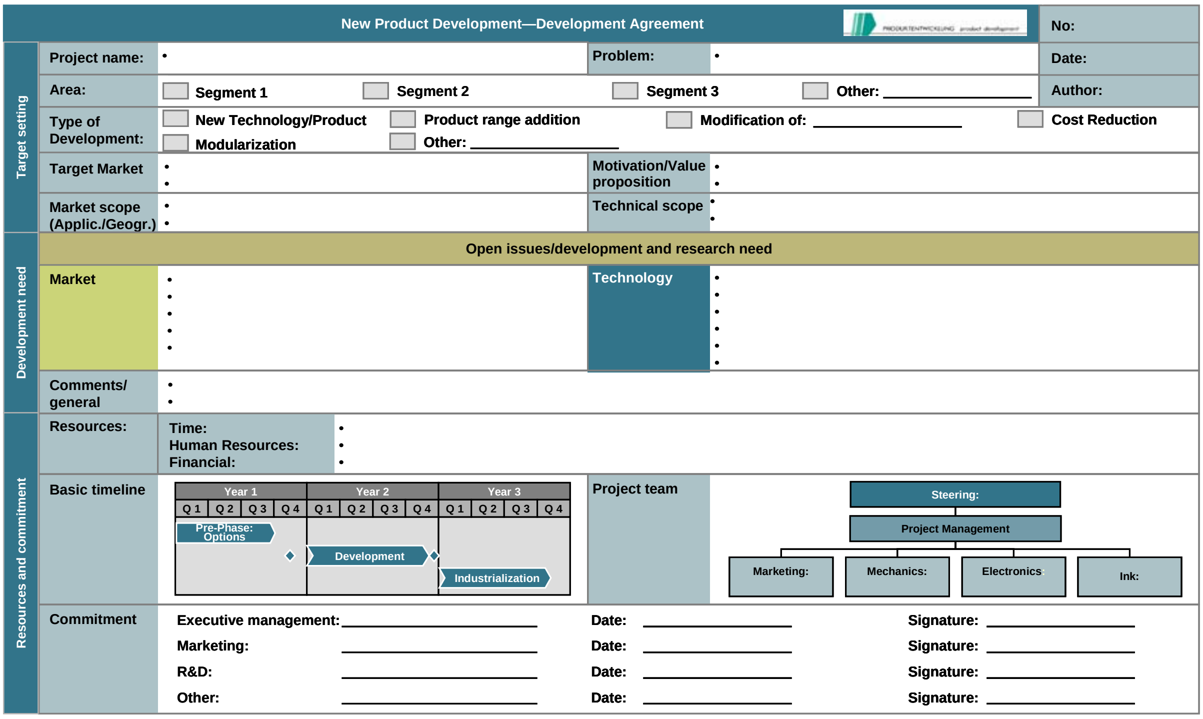

Figure 5-13: Mutual development agreement

In order to capture technical options, stress is laid on actually sketching an idea. This behavior promotes the exchange and discussion of options in cross-functional teams. Furthermore, ideas and solutions are documented and can be stored for later projects [SCHWANKL 2002, p. 83ff]. Ulrich and Seering [ULRICH, SEERING 1989, p. 5] argue that sketches in the form of schematic descriptions reduce the complexity of design and enhance the conceptual understanding of a design problem by treating functional and physical issues of a possible solution separately. Next to sketches, the results from experiments and models document the capabilities and limitations of an option. For the purpose of storing and reusing options it is vital to categorize technical options with regard to the respective technical area and the initial problem, and to provide a broad assessment of advantages and disadvantages as well as indications for further usage. Figure 5-14 shows the set up of a technical option sheet.

Market options can also be captured by using a standardized tool that provides summarized answers to essential questions about market options (e.g. market segements, technology, customers, competitors and business case). It thus provides an overview of the information gathered and the analyses conducted for a certain market or its segments. Similar to the technical option capture template, it provides a base for structured documentation and storage of acquired knowledge on the market side. Figure 5-15 gives a guideline that can be used to capture market options.

Next to the described idea capturing and documentation purpose, the sketches are also an essential means in the collaboration in the development teams. Sketches turn ideas into tangible concepts and support the cross-functional communication and discussion. Smickl and Kieser [SCHMICKL, KIESER 2008, p. 476] refer to such a usage of documented ideas as "*mental prototyping*" and regard it as an essential contributor to the interdisciplinary work in radical innovation projects. A more formalized version of idea documentation and exchange typically used in software design is "*paper prototyping*" [SNYDER 2003, p. 49ff] for which specialists exchange ideas for components in written form in order to receive comments from collaborators.

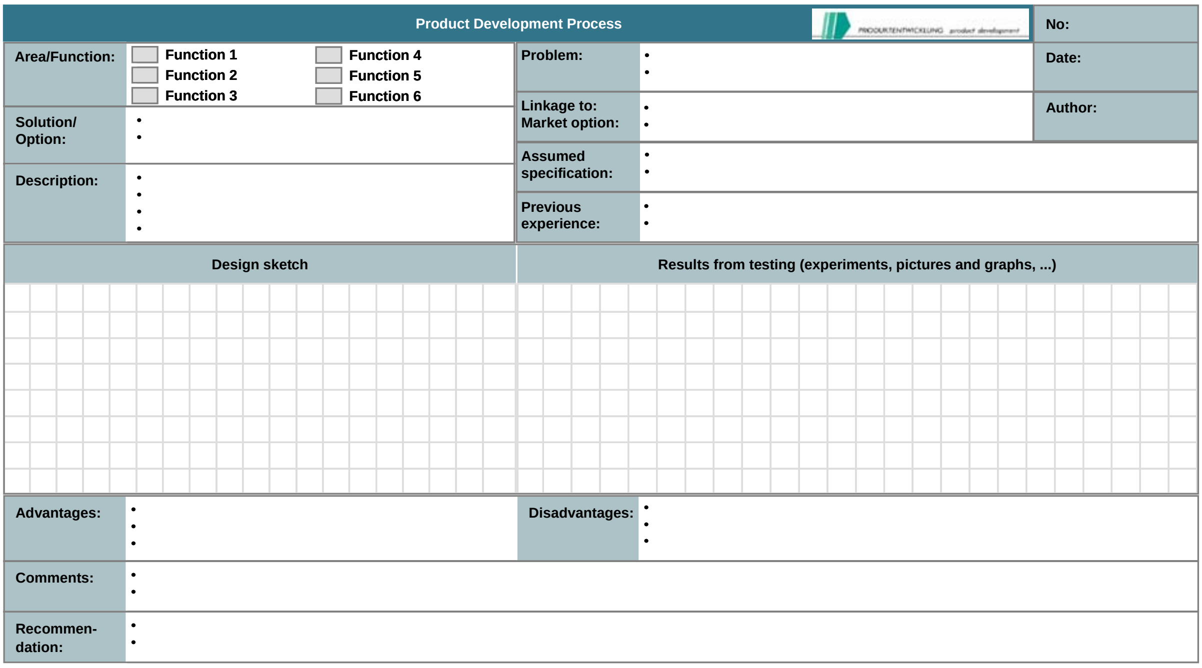

Figure 5-14: Form for the capturing of technical options

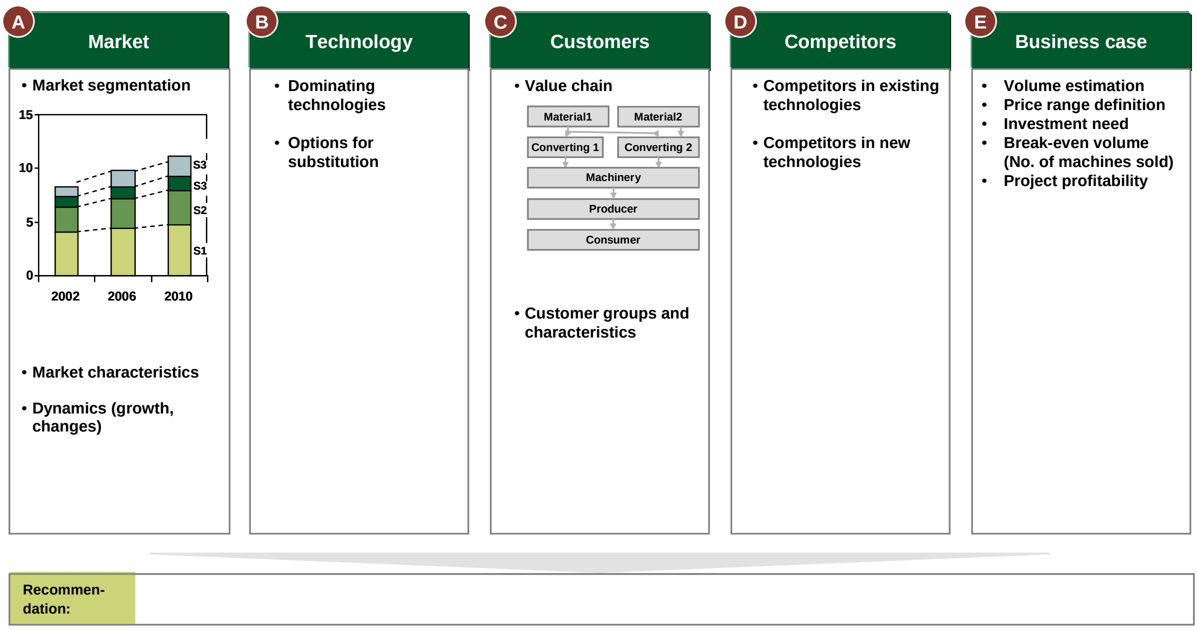

Figure 5-15: Form for the capturing of market options

Finally, the scoring logic in the evaluation and decision on the selection of options can be supported by a tool and the results can be visualized. Essentially, the matrix introduced in formula (5.3) is arranged into a table and the score can be illustrated using the filling degree of circles or boxes. The resulting chart also gives an impression of the technical options' overall fulfillment of the derived market requirements. Thus, the chart supports the analyses and decisions outlined in section 5.3.2, namely:

- the selection of optimal technical options for a chosen market option;
- the assessment of which market option is best supported by the given technical options.

Moreover, a matrix consisting of predominately low or medium fit levels can indicate a situation where the appropriate options have generally not yet been generated. Thus, the indication can result in a stop or restart of the project with changed parameters.

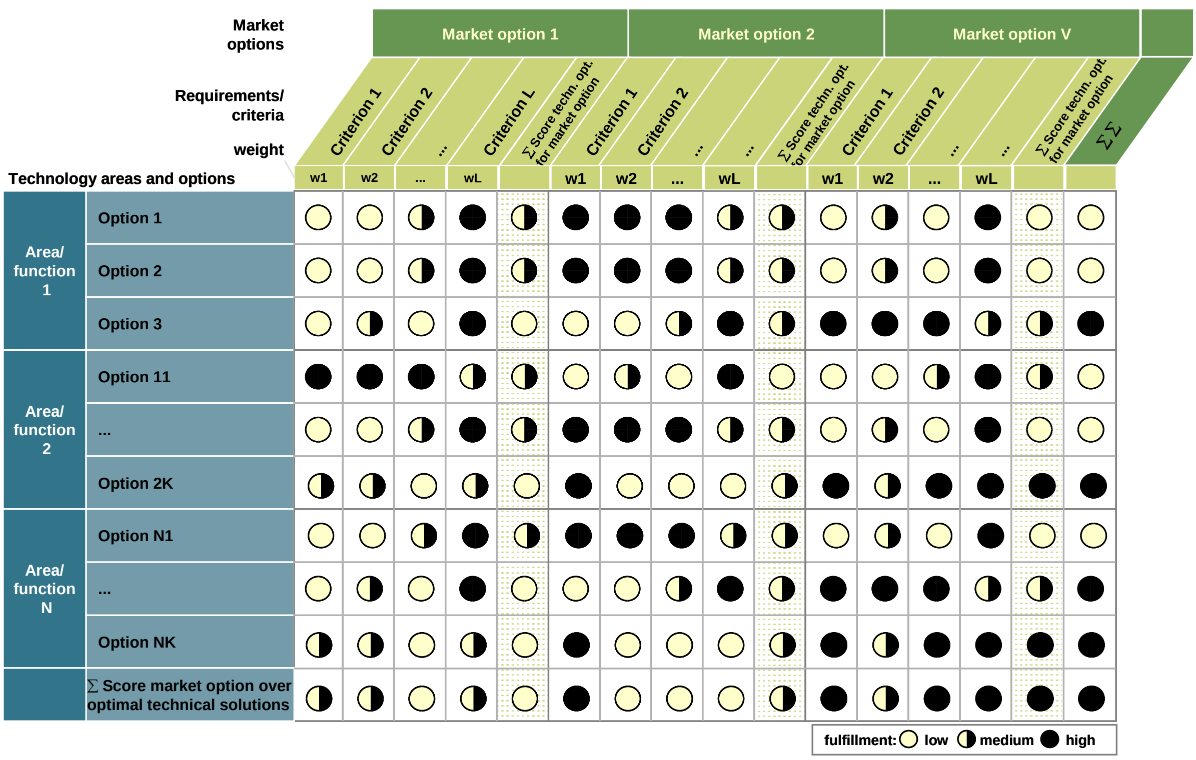

Figure 5-16: Evaluation and decision support matrix

5.5 Individuals, Teams, and Organizations

While processes and their respective tools and methods can support a product development venture, the tasks and decisions are ultimately carried out by individuals, teams, and organizations. Consequently, their individual behavior and the interaction of groups within companies play an essential role in the proceedings and success of product development ventures. Thus, the relevance of the human aspect in design and product development is stressed by several authors [For example BIRKHOFER, JÄNSCH 2003, p. 200f; LINDEMANN 2005, p. 22ff]. With regard to radical innovations that are treated in this work, two aspects of human behavior become of special importance and are elaborated further: First, both the risk and the uncertainty embedded in a radical innovation project have an impact on people's tasks and decisions. Second, radical innovations typically aim at new products in new markets which are consequently calling for a close collaboration of all functions within these projects.

5.5.1 Dealing with Uncertainty and Risk

The fact that significant uncertainty and risk are involved in radical innovation projects as outlined in this work implies the need to enable the process and the design team to deal accordingly with these issues. Two aspects are of central relevance here: First, the proceedings and decision mechanisms should be adjusted to this uncertain environment, and secondly the specifics of human behavior under uncertainty should be considered.

With regard to process related risk dimensions, Andreasen and Hein [ANDREASEN, HEIN 1987, p. 155ff] separate the two basic risk categories into internal and external risks: Internal risks contain the risk of failure of the project team whereas external risks result from unforeseen changes in the market, technology or a competitive environment. Similarly to the financial theory, Andreasen and Hein define risk as the probability of failure multiplied by the consequences.[17] Following this dual logic, two basic strategies to reduce the risk potential can be derived: Putting adequate resources against a project decreases its chances to be a failure. This might involve financial and human resources but also external ones like market information or analysis of competitors' products and strategic moves. Secondly, the consequences of a failure should be reduced wherever possible. The negative impact of failed projects increases with their progress over time: A project idea that is dropped after a quick market plausibility check does create a limited level of sunk cost, whereas a product that has to be taken from the market after its introduction will mostly lead to significant non-recoverable costs in the build-up of a production and sales system. Hence, it is vital to stop projects early enough if their chances for success decrease in order to minimize the consequences of a default. While such an action is fully rational, it is a commonly observed problem that non-performing projects are not stopped due to several reasons: Project team members get attached to a project, fear the risk of personal failure or even the loss of their jobs if their project is abandoned. In order to facilitate a necessary stop or holding of decisions, the process should include specific decision points enabling fact-based decisions on the procedure of the project. In the discussed model, two steps of the project progress can be regarded as designated exit points: First, during the idea and development agreement phase an idea can be abandoned after a quick market and technology screen causing minimal costs. Second, the evaluation and decision step during the market and technology options generation phase also deliberately serves as an exit point where a project can be stopped and resources can be withdrawn from it. The evaluation logic discussed in 5.3.2 provides an analytical support to this stop decision: A low score for $x_{p^*} = \sum_{i=1}^{N} y_{ij^*,p^*}$, where

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17 For example when describing credit risks in financial markets, risk is referred to as the probability of an obligor's default times the loss given default. The impact is thus described by the loss given default or, in other terms, the portion of credit that cannot be recovered after a default [For example JORION 2001, p. 320f].

$p^* = \{p | x_p = \max_p \{x_p\}\}$ indicates that the technical options generated do not sufficiently meet the market requirements derived with a market option. Using a scoring from 1 to 4 as in equation (5.2), a low overall score is indicated if $\frac{x_{p^*}}{N} \leq 2$.

This analysis can lead to the conclusion to stop a project after the options generation and assessment phase and not to continue with the actual product development. Generally, the methodology discussed in section 5.3.2 and supported with tools as proposed in section 5.4 provides a mechanism to ground these decisions on the continuation of a project on underlying facts. Even in the case of project termination, the generated and documented market and technology options can be recycled for further projects. The project team members should thus be put into situations where they are comfortable with the risks the project is carrying and empowered to also take unpleasant decisions without fearing the risk of personal effects. Enabling such a risk taking position without neglecting its danger is an essential leadership task for the project leader and the top management supervising the project.

An approach dealing with uncertainty and risk also has to incorporate individuals' and teams' characteristics in information processing and decision-making. Recently, the product development and design research has been enhanced by the consideration of human behavior in individuals and teams [For example ADELSON 1989; HACKER 2002; LINDEMANN 2003]. From the perspective of cognitive psychology, some issues in product development and design are complex problems as they exhibit five key characteristics [For example PUTZ-OSTERLOH 1981; SCHAUB 1993; FUNKE 2003]:

- Complexity of the situation as a large number of variables and sources of uncertainty are involved;
- interdependence and connectivity between a large number of variables forcing the decision makers to reduce the complexity;
- the dynamic nature of the problem requiring the prediction of future developments;
- opaqueness, i.e. impossibility of taking optimal decisions due to lack of necessary information;

- careful elaboration of priorities and a balance between contradicting, conflicting goals in order to achieve multiple goals.

Along a conceptual problem solving and action regulating process, Dörner and Schaub [DÖRNER, SCHAUB 1994] studied the common human errors in decision-making and information processing in a complex system. When being confronted with a complex problem, individuals and teams typically elaborate the goal, collect information and form hypotheses, predict future developments, plan monitor effects and finally self-reflect on their proceedings and behavior. Relevant human limitations come into play at any of those phases. For example, subjects may jump to action without clarifying goals or balancing contradictory objectives or they may reduce information to the content that supports already defined hypotheses while neglecting or devaluating other parts. In the actual course of decision-making, people often disregard side effects and long-term effects or do not monitor the consequences of their action. (See Figure 5-17)

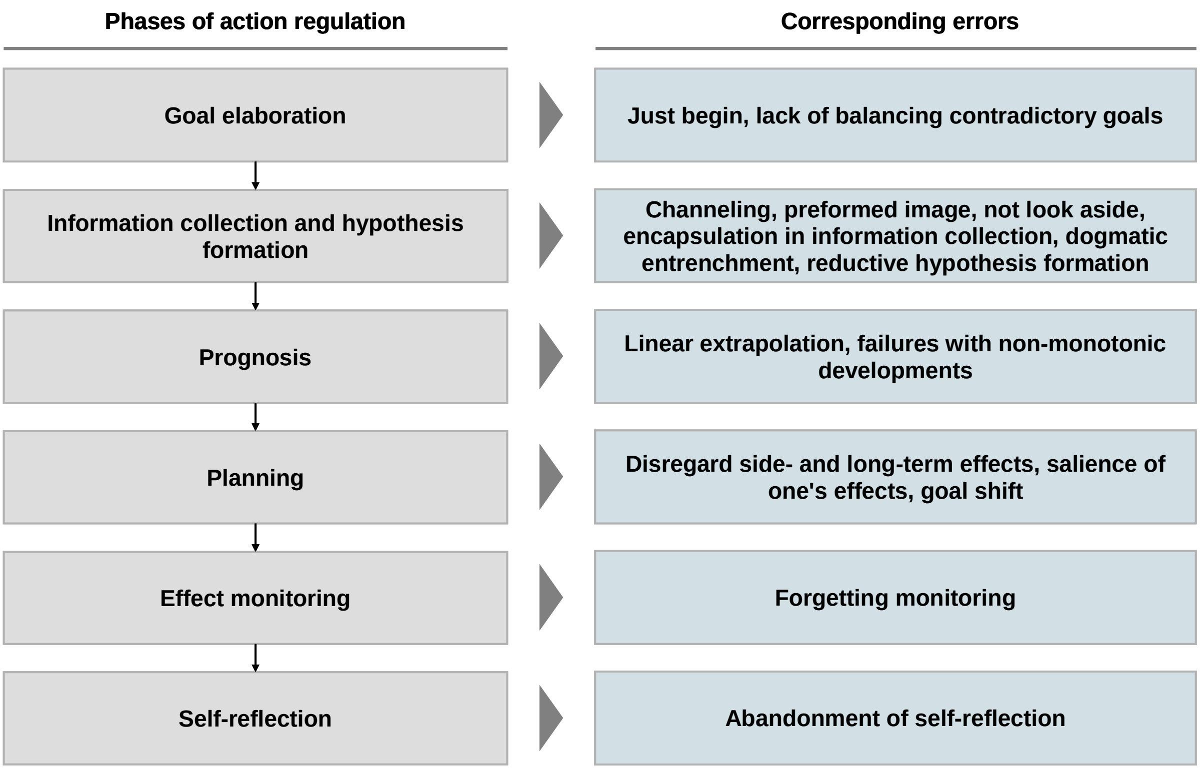


Figure 5-17: Phases of action and corresponding errors [DÖRNER, SCHAUB 1994, p. 447]

These deficiencies and their results on simulated environments have been observed in numerous experiments and are stable across user groups and over time [DÖRNER, KREUZIG et al. 1983, p.105ff]. According to Dörner and Schaub [DÖRNER, SCHAUB 1994, p. 448] the root cause for these behavioral weaknesses can be found in four areas:

- The restricted capacity of human conscious thinking
- the tendency of humans to guard their feeling of competence and efficacy,
- the weight of the actual problem,
- forgetting.

Dörner and Schaub [DÖRNER, SCHAUB 1994, p. 449f] state that in order to avoid or counterbalance these effects and to develop an ability to cope with complex realities, humans have to be confronted with their error tendencies. As this can hardly be done in reality as the cost of such implications would be too high, they argue that subjects should experiment with their information processing and decision-making behavior and reflect on actions and their impact in a simulated environment. Hence, computer simulations are seen as an effective means to train people on such situations and strengthen their awareness for possible unconscious deficiencies.

Next to the self-reflecting and self-correcting aspect, Sitkin and Weingart [SITKIN, WEINGART 1995] propose actions that team leaders can take in order to promote information processing and decision-making under uncertainty. As a result of several experiments studying the mediating roles of influencing factors on risky decision-making, they derive three key measures that predict and influence individuals' and teams' behavior in uncertain situations: a) risk perception as a measure of how positively or negatively risk can be influenced by framing; b) problem framing that underlines the threats to existing resources and induces risk-averse behavior whereas framing that puts emphasis on the upside potential in uncertain outcomes increases the salience of opportunities and induces risk-seeing behavior; c) the attitude towards risk perception and propensity can further be altered by team dynamics. Empirical research shows that teams act more risk-seekingly than individuals and tend to take risky decisions individuals would not take [BRITTAIN, SITKIN 1990; PETERSON, OWENS et al. 1998].

The proposed procedural model and its associated methods and tools address the discussed issues in human behavior under uncertainty and should help a project team to fall into the typical failure modes mentioned above. Specifically the front-end process and its associated methods support robust and holistic decision making and offer project management tools for project managers running such uncertain development projects:

The idea phase and development agreement stress on scoping the problem and defining open and uncertain areas. Thus uncertainties on the market and technology are brought to visibility at an early stage. The codified mutual development agreement makes the exploration of uncertain areas an explicit project goal. Hence, uncertainty is not seen as an individual burden for project team members, but it becomes an overall project component.

The options generation follows addresses the exploration of uncertain areas through the development of possible solutions [SIMON 1996, p. 85ff]. This proceeding is meant to avoid the abovementioned failure modes in information collection and prognosis. The deliberate generation of competing solutions supports in avoiding negative channeling of information or reductive hypothesis formulation. Furthermore, the captured and documented options on the market and technology side facilitate an exchange of ideas and discussion of single ideas, thus reducing the dependency of the solution on single individuals' preferences or preformed images.

The evaluation and decision step aims at a broad scoring and evaluation of the generated options on both sides to find an optimal combination. In order to provide a holistic non-biased foundation for the concept choice, the requirements forming the basis of the evaluation of technical are derived from market analysis during the generation of market options.

Nevertheless, the procedural model and its methods and tools cannot entirely suppress any error tendencies in human behavior. Thus, it is vital for the subjects involved in such projects to be aware of their own limitations in information processing and decision-making. Furthermore, along the above-mentioned discussion, individuals should take corrective actions if team members are tending towards extreme positions in their attitude towards risk. Next to their essential role in content and process management, this can be understood as a third key task for project managers leading innovation projects under a high degree of uncertainty.

5.5.2 Cross-functional collaboration

Eversheim, Schuh et al. [EVERSHEIM, SCHUH et al. 2005, p. 8] claim that development processes should support a team-oriented and cross-functional work mode especially in the front end, where market and customer requirements need to be transported into the product concept and where previously unknown technical areas are being explored. Particularly in radical innovations, a new product and technology can induce several changes within a company, i.e. production and sales processes can be altered and new business models may be applied. Exemplary shifts of paradigms following radical product innovations are illustrated by the case of Nokia and a packaging systems provider in chapters 1.1 and 1.2.1. As target markets may shift from industrial markets to consumer markets, success factors in production, sales and in the company culture as such may change dramatically. It is thus important to involve several functions like marketing, research and development, production and sales in the product development process. Extant studies suggest that radical product innovations require a more intensive knowledge transfer between specialists. For example, Mikkola [MIKKOLA 2003, p. 449f] argues that newness reduces possibilities for modularization what, in turn, increases the need for specialists' knowledge exchange. Grant [GRANT 1996] points out that projects aimed at radical, discontinuous change present specific problems that call for more inter-specialist problem solving. Carlile and Rebentisch [CARLILE, REBENTISCH 2003, p. 1188] argue that the degree of innovativeness is correlated with the rate of errors, which necessitates collaboration between specialists. This is supported by Schmickl's and Kieser's [SCHMICKL, KIESER 2008, 484f] study of seven innovation projects with varying degrees of innovativeness within a single technology-oriented company. They conclude that radical innovation project exhibit about three times as many cross-functional iterations as projects aimed at incremental innovations.

Andreasen and Hein [ANDREASEN, HEIN 1987, p. 78f] claim that the knowledge of the different members should supplement one another and add up to occupy the whole space of knowledge in the areas market, design, and production. The underlying reasoning is that the functional diversity of these teams increases the amount and variety of information available to design products. In a synthesis of the current product development research, Brown and Eisenhardt [BROWN, EISENHARDT 1995] further argue that cross-functional teams are critical to process performance. Following the argumentation of Andreasen and Hein, the underlying reason is seen in the information available in diverse teams. Moreover, the increased information helps the team to catch downstream problems such as manufacturing difficulties or market mismatches in an early stage, when these problems are generally smaller and easier to fix. Thus, cross-functional teams are often associated with high-performing processes [For example ZIRGER, MAIDIQUE 1990, p. 872ff; DOUGHERTY 1992, p. 181ff].

Rather than forcing people of various functions to participate in a product development project, an approach that stresses their intrinsic motivation to participate in the project can be adopted. These tactics gain special relevance when one individual's participation is of great importance to the project but not among the individual's primary objectives. Figure 5-18 illustrates the key stakeholders within a product development project and their respective output from the project. Senior management allocates the required resource, sets the target, and takes the necessary decisions, but is gaining transparency on the process and a product that suits the economic needs. Marketing has a crucial impact by narrowing down the target market and deriving key requirements for the product. In return, it is actively participating in the project decision and can maintain a direct feedback to potential customers. Lead customers in an industrial setting will allow access to its internal processes and express their need but will be able to affect the product's properties by influencing specifications. Operational functions like production, sales and service can state their position towards options and requirements into the development process in order to optimize the product for later use. This corresponds to the "*design for x*" concept [For example ULLMAN 2003, p. 286ff] resulting from the basic notion that 70% of all product costs are established in the development step. (See Figure 5-2)

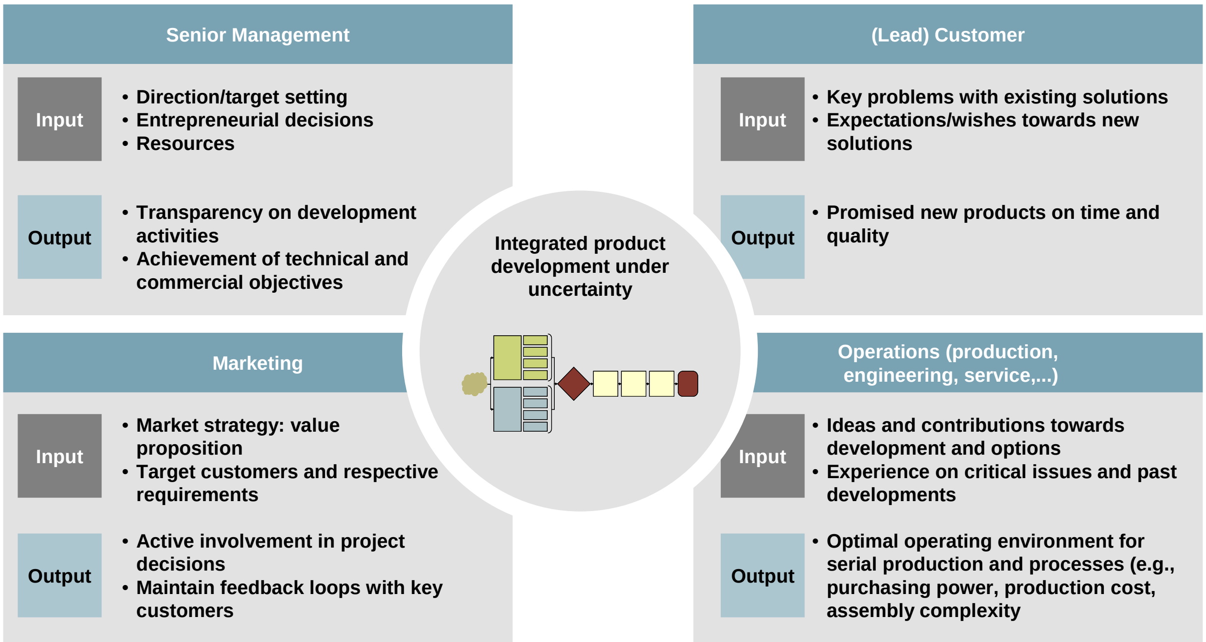


Figure 5-18: Stakeholders in product development and their participation

In order to achieve a true commitment to the project, it is crucial to have experts who not only participate in the work streams affecting their domain but also to have them join work streams or meetings seemingly outside their own functions. An example is to have designers or production engineers take part in workshops that aim at deriving target market segments. Such measures should promote a better understanding of the overall complexity of the problem on hand and the need to collaborate rather than dissociate oneself from certain tasks and decisions in the process.

Thus, providing the platform and motivation for cross-functional collaboration within a highly uncertain innovation project becomes a key task for the project management and the management supervising the initiative.

5.6 Comparison to Prevailing Product Development Models

While the characteristics of the proposed model are a logical implication from the requirements postulated in chapter 4.2, comparing the actual resulting model to the prevailing approaches discussed in section 3 aids in creating an accentuated profile of the proposed model. The design of the model for uncertainty handling in integrated product development exhibits some major differentiation points in the handling of commercial and technical topics, problem specification and solution mode, and the dealing with uncertainty and risk.

As discussed in section 4.1 the prevailing product development models tend to focus either on technical on commercial aspects of the problem. Herein, the chosen focus area is typically dependent on whether the roots of the model lay in the managerial or commercial domain [For example LYNN 1993, p. 288; ULLMAN 2003, p. 86ff]. Furthermore, there is also often a sequential logic established in a sense that commercial issues are treated ahead of technical issues. Yet, the initial considerations on radical innovations and the case of PackagingCo show that more radical innovations contain market and technology problems which can not be brought into a sequential logic. The proposed model engrosses these thoughts and stresses on the equipollent and simultaneous handling of technical and commercial aspects especially in the front-end of the product development process. Options on the market and technology side are generated in parallel and an integration of both aspects takes place in an evaluation and decision step which is supported through an assessment matrix.

Second, with regards to problem specification, especially engineering models stress on the importance of having a complete list of specifications at the beginning of the development project [EVERSHEIM, BOCHTLER et al. 1995, p. 21ff; VDI/VDE RICHTLINIE 3694 2005]. Jung [JUNG 2006, p.81ff] argues for a more dynamic and iterative setting of requirements along the development process. In addition to this consideration, the proposed model lays emphasis on the identification of open issues and definition of uncertain areas during the idea generation and development agreement phase. Hence, the complex task of defining requirements against an uncertain background is interchanged with a profound definition of open areas and derivation of questions that have to be answered in the market and technology work streams during the options generation phase. Thus, the product development process is not merely delivering solutions according to a predefined specification but is explicitly creating knowledge on the market and technology side and is generating solution options.

Third, the problem solving and solution finding mode in the proposed model is characterized by a multi-options approach. This represents a difference to most engineering product development models where the process aims at a single solution that is detailed from a basic functional structure to its completed design [For example VDI RICHTLINIE 2221 1993]. While linear models stress on the importance of iterations and the possibility to step backward and forward during the course of a development project, the presented approach builds on a broader solution space at large. This reduces the dependency on a single concept and supports the aspect of learning through the generation of solution options [SIMON 1996, p. 85ff].

Finally, the proposed model takes a distinct stance towards risks and uncertainty. Product development models and project management guideline stress on identifying potential risks, assessing their negative impact on a project, and on mitigating actions [For example SMITH, MERRIT 2002, p. 29ff; PROJECT MANAGEMENT INSTITUTE 2004, p. 237ff]. While the proposed model also provides procedures and tools to control the risk involved in an uncertain innovation project it also applies an additional perspective to uncertainty and risk: Radical innovation projects will contain an inherent uncertainty due to the novelty of the solution on the market or technical side. Thus the model aims at defining and scoping the uncertain areas and exploring the problem through the generation of solution options. This procedure also makes risks transparent and offers a decision base and exit points in order to reduce the negative impact from encountering risky ventures. However, it also sees the uncertain starting point as an opportunity to develop new solutions. Ultimately the model is governed by the notion that the inherent risk cannot be reduced to full extent but is rather seeking ways to deal effectively with the risk and uncertainty.

Figure 5-19 summarizes these main differentiation points of the discussed model in comparison to prevailing approaches in product development.

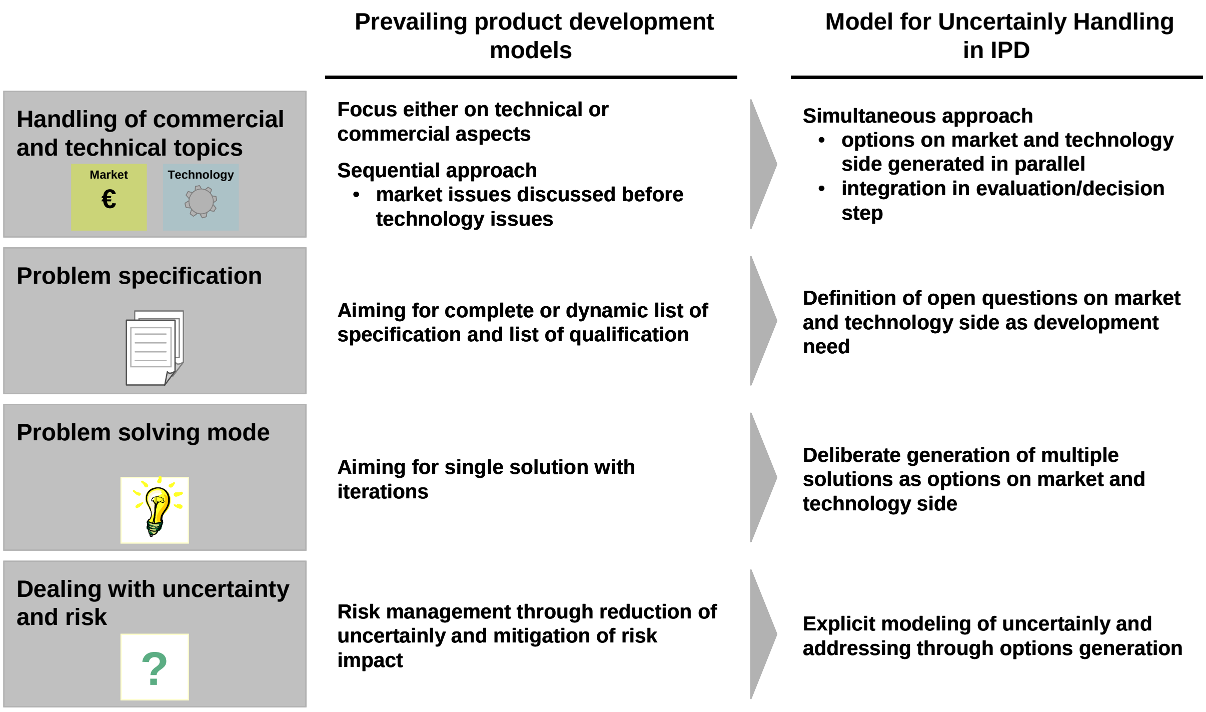


Figure 5-19: Differences to prevailing product development approaches

6 Application of the Model for Uncertainty Handling in Integrated Product Development

The following chapter describes the industrial implementation of the model derived in chapter 5. The case studies conducted serve as a means to indicate whether the requirements for uncertainty handling postulated in chapter 4.2 are met by the model discussed in the previous section. Thus, the industrial implementation forms an important base for the evaluation of the model and the derivation of further research areas.

6.1 Radical Innovation in Digital Printing Equipment

6.1.1 Starting Point at PrintCo

The case study targeting at radical innovations in the printing equipment market at PrintCo has been introduced in chapter 2.1 laying out the challenges on the market and technology side. PrintCo introduced a new product development model in 2002, mainly with the motivation to bring structure to the development process. As shown in Figure 6-1, the chosen process is essentially a customization of the stage-gate model discussed in chapter 3.1.1. In contrast to the original stage-gate logic, PrintCo's processes follow a more throughput-oriented logic as the process steps 1, 2 and 4 represent intermediate steps towards the industrialization of a product instead of tasks leading to stop or go decisions.

The process and its embedded tools provided a rigid guideline but showed little tolerance for ambiguity and uncertainty. It functioned well as long as PrintCo was focusing on incremental innovations in the photo technology and the large format printing market but showed significant shortcomings when being applied to radical innovations in the industrial inkjet segment.

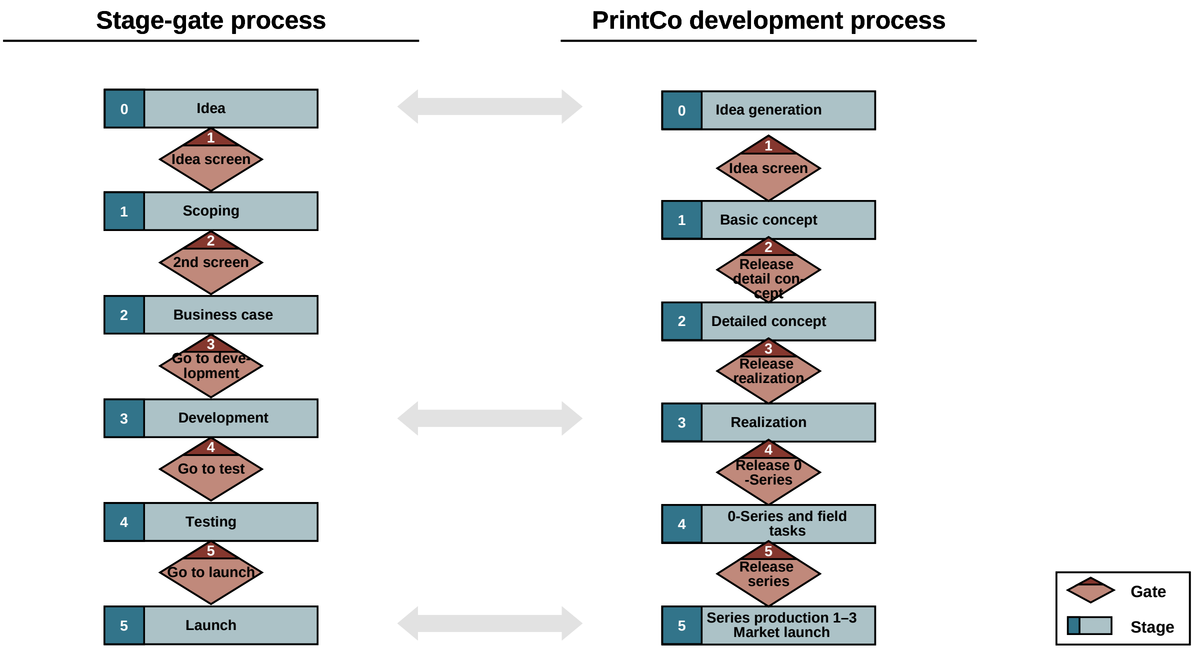


Figure 6-1: PrintCo's stage-gate development processes [COOPER 2001, p. 130]

Driven by the sequential logic of stage-gate models that require a process step to be complete before moving on to the next step, the front end of the process was strongly sequential with consecutive actives pursuing a single solution each. As rather ambitious deadlines for the presentation of prototype products were set by trade fair dates, significant pressure was put on the back end activities. Thus, prototype design and testing, field test and internal 0-series ramp-up ran in parallel, causing operative frictions. For example, due to long lead times of supplier parts orders had to be taken before having ensured the configuration of certain modules of a new machine. In sum, as opposed to the linear front end, the back end was characterized by recursive and iterative proceedings and frequent jumps. Figure 6-2 illustrates the structural difference between the front end and the back end.

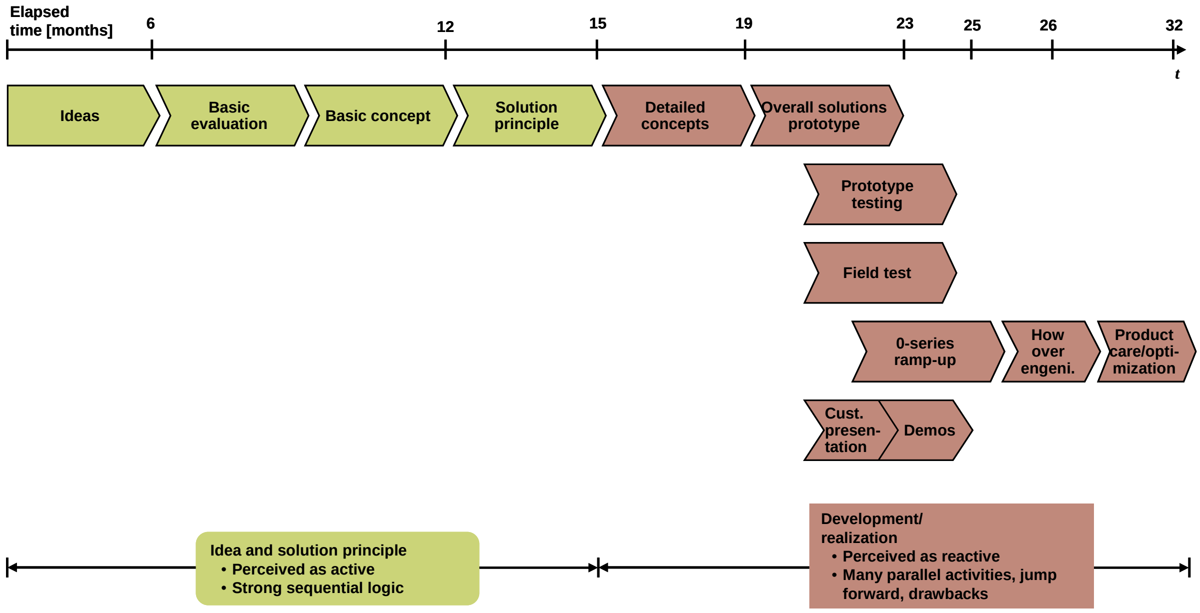


Figure 6-2: Schematic product development process

Although the ideas and solution concepts generated in the first two process steps were neither optimal nor final, they often already codified in CAD-drawings due to a perceived time pressure. These solutions were often chosen as "top of the mind" ideas without significant reflection or consideration of a broader solution space. This led to a situation where the fact that non-optimal solutions were embedded in the product was not discovered until testing or assembling the product. A member of the development referred to this as "*in the back-end we try to optimize a non-optimal product*".

The product development process and its output causes discontentment across several functions and hierarchies of PrintCo:

- Management regarded the results of product development as unsatisfactory, as the approach required significant after-work and did not produce the desired market effects. Hence, the company’s strategic advantage of innovativeness and speed over its financially prudent competitors was threatened.
- Designers experienced a stretch, as they had to simultaneously work on product problems in the back end while being staffed on new projects.
- Marketing and sales had to console potential customers as promised dates or performance levels could not be kept.

- Finally, the recursive process flow in the back end represented an obstacle towards efficient operations in purchasing, production and service.

The above-mentioned issues also resulted in an explicit need to change the basic set-up of the product development process at PrintCo.

6.1.2 Implementation of the Model for Uncertainty Handling in Integrated Product Development

The model for uncertainty handling in integrated product development was introduced mainly as it enabled a focus on the front end and a broadening of the solution space while providing structure and orientation to the development process. In order to utilize the existing tools and methods, the process design discussed in chapter 5.3 was embedded in a logic similar to the existing process. The resulting process strongly emphasizes the front end with options generation on both the technical and the market side and an interplay of all involved functions in general. (See Figure 6-3)

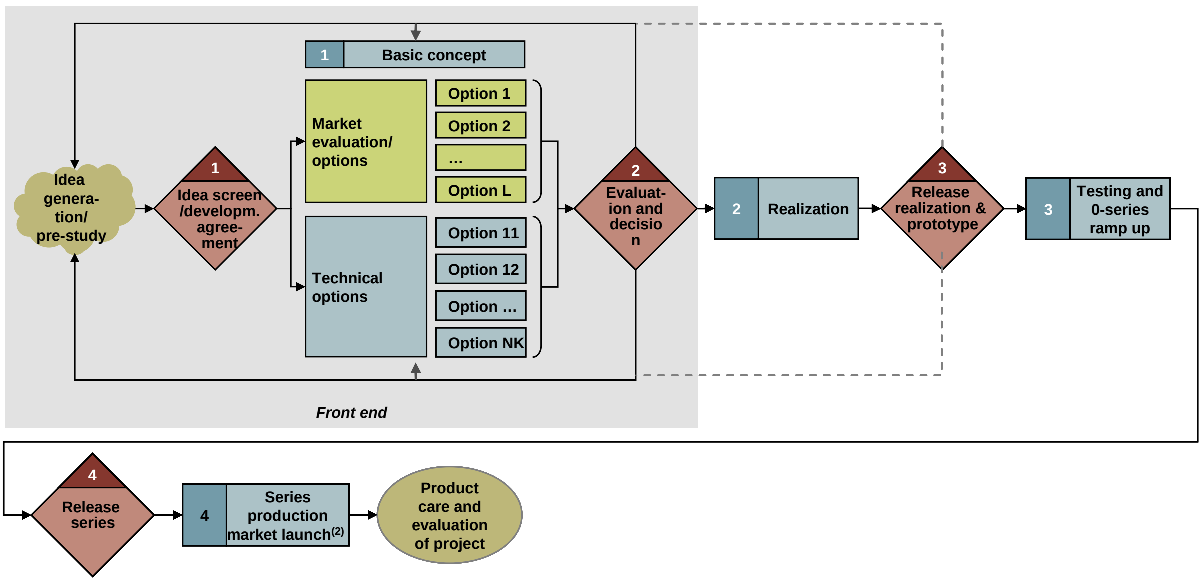


Figure 6-3: Modified product development process at PrintCo

PrintCo had gone through a collection of broad topics and structured idea generation for new products in the industrial printing market and had evaluated them along the criteria of dimension market attractiveness and technological proximity. Some of the prioritized substrates that could be printed with a digital inkjet printing system are illustrated in Figure 6-4.

Figure 6-4: End products potentially printed with digital inkjet printing system

Industrial printing on furniture and wood based products was one of the product areas appearing most promising in the idea development stage. The new product development model was thus first fully introduced with the development of an industrial ink jet printing system aiming at printing on wood or wood based panels. Possible applications could be the printing of laminate floors, doors, furniture components or edges and profiles. Through the implementation of the new product development process the attention of the project team was first directed towards the description of open issues and concerns in the development agreement. An extract of this mutual development is shown in Figure 6-5, which lists open issues both on the market and on the technology side as well as the main dependencies between market and technology issued or within one area. Listing open issues and especially pointing out the links between open questions proved to be a strong motivator for an integrated and option-based approach.

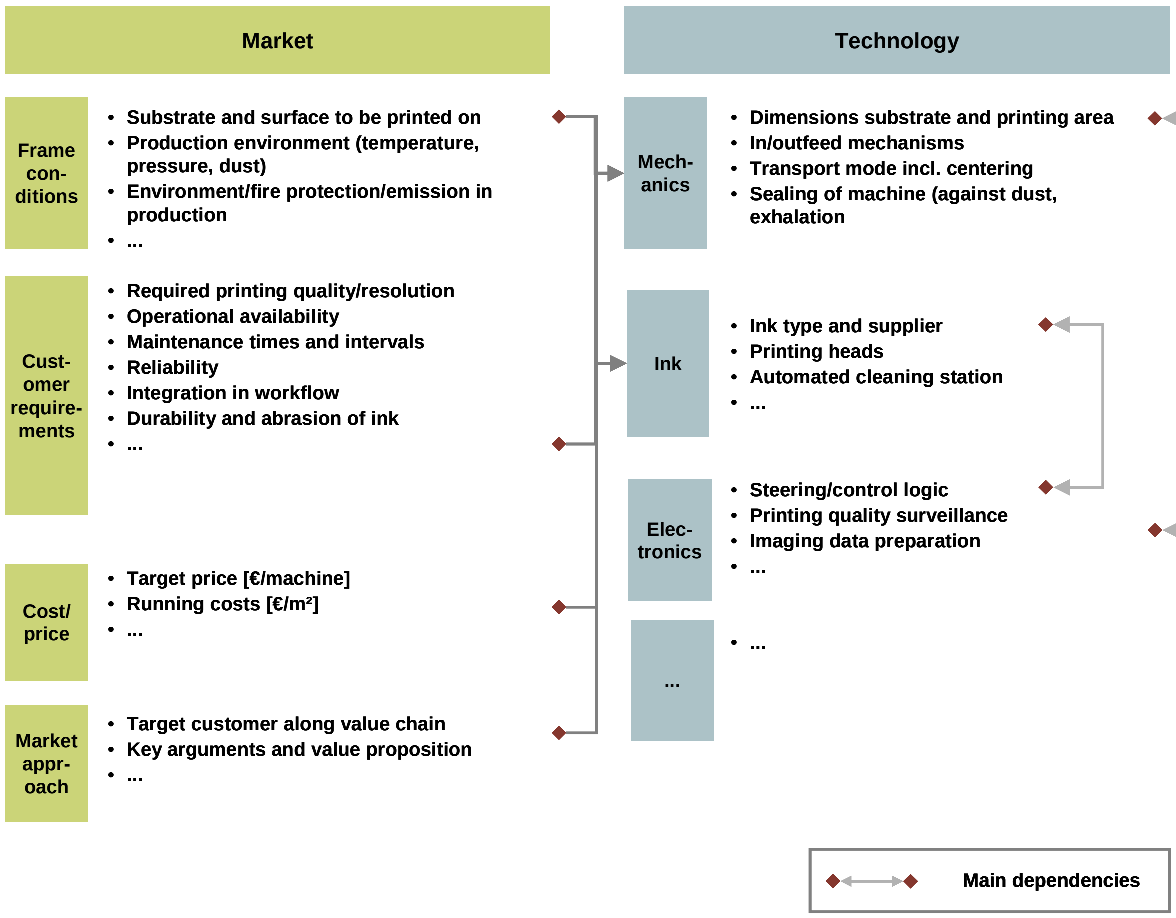


Figure 6-5: Dependencies between open issues on the market and technology side

On the market side, it quickly became apparent that laminate printing is not necessarily one market, but can be seen as several market entry options due to the variation of substrate material. The market option sheet shows these variations under point C) Customers as shown in Figure 6-6. The market option sheet was in this case understood as a summary for a more detailed market analysis, which covered market studies, competitor analyses, lead customer interviews and the derivation of a business case. Based on this work, specific implications of entering the laminate printing value chain at a certain step were discussed in the product development team with the management.

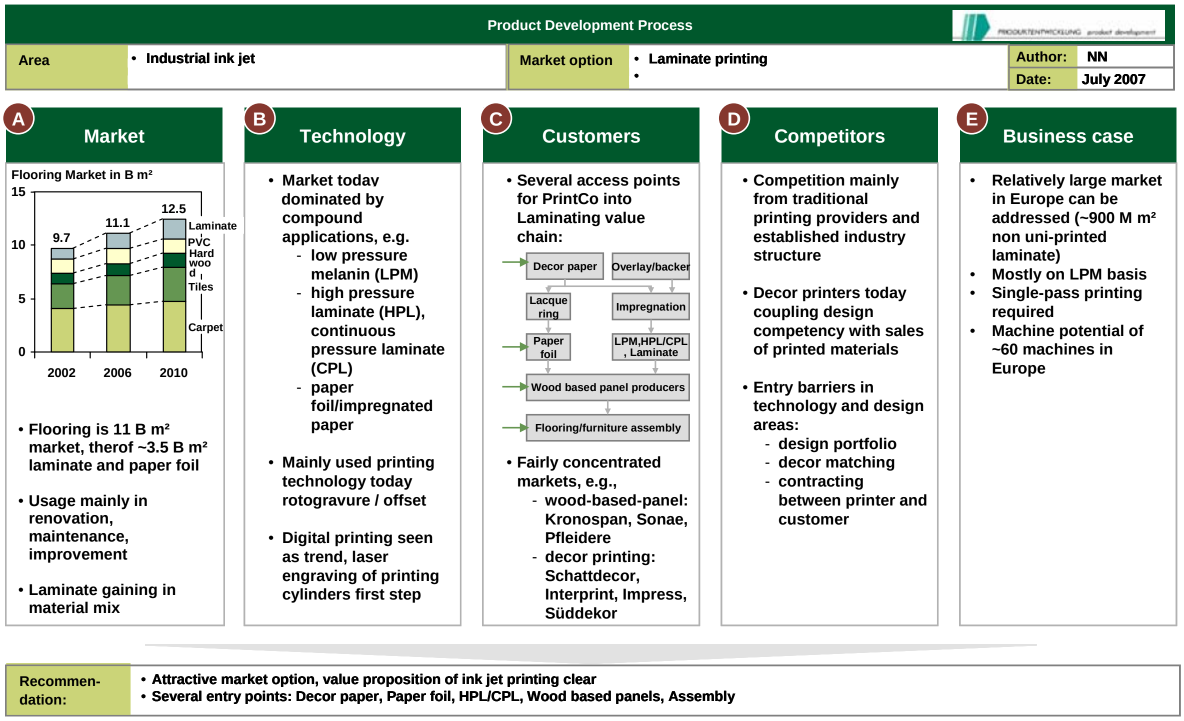


Figure 6-6: Market option form for laminate printing

On the technology side, stress was laid on generating a diversity of solution ideas for several open questions, for example:

- How can the substrates be guided and transported through the printing machine to provide precise alignment under the print head but also to keep the machine in pace with the overall production line?
- Which print heads and ink technology should be used in order to guarantee the desired image quality and resolution, robustness and cost efficiency?

The solution finding on the technological side emerged as a two-step process: First, very rough solution principles were captured using simple sketches. Although this is a rather simple action, it already significantly improved the exchange of ideas between the technical experts from various fields and also the exchange between technical and commercial functions. Interestingly, already on the base of rather basic sketches as illustrated in Figure 6-7, marketing managers gave very helpful input on solutions by making use of potential competitors' solutions and customers' work flow.

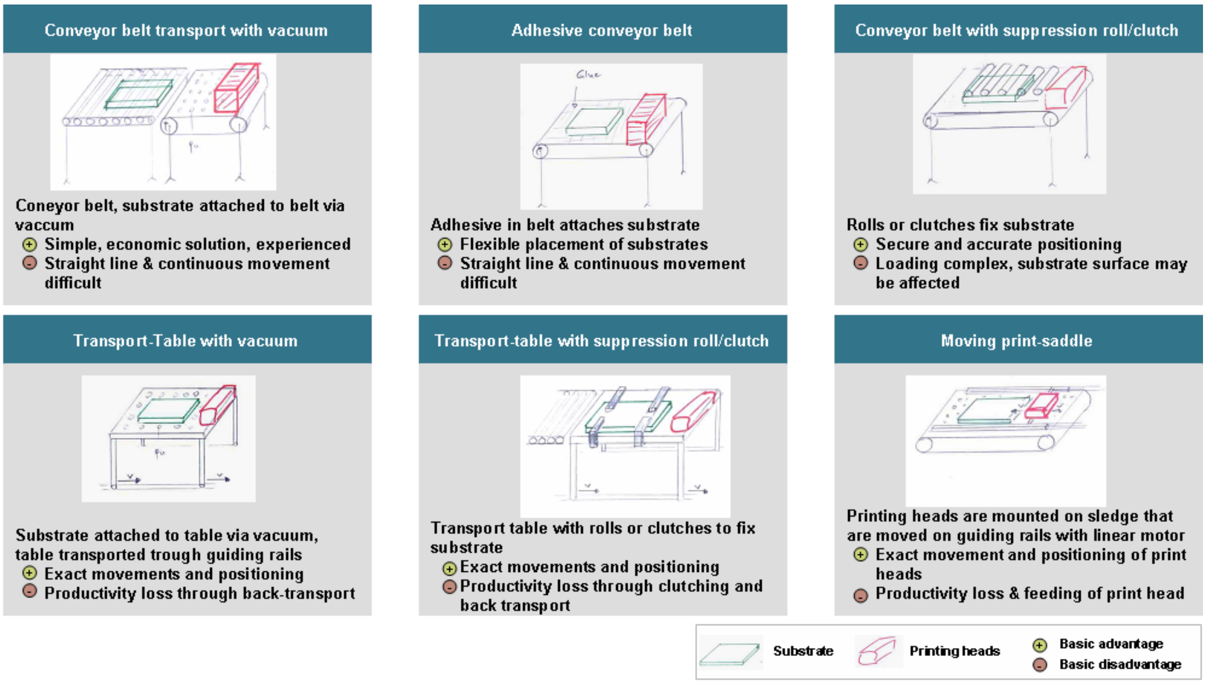


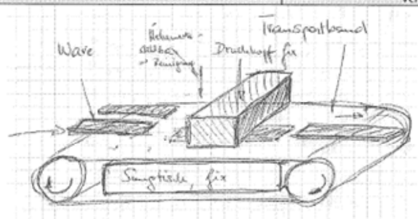
Figure 6-7: Rough design sketches for transportation mechanism

When options were being investigated further, the technical option sheet proposed in section 5.4 assisted in deriving and documenting their properties. Figure 6-8 shows an option sheet prepared by a member of the design team who was responsible for most of the mechanical engineering parts. The members of the design team reported that while at the beginning it felt unusual to document results in such a way, it helped the designers to structure and clarify their own thoughts. Moreover, the documentation with fairly easy-to-understand sketches made it easier for them to exchange and get feedback on ideas and proposals. This exchange worked well between peers, colleagues in other sub-teams as well as with the senior management.

Transport Industriedrucker
Industrial Printer X451

Bereich:	Mechanik	X	Software		Problem		No: 1
	Elektronik		Anderes		Beziehung zu Marktoption		Datum: 4.4.2007
Lösung/ Option	**Bandtransport**						
Beschreibung:	Die Ware wird von einer Vorgelagerten Transportstraße auf das Transportband gelegt. Die Ausrichtung der Ware geschieht dabei vorher, es kann also von einem parallel am Band liegenden Gut ausgegangen werden. Der Startpunkt des Druckes ist allerdings zu ermitteln, indem die Lage der Vorderkante über einen Sensor bestimmt wird. Die Laminate werden mit Hilfe eines Vakuums welches unterhalb des Bandes erzeugt wird und über die Perforation des Transportbandes auf die Ware wirkt mit dem Band verbunden und mittransportiert. Die Länge des Bandes errechnet sich aus der doppelten, maximalen Warenlänge zusammen mit der Länge des Druckkopfes und unter Berücksichtigung eines Beschleunigungsweges.				Angenommene Spezifikation		Autor: EPT/Sj
					Vorhandene Erfahrung	Beim Gamma und der RHO Serien von DIT Lienz	

Design Sketch



Versuchsergebnisse (Experimente, Bilder, Grafen etc.)

Vorteile:	• Einfache, wirtschaftliche Lösung • Erfahrung vorhanden (mit RHO Baureihe) • Versuchsaufbau steht zur Verfügung • Flexible Lösung, für unterschiedlichste Warentypen geeignet • Externes Know How beschaffbar	Nachteile:	• Geradlauf des Bandes nicht vorhersehbar und schlecht automatisiert zu beeinflussen • Umgebungseinflüsse können gravierende Veränderungen bewirken, welche direkten Einfluss auf die Qualität des Druckes haben. • Gleichlauf des Bandes schwierig einzuhalten, Gutbelegung und –entnahme beeinflussen Schlupf im Antrieb • Lebensdauer beschränkt • Austausch des Bandes beim Kunden aufwändig • Bei sehr langen Bändern etwa für die Verarbeitung von Leisten ist die Genauigkeit des Bandlaufes durch die großen Dehnungen über die Länge nicht mehr zu garantieren • Druckkopf muß zur Wartung in der Höhe verstellt werden, sonst kann keine Wartungseinheit zu den Köpfen gelangen
Kommentar:	Anstelle eines Saugbandes sind auch Lösungen mit Kleber oder Klauen denkbar		
Empfehlung:			

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Figure 6-8: Technical option sheet for transport mechanism (in German)

The discussed options-based approach also helped in expanding PrintCo's overall technology, market knowledge, and solution assortment (See Figure 6-9). Specifically, four selected transportation mechanisms where evaluated with regard to their usage in two different market segments (laminate printing and furniture panels) along market criteria derived during market analysis. In this example, laminate flooring is best supported by a moving print saddle, whereas furniture panels are best supported by a vacuum-table. The circled numbers indicate the total scores regarding a technical or a market option, respectively. Reading the matrix downwards in the columns indicates, which market option is best supported by the existing technical solution options (in the mentioned example, the two options are equally strongly supported). Thus the structured documentation and evaluation of options did not only contribute to the selection of an appropriate solution but also to the development of construction options and the re-use of technical approaches in later projects.

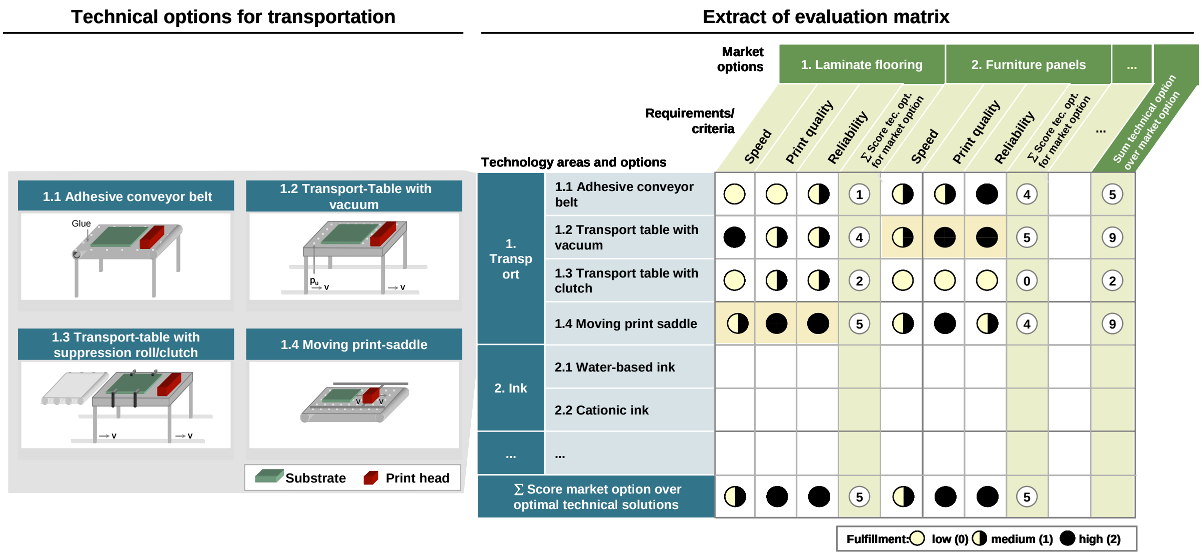

Figure 6-9: Technical transportation options and evaluation matrix

Having finished the options generation phase for the pilot project and having reflected on the results, it became obvious that the new procedure had not only altered the proceedings but also brought new results. The type of print heads, for example – a key component of the new printing system – was switched to a new type with a different mechanism. This decision was driven by conceptual analyses as well as the evaluation of tests with different fabricates. It was commonly agreed on that such a shift in design could probably not have been realized by the old sequential product development method with a strong division of labor. As a preliminary result, two prototypes of a digital laminate printing system representing a product new to the company and the world were developed within 12 months. One system was handed over to a lead customer for a "real life" field test, the other one was kept in house for further development.

On the organizational side the collaboration of various stakeholders and their contribution to the new product development process were defined. Figure 6-10 visualizes this interplay along the process logic. A key objective was to bring in the input and experience of all functions, i.e. R&D, marketing, senior management and operations at an early stage in the front end which served two purposes: First, the input came at a point where the degree of freedom with respect to the new project was still very high and could actually be transformed into the product and production concept. Second, the early involvement also enhanced the overall buy-in to the project. People in functions more remote to the actual product development like production and service were credibly involved in the design process. Thus, their attitude towards a new product causing frictions in their operations was positively affected.

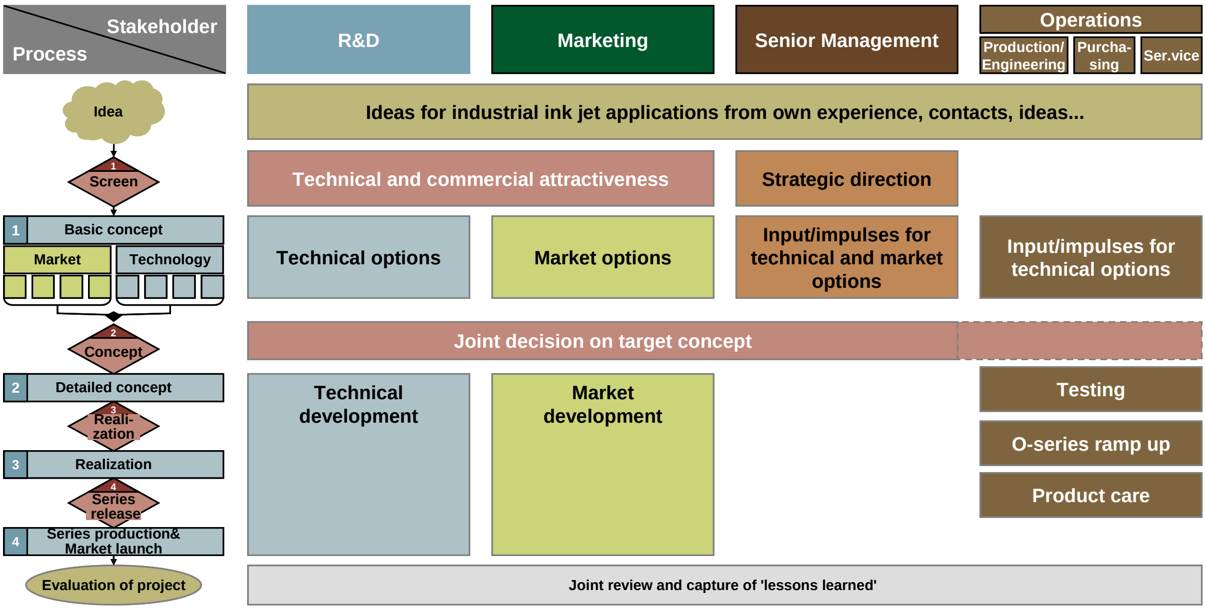

Figure 6-10: Stakeholders' contribution to PrintCo's development process

Furthermore, the project very much brought the underlying change of the company to the surface. PrintCo's success in the "old" photo technology market relied mostly on the criteria quality, durability and a strong brand. Through the project and the research in potential target markets it became apparent that success factors were changing, particularly because customers turned from craftsmen operating a stand-alone machine into industrial clients running mass production processes. Figure 6-11 shows how a change in products and markets influences the domains of production, sales processes and finally even business models and organizational success factors.

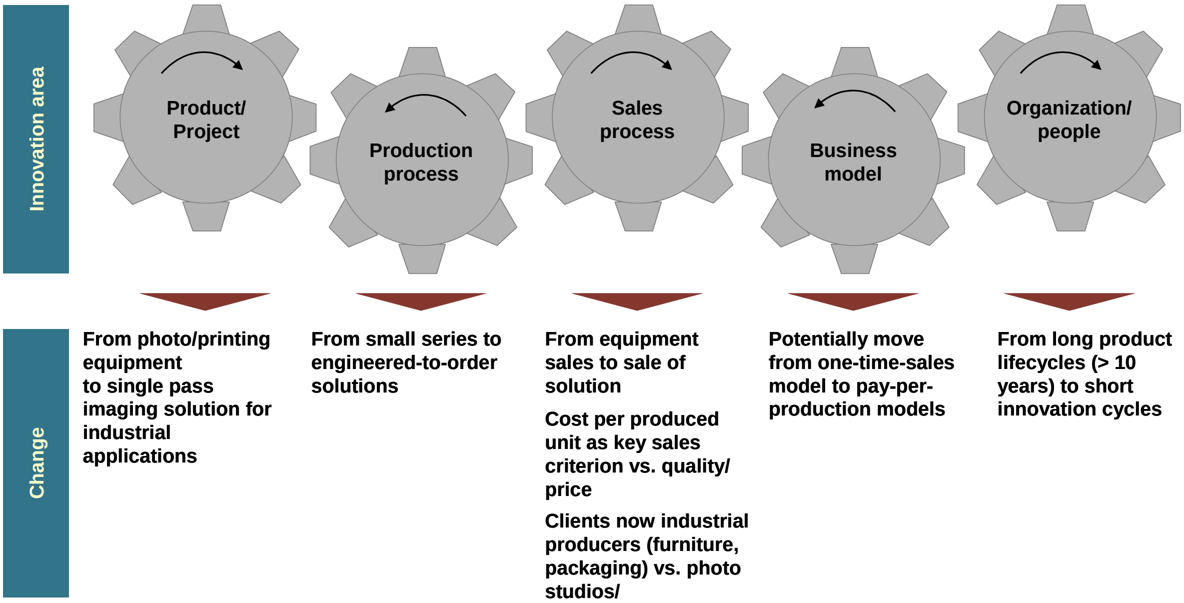

Figure 6-11: Changes in PrintCo's success factors and culture induced by new products and markets

While the project team could concentrate on the content and the results of the project, it was noticeable that the change of the company's environment and possible direction caused a certain anxiety towards the future direction. The team gained structural support and guidance from the process but also referred to the senior management in order to set guidelines for further development areas.

6.2 Radical Innovation in the Packaging Industry

The case of radical innovations at PackagingCo was already introduced in section 1.2.1. While the model developed in this thesis has not fully been implemented in this setting, the company's handling of this innovation venture allows for the derivation of effective procedures in innovative projects. These measures can be translated and compared to the proceedings, methods and tools proposed by the model for uncertainty handling in integrated product development.

First, the notion of option building that span the commercial and technical side of the project can be observed within this project. On the market side, the size of the retort market which was targeted with the innovation comprised a large market potential with 90 billion units of packaged products per year. Since PackagingCo typically supplies the processing and packaging machinery as well as the corresponding packaging materials as a consumable, a large number of packaged units in the consumer market can lead to sustained packaging material sales. When sizing the market and its segments it became obvious that the 90 billion units were composed of various products which were produced in various regions, packaging substrates and sizes. The heterogeneous composition of the market regarding products, geographies, packaging substrates and sizes is illustrated in Figure 6-12.

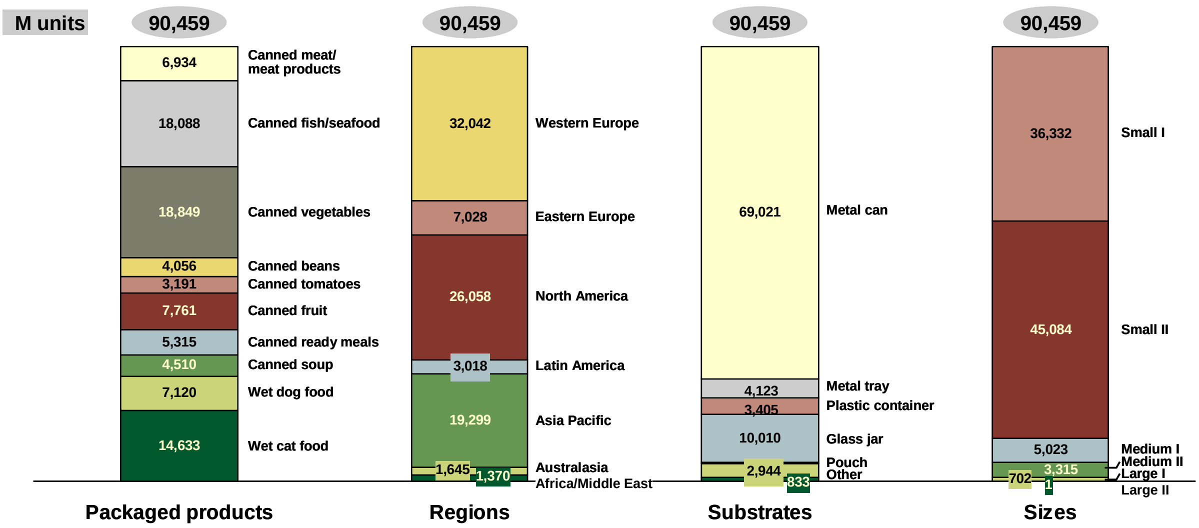

Figure 6-12: Retort food market segmentation, global market 2003 [EUROMONITOR 2005]

The heterogeneity of the market is further reflected by the characteristics of various product sectors. Canned vegetables, for instance, are mainly produced an consumed in Western Europe (8,800 of the worldwide 18,800 units are produced here), and the market is dominated by private label producers, holding 23% market share. By contrast, canned ready-meals constitutes predominantly a North American market (3,900 of 6,800 units in total are produced there), and the top three branded goods producers account for approximately 30% market share [EUROMONITOR 2005]. These distinct characteristics lead to the definition of market segments along the major products that can be seen as market options describing possible access points into the retort food market.

On the technical side, several problems had to be addressed in order to realize the envisioned packaging system, which can be grouped in the following four development areas:

- Autoclave machinery and process that sterilizes the product and the packaging through heat and pressure: The filled packages are thereby exposed to temperatures of 130°C and a humidity of 100% in order to neutralize any bacteria in the product.
- Packaging compound that protects the content against gas diffusion and mechanical impact during packaging, storage, and transport. The laminate compound also has to withstand heat, moisture, and pressure during an autoclave process.
- Processing and filling machinery that portions the product into doses for packaging and thereupon fills and seals the package.

- Line and process automation that enables an automated process between the main machinery for processing and filling, sterilization, and secondary packaging.[18]

Out of those four main areas, the processing and filling machinery was perceived as one representing significant complexity and uncertainty. Whereas the compound design, autoclave and line automation processes are rather invariant to the actual product to be filled, the design of the packaging machinery is heavily impacted by the product's content. In other words, no single packaging technology could fulfill the requirements for all use cases. A core aspect here was the definition of the actual filling principle. During the filling process the product is transported from a storage container, portioned into doses and finally filled into the substrate. This task was seen as a major open issue by the design team, which thereupon decided to create possible options for filling principles. Hence, several structurally different technologies were sketched and evaluated theoretically and in orienting tests. Figure 6-13 shows the relevant options for filling principles.

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[18] Secondary packaging refers to those activities that take place after the actual filling of the product into the package in order to improve the handling, storing and presenting of the package properties. For instance they include labeling, straw or caps application, tray packing, and stapling onto pallets.

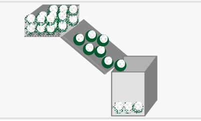
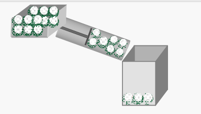
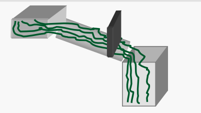
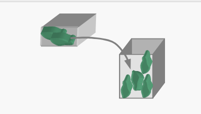
Option	Filling principle	Product properties	Typical products
Pouring		Bulk solid, pour-able, products able to trickle, not to sticky chunky products, only one mixture	 Peas, olives, maize, beans, cutted beans/string beans, pieces of fruits and tomatoes, plums, cherries, mushrooms, dried pet food
Pumping		Pumpable, viscose products with and without chunks	 Soups without high ratio of chunks, bigger chunks and less damaged chunks, some kinds of pet food
Cutting		High viscose products or products which can be cut	 Variants of pet food, sauerkraut, kale, red cabbage etc.
Others (single placing)		Products which are normally filled manually or in an orientated way, products with fixed concentration rates	 Cucumbers, sausages, mixtures in specific fixed concentration rates, asparagus, long beans, pet food etc.
			Packaging substrate / Product

Figure 6-13: Technical filling options and market implications

After mapping the options on the market side along the market segments and the technical options for filling systems along the basic filling principles, those two perspectives were brought together. Thereby, the two key decisions in the early phase of this innovation project were treated simultaneously, namely:

- Which market segments should be targeted for an entry?
- Which technical filling should be pursued?

The technical options are assessed for their fulfillment of the requirements of the defined market segments. The resulting matrix that is similar to the decision support matrix proposed in section 5.4 is reflected in Figure 6-14. From this analysis, the market segment vegetables that represents 20% of the global market and is characterized by a dominance of branded goods manufacturers which are typically more receptive towards processing and packaging innovations is seen as an attractive market option. With the filling technology "pouring" which provided the strongest fit with this segment and which already had been tested positively, the preferred combination of market and technology options was found in vegetables processed with a pouring technology.

Segment/market option		Volume (in M units)	Technical options				Comment
			Pouring	Pumping	Cutting	Other (single placing)	
Meat	Beef, others	4,546	○	◑	◑	◑	
	Sausages	2,388	◔	○	◑	◑	
Fish/ seafood	Tuna	7,942	○	◔	◔	◑	
	Whole fish, others	10,146	◔	○	○	◕	
Vegetables	Peas	1,485	◕	◑	○	◔	
	Mushrooms	2,338	●	◔	○	○	
	Corn	2,078	●	◑	○	○	
	Cabbage	1,041	◕	○	○	○	
	Olives	2,236	●	◔	○	○	
	Gherkin	2,163	◑	○	○	◑	
	Beans	2,000	◑	○	○	◑	
	Carrots	1,093	◑	○	○	◑	
	Asparagus	751	○	○	○	●	
	Baked beans	4,056	◕	○	○	◔	
	Tomatoes[1]	3,191	◕	○	○	◔	
	Other	3,666	◑	○	○	◔	
Fruit	Peaches/apricots	1,377	◑	○	○	◑	
	Pineapple	1,896	◔	○	○	◑	
	Cherries	545	●	○	○	◔	
	Pears	538	◔	○	○	◕	
	Other	3,404	◑	○	○	◑	
Ready meals		5,315	◔	◔	◔	◑	
Soup		4,510	◔	◕	○	○	
Pet food		21,783	◑	◑	◔	○	

1. Allocated under vegetables due to positioning in retail market

Fullfillment/fit: ○ Low ◑ Middle ● High

Figure 6-14: Matching of market and technical options

While this early decision required a profound analysis and also contained the risk of betting early on the wrong horse, it also provided a fruitful goal stability and clarity to the project: The project team focused on the industrialization of a chosen technique and the acquisition of pilot customers in the field of vegetable processing and packaging. Thus, the decision accelerated the overall development project. Moreover, since over 40% of the global canned vegetable production takes place in Western Europe, this emphasis on a preferred technology and market option provided further regional focus which reduced the complexity of this radical innovation project. This procedure supports the thesis postulated in section 5.4, namely the exploration of new markets and technologies through options development and integrated decision-making under uncertainty.

Second, effective collaboration between commercial and technical work-streams and respective project members can be observed in this project co-headed by a technical and a commercial project leader and reported directly to the CEO of the company which gave the project a high visibility and priority in the organization. The technical project leader was responsible for the development of the key components laminate structure, packaging machinery, autoclave and line equipment, and had formed respective sub-projects in order to address these issues. The commercial project leader was in charge of the market research, definition of a value positioning, derivation of key requirements, selection and acquisition of lead customers, and a marketing strategy. The two project leaders took all relevant decisions after consultation with their partner, reported jointly about the progress of the project and involved the senior management in key decisions. While the top management was constantly challenging the proposal of the project team, this proactive involvement also created a sense of ownership and support at this level. Moreover, for the course of the project, the two project leaders and the technical and commercial sub-teams were located within walking distance in the same or adjacent buildings which enhanced the information flow and collaboration between the various work-streams.

The project team and the senior management of PackagingCo perceived the early focus on radical development projects and the described cross-functional working head as strongly beneficial to the project proceedings and results. Consequently, despite inherent risks and the distance to PackagingCo’s core business the product development was successfully driven to the prototyping and field testing phase.

6.3 Comparison to Successful Product Innovators

The developed approach for uncertainty handling has been implemented and evaluated in detail at PrintCo, and significant commonalities to the proposed processes and mechanisms were found in PackagingCo’s procedures and organizational setup for radical innovation projects. Further evidence for the suitability of the proposed measures can be drawn from a comparison between the proposed measures and the experiences of companies with a strong success path in innovations. This was accomplished by research and semi-structured interviews with experts for new business and product development at W.L. Gore & Associates in its fabrics division. The company is frequently mentioned in the context of successful product innovation and product development in industrial markets [For example

ANDREW, SIRKIN 2007, p. 64f; HAMEL 2007, p. 87ff]. Its best-known product is GORE-TEX, a waterproof and breathable fabric that is used in a wide variety of garments. Today, W.L. Gore & Associates is a company globally active in various markets with 7,000 employees and sales accounting for €2 billion. The firm is entirely held by the founder's family and employees who are called associates. Since its foundation in 1958 the company has frequently applied innovative products in new markets, for example medical devices, membranes and signal transmission. The core of its technology is expanded to Polytetrafluorethylen (or ePTFE), which was invented by W.L. Gore & Associates. Bill Gore, the company's founder, discovered that PFTE, a polymerized tetrafluoroethylene known for its chemical inertness, high thermal stability, low coefficient of friction and other distinctive properties, can be stretched to create strong micro-porous material known as expanded PTFE or ePTFE. It has a low dielectric constant, making it a strong isolator against electric current and a low coefficient of mechanical friction. Moreover, it exhibits a high strength-to-weight ratio and is biocompatible qualifying the material for usages within human bodies. This technology has since been integrated in consumer and industrial products like sports and outdoor apparel, industrial membranes, and high-performance textiles [CLOUGH 2007, p. 2ff].

Figure 6-15 illustrates ePTFE fibers and their application in high performance fabrics.

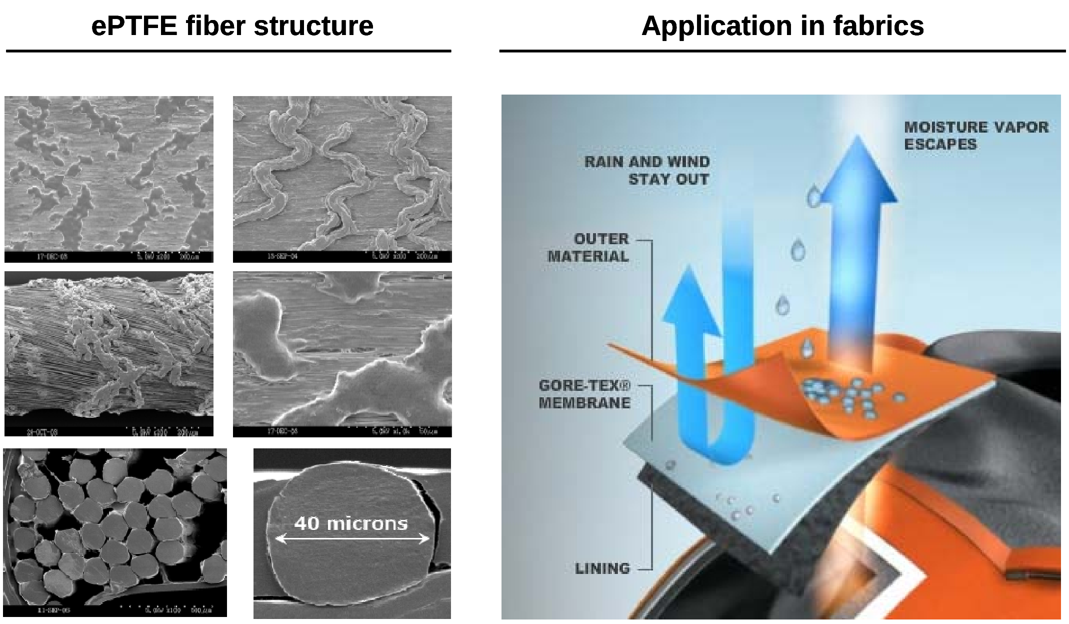


Figure 6-15: ePTFE structure and applications [CLOUGH 2007, p. 8]

Gore is not directly marketing its product to end consumers, but supplies original equipment manufacturers with the PFTE technology in order to enhance the performance of their products. By doing so, W.L. Gore & Associates has demonstrated its ability to successfully enter markets, which previously were not covered. The company is known for its innovation focus and its special corporate culture characterized by flat open networks and a hierarchy-free organization that has been studied in the product development literature [For example BRAUNSCHMIDT 2005, p. 246ff; HAMEL 2007, p. 87ff].

On the one hand, Gore's already established brand made the company overcome barriers to enter markets and helped to acquire new customers. On the other hand, Gore's internal way of aligning marketing and product development processes and decisions can be seen as a further factor to its innovation success. The processes, methods and tools as well as organizational mechanisms applied by Gore are herein comparable to the requirements for product development under uncertainty and the model discussed in this work.

Gore's product development focuses strongly on projects in the area of new business development. While the operations and sales processes are executed in the business areas, a special new business development process is set up to find new applications and markets for the PTFE technology. This process comprises the generation and screening of ideas, the development of business plans and start-up activities for the exploration of new markets. After a successful market launch technology and business concept are taken over by the responsible business units.

With the company representing a more technical and engineering-oriented culture and viewpoint, stress is laid on creating the necessary commercial transparency and hence on integrating market and technology perspectives. This integration is ensured by deploying multifunctional teams with experts from various fields of expertise and seniority. The proceedings are supported by methods and tools like a "real-win-worth it" screening [DAY 2007, p. 114ff], where a technical novelty and its associated product are tested for their commercial viability and sustainability along a series of compact questions, namely:

- Is it real?: Is the market real? Is the product real?
- Can we win?: Can the product be competitive? Can our company be competitive?

- Is it worth doing it?: Will the product be profitable at an acceptable risk? Does launching the product make strategic sense?

Gore's process approach thus supports the notion of stressing the front end – in Gore's case it is even organizationally separated from the rest of the actual design and operations processes. Furthermore, the procedure is characterized by option building even though this not yet formalized in the product development process. Gore has been using a stage-gate process to guide the product innovation process, which worked quite well for incremental innovations. When retrospectively evaluating a radical innovation project in the fabrics division that dealt with a new technology in a direct consumer segment, i.e. a market new to the company, the stage-gate process proved to be too rigid and linear to support this project. As a consequence, the stage and gate regimes were only followed in the first two stages. Afterwards, the project team referred to a *"normal technical driven project management"* that also embedded the use of options to guide the project.

The organization for product development as well as the working mode and corporate culture at Gore is also seen as an important enabler of successful new product ventures. Every employee – in Gore's terminology an associate – can initiate new projects and activate his or her network within the firm in order to gain resources for the initiative. Thus, the organizational culture is concentrated on individuals, informal networks and life-long learning rather than structured departments, hierarchies and clear lines of command. Gore even postulates a "no ranks, no titles" system to promote information sharing and a flexible composition of project teams. The corporate culture also supports a positive perception of new tasks, uncertain areas and the risk associated with these activities. Mistakes are seen as knowledge-generating incidents that are inevitable when navigating in uncertain waters.

Summing up, the structured review of Gore's product development processes supports a large number of requirements for effective radical innovation and uncertainty handling postulated in section 4.2. Additionally, the proceedings and core beliefs at Gore reflect the elements of the model for uncertainty handling in integrated product development. In some respects, Gore's mode of conducting new business and product developments may be seen as a very pronounced implementation of a front end focus, team enablement, cross-functional integration and decision-making. Its corporate culture with a strong emphasis on information sharing, individual initiatives and flat hierarchies can also be seen as a strong driver for new ideas and innovativeness at large. Especially in the engineered goods sector, this form of collaboration and culture can be regarded as exceptional.

6.4 Radical Innovations in Large-scale Companies

The aforementioned examples describe innovation processes and organizational approaches towards new product developments in small to mid-sized companies with sales ranging from €100 million to € 1,5 billion. While all of the discussed cases depict radical innovations that target worldwide markets, the size of the companies investigated is rather limited. By investigating product development mechanisms in large-scale companies, a preliminary estimation of the applicability of the developed model in such enterprises shall be derived.

Several authors argue that it is often difficult to get support for radical projects in large firms [14], where internal cultures and pressures often push efforts towards lower risk, immediate reward and incremental projects [DOUGHERTY, HARDY 1996, p. 1144ff; MCDERMOTT, O'CONNOR 2002, p. 425]. In a longitudinal study of radical innovation projects in ten large-scale North-American enterprises, McDermott and O'Connor [MCDERMOTT, O'CONNOR 2002, p. 427ff] identify the critical issues for innovative ventures in such firms. The study includes well-known innovative companies like Dupont, General Electric, IBM, Nortel, Polaroid, Texas Instruments, and United Technologies. The results are grouped into the major areas market scoping and exploration, competency and risk management, and finally people issues. Market scoping describes the challenge of defining and exploring a potentially unknown market. Especially if the innovation takes place in markets not yet existing or explored by the company, the topic of market scoping often represents a major challenge. In these cases, the task of generating the necessary market insight cannot be taken over by marketing and sales organizations or lead customers, explains why distinct pre-development teams are rather put in charge of market exploration and the forming of market options. Competency management refers to the generation of required but missing know-how and skills within organizations. Companies take various approaches to risks arising from new product ventures which include systematic competency management to stretch the existing capabilities, outsourcing to forward the risk to a third party or simply ignoring the risk. Finally, people and team issues are assigned a high priority in the context of radical innovation. On an individual people level, two roles are predominant: A sponsor from the senior management, who supports the project, assigns priority to it through his or her involvement and provides financial backing for long-lasting innovation ventures. On an operative project level, a passionate champion is a success factor to keep up the momentum and enthusiasm in a project. Six of the twelve radical innovation projects studied in the aforementioned context were affected by a senior management turnover. In such instances an intrinsically motivated champion was often the key to keep a project alive. The role of senior management sponsors and project champions is further studied with similar results [For example HOWELL, HIGGINGS 1990, p. 329ff; HAUSCHILDT, GEMÜNDEN 1999]. In terms of a cross-functional team composition, the authors observed that teams consisted of experts of various functions but also noted that marketing was quite underrepresented in such new product development teams for radical innovations. Rather, informal networks enabling team members to access vast information and knowledge became a major success factor [MCDERMOTT, O'CONNOR 2002, p. 433]. A similar observation is reported by Wood and Brown [WOOD, BROWN 1998, p. 170ff] studying Sony's breakthrough development of laser diodes in the 1980 and 1990s. The divisional structure and segmentation of technologies, markets, and functions into monolithic departments represent a major obstacle to radical innovations. Hence, Sony's laser diode innovation that is today a mainstream application in various kinds of media players was not only supported by the above-mentioned product development process mechanisms, sponsors, and champions. The realization of the project furthermore required distinct network building capabilities such as internal symposia and technology expositions.

The description and analysis of radical innovation projects conducted in large-scale companies is still lacking breadth and depth. Nevertheless, a preliminary estimate of the applicability of the model in such environments can be derived from the discussed examples. The basic principles of front-loading and option generation can work as pointed out by McDermott and O'Connor. While the basic notion of cross-functional working modes also applies to large-scale corporations, its realization in the practice of large corporations seems challenging. Next to sponsors and champions who overcome some of the hurdles present in such environments, special instruments such as job-rotation, internal conferences, and symposia are essential. Another question arises from the disparity of the project duration for radical innovations and the stringent quarterly financial reporting demanded from listed companies. With senior managers’ tenure in leadership positions and financial reporting cycles undercutting the throughput time of radical innovation projects, there might be little support for these kinds of projects. Consequently, while the basic transferability of the developed model to large-scale companies is feasible, its successful execution will most probably require further research and adoption to the specific environment.

6.5 Conclusions from Industrial Implementation and Comparison

In the following, the results of the in-depth case studies as well as the accompanying interviews are taken as a basis for an evaluation of the validity of the model proposed in chapter 5. In particular, the real-world observations of the innovation projects at processes at PrintCo and PackagingCo as well as the review of W.L. Gore & Associates procedures are assessed against the requirements postulated in section 4.2. Thus, important feedback on the effectiveness of the developed model is generated and thrusts for further developments can be derived.

The industrial implementation shows whether the proposed model for uncertainty handling meets the requirements set up, namely:

- Providing process guidance but also offering flexibility for jumps, iterations and switches in the level of embodiment in a project;
- shifting information gathering and key decision-making on technical and commercial aspects to the early phases of the development ("front-loading");
- embedding options in the development process in order to explore the uncertain space and to derive an optimal solution as soon as possible;
- fostering the combination of technical and commercial aspects in development projects;
- supporting the development process and enhancing its robustness through tools and methods.

The necessity of providing a guiding framework for the process that also offers a large part of flexibility became apparent in all case studies. The developed model met both demands by offering a process in the three basic phases (idea development and agreement, options development and assessment, and solution development) while providing room to broaden analyses and experiments especially during the options generation phase. A deliberate setback from the evaluation and decision step to the options generation phase proved to be helpful, particularly in the case of PrintCo. Here, upon the assessment of the printing quality for digitally printed laminate panels, the concept was reiterated using a different set of printing heads and corresponding ink. In the case of PackagingCo it was vital to test product ideas with a focus group of consumers and retail experts already in the process. The proposed approach can handle such forward and backward jumps as well as switches in the level of embodiment especially in the early phase. Once the decision is made to pursue with a combination of a technical and commercial option, the process flow is designed for rather linear and sequential proceedings towards the completion of a project.

Front-loading was also confirmed to be a strongly beneficial habit in radical innovation projects as most decisions had to take place here against a high level of perceived uncertainty causing the project team members to experience internal and external pressure. The model responds to this with a clear focus on the early stages and the generation of an option space on the market and technology side. Especially in the case of PrintCo and PackagingCo front-loading and option generation were seen as a vital support to both the innovation project and its members. Through the building of options people were able to learn about unknown areas in a structured way and also were inclined to generate a variety of solutions even in situations where one initial solution seemed sufficient. An additional aspect came into play when considering senior managements' contributions to key innovation projects. Derived and documented options provided a base for the senior management to participate in the key decision of a project and to balance the risk in the moves. In the case of PackagingCo's innovation in the retort food market, the option building and subsequent narrowing down of the project's market and technology were even seen as a key factor in the company's decision to pursue the project further.

While the need to work collaboratively especially across the technical and commercial function was obvious in all the projects considered, the developed model could only supply a part of this collaboration. The evaluation and decision step structurally integrated the market and technology view in PrintCo's and PackagingCo's innovation projects. In the case of PrintCo the decision matrix as well as the codified option sheet represented focal points for this integration. However, PackagingCo was striving for a more continuous integrated working mode between market and technology-oriented tasks. One of the means to achieve this integrated mode was the deployment of a technical and commercial co-project leader each and the physical integration of the sub-project teams by moving into adjacent offices. In the case of W.L. Gore & Associates, projects were typically initiated and steered from a technical viewpoint and the commercial perspective was added by the very same project members during the course of the project.

In terms of method and tool support, the implementation of the model at PrintCo and PackagingCo proceedings showed that the contained tools provided the desired support and orientation. In PrintCo's case the initial development agreement was seen as a key enabler to reach consensus and commitment among marketing, R&D and the senior management on framework, resources and goals of the project. Capturing proved to be a valuable tool beyond an actual project as it led to the development of a company-specific solution database. The decision matrix was used at both in-depth case studies and provided a valuable overview of the status of the development project and an important base for decisions on the proceedings of a project. A comparison to successful innovation projects at Gore revealed that here a small set of robust methods and tools was also deployed in order to support innovation ventures. Most decisive among these was the "real-win-worth it" screening that provided a quick but comprehensive overview of the sustainability of the project by challenging it with a series of questions [DAY 2007, p. 114ff].

Figure 6-16 summarizes the fulfillment of the implemented model with the above-mentioned criteria. Taken as a whole, the industrial implementation and comparison show that the proposed model is able to support radical innovation ventures by providing flexible guidance as well as a front-loaded and options based approach. The methods and tools provided valuable support for the product development teams and hence increased the robustness of the proceedings. The model supports integrative and collaborative behavior between technical and commercial activities in the project. At the same time, it became apparent that a process alone could not enhance this integration but that team composition, leadership and attitude towards risk played an integral role. Furthermore, especially the implementation at PrintCo showed that further uncertainties could arise during a radical innovation project calling for a similarly structured handling. Figure 6-11 illustrates how a radical new product can induce changes in the production system, the sales approach and the business model. Covering these additional aspects leads to a possible expansion of the presented model.

Requirements towards Procedural Model	Model's requirements matching in industrial implementation and comparison		
	PrintCo	PackagingCo	W.L. Gore & Associates
1 2 Orientation, yet with flexible process set-up	● Process allowing for frequent iterations and jumps in front-end, linear in back end	◐ Orientation for major innovation given, yet several options already tested in experiments	◐ Several forward and backwards jumps in typical innovation projects
3 Embedding of options	● Set of options generated: • market: product segments • technical: transportation, print-heads, ink	● Large variety of options generated on technology and product segment, senior management decision prepared	◐ Options mostly used for market related questions
4 Front-loading	● Major decisions on technology and market segment choice shifted to front end, rather linear procedure afterwards	● Major decision on market and technology taken very early, project thereby focused and streamlined	● Lack of front-loading observed in former projects, market approach and technology choice deliberately pulled forward
5 Cross-functional collaboration	◐ Commercial and technical aspects integrated using defined focal points	● Market and technical options systematically linked, technical and commercial project co-lead	● Approach traditionally very technology-driven, market perspective added
6 Tools and methods support	● Robust support with three key tools: Development agreement, options capturing, holistic evaluation	◐ Linkage of technology and market option in matrix tool	● Process supported with tools similar to options capturing sheet and decision matrix (E.g., Real-win-worth check)

Fulfillment/fit: N/A Not applicable ○ Low ◐ Middle ● High

Figure 6-16: Requirements matching in industrial implementation and comparison

7 Summary and Outlook

7.1 Review of Research Questions and Findings

Innovation projects have to face external and internal uncertainties, which result from lacking or imperfect information on the market, customers' behavior, competitors' moves and unexplored technological fields. Generally, the level of perceived uncertainty increases with the degree of innovativeness and novelty of the product, as those projects cannot draw from past experience. Hence, for radical innovation projects dealing with uncertainties of various sources becomes a major challenge. This thesis aims at providing a procedural model for the support of radical innovation ventures taking place under uncertainty.

A review of the prevailing literature on product development processes shows that most models exhibit some form of shortcoming in promoting radical but uncertain development projects. Models stemming from a managerial as well as from an engineering background possess several critical commonalities in their handling of product development processes in general and in their addressing of uncertainties in tasks and decisions in particular.

With regard to radical innovation projects the linearity common to several process models does not fully support product development under uncertainty. The ambition to also handle more radical and innovative product development processes in a linear mode is understandable. However, especially these types of innovation require jumps not only along one dimension but will also call for jumps to the side or between different levels of concreteness. A further common aspect of most prevailing models is based in the handling of market and technology uncertainties. Typically, a model will support the product development team in discussing one of these sources of uncertainties. Nonetheless, market and technology are often not considered in an integrated way although they coexist in the company's environment and show interdependencies.

Hence, from the analysis of the state-of-the-art a gap with respect to supporting radical innovations can be shown.

Based on the discussion of existing product development models as well as on the observation of radical innovation project teams, the following requirements towards procedural models supporting projects under uncertainty are derived:

- Flexible process set-up: Procedural models supporting such ventures need to offer the necessary flexibility for iterations, switches and jumps in the level of embodiment.
- Front-loading: The early phase is of particular relevance for the design of innovative products. It is characterized by a chronic lack of information and a high level of uncertainty, yet the decisions taken in the early stages have the strongest impact on the final product.
- Embedding options: Thinking in options essentially means the generation of several possible solutions from which an optimal one can be chosen. The embedding of options serves two main purposes: Firstly, the solution space is deliberately enlarged in order to seek an optimal solution that might not have been available when following an initial idea. Secondly, through the development of options a solution space is created which contributes to a better understanding of the initial problem and the independencies within solutions.
- Interdisciplinary work mode: An integrative and interdisciplinary work mode between all technical functions (e.g. mechanical and electrical engineering) and between the technical and commercial functions is a key objective of successful radical innovations as they contain a commercial and a technical part. In particular, the uncertainties on the commercial and technical side need to be treated simultaneously not consecutively, and results from both areas have to be integrated.
- Support by methods and tools: The project team and the process should be supported by methods and tools that enhance the stability and traceability of the process. Radical innovations with a high degree of perceived uncertainty are likely to benefit from tools providing orientation and guidance. Through established tools and methods, which rely on a solid documented base, the communication and decision-making between different functional units can also be improved.

Following these requirements, an enhanced approach to uncertainty handling in integrated product development can be put forward. The model is based on the three pillars process design, method and tool support, and individuals, teams, and organizations.

For the modeling of structured uncertainty handling in integrated product development, the process model in general and the early phase in particular are of significance as the highest level of perceived uncertainty is experienced here and the most direction-setting decisions are made. In the integrated model, fields of uncertainty are defined and subsequently explored through options. This method embeds the notion of building and evaluating real options in product development. Following a structured idea generation phase, possible market approaches and technical solutions towards an idea are drafted as options in the front end. A key element of the procedural model is the evaluation and decision step. Here, the options from the technical and market side are integrated, evaluated and finally decided on. It is noteworthy that options need to be considered from commercial and technical perspectives and that their implications and interdependencies have to be discussed broadly. Following the expanded and multi-option based front end, the development project is funneled down to a single-option process through the evaluation and decision step. Hence, the detailed design, prototyping and 0-series ramp-up aim at the solution chosen in the evaluation/decision step.

Methods and tools support this process logic in order to stabilize the process and to document key analyses and decisions in the process. With regard to radical innovations that are treated in this work, two aspects of human behavior gain special relevance and are elaborated further: First, the risk and uncertainty embedded in a radical innovation project have an impact on peoples' tasks and decisions. Secondly, the fact that those radical innovations typically aim at new products in new markets call for a close collaboration of all functions within a corporation.

The organizational aspects of the model concentrate on enabling an integrative work mode between the various participants of a project. Furthermore, the limitations of human beings in dealing with uncertainty and risk need to be considered. Specifically the tendency of individuals and teams towards selective information collection and processing and their disregard for side effects or long-time effects has to be taken into consideration. A process logic that stipulates structured reviews and reflections is used to offset these issues to a certain degree. Nevertheless, a risk taking and failure tolerating approach remains a key factor that has to be ensured by the project leadership and a corresponding corporate culture.

The discussed model for uncertainty handling in product development has been implemented in an industrial setting in order to assess the validity of the model and to evaluate its degree of fulfillment with the above-mentioned requirements. Additionally, the processes and behavior of successful innovators were reviewed and transferred to the proposed approach. As a result of the industrial implementation in the case studies and the comparison to successful product innovators, it can be concluded that the model enables a flexible process set up and dimensioning of the technical and market work streams while providing structure and guidance to the development team. The embedded options helped to gain a better understanding of the problem at hand and to derive integrated decisions incorporating the market and technical view early in the process. While the approach cannot eliminate the immanent uncertainty of a radical innovation project, its proceedings contributed in aligning top management, marketing and the R&D department towards joint risky decisions.

Generally, the model can be broadly implemented as it allows for a flexible scaling and setting of focal points. However, a limitation of the model lies in one of its inherent components. The handling of market and technical uncertainties relies on the development of effective options. Hence, the ability of individuals and teams to form viable options from external information, discussions and experience becomes a key prerequisite. Furthermore, a procedural model can add structure and guidance to a product development process but it largely fails in fully reducing the anxiety underlying radical innovation projects. Thus, the management of a company undertaking radical innovations will have to make direction-setting decisions and should encourage the development team to take decisions under uncertainty. Thereby, teams should be fully aware of the risk, but at the same time they must not be guided by a fear of the personal consequences following such decisions.

Another possible limitation is immanent to the research design set-up which needs to be considered: The uniqueness of each design project and the active involvement of the researcher represent a restriction especially with regard to the issue of general applicability of the methods developed within this work. To counterbalance this, interviews with experts in companies in similar situations outside of the case study context are attached and the respective results complement the insights from the in-depth case study.

In sum, the proposed model is seen as an addition and further development to the product development science and practice.

7.2 Future Development

In design research and industrial practice there is a large and increasing variety of procedural models supporting product development problems. The research within this work has shown that the challenges brought by radical innovations are not fully met by the prevailing approaches. An enhanced approach building on flexible set-up, front-loading, options and an integrative work mode has been derived and validated in industrial practice. The model can further be implemented in industrial settings in order to enhance its validity and robustness. Specifically, while the basic transferability of the developed model to large-scale companies is shown, its actual successful application will most probably benefit from an adoption to the specific environment.

In the early phase, the model depends on the development of alternative options on the market and technology side. Hence, the ability of a product development team to generate ideas and alternatives is an implicit requirement for the effectiveness of this phase. The generation of ideas and solutions can be stipulated with a range of proven tools and methods like brainstorming, morphologic boxes or Delphi analyses [LINDEMANN 2005, p. 217ff]. Nevertheless, the reliance of the product development team's ambition to develop not only one possible solution but to deliberately build up an option space remains. An expansion of the model could thus focus on the initial idea and options generation aspect.

In its current form the model considers market and technology as the main sources of uncertainties and models the exploration of unknown areas through the development of options. Hence, on a conceptual level, the model and the research on uncertainty handling in product development can be expanded by considering more factors and occurrences of uncertainty. Building on the logic introduced in Figure 2-6, this expansion logic is shown in Figure 7-1.

The industrial implementation of the model has particularly shown that radical innovations have the potential to alter fundamental mechanisms in a company. For example, when moving from analogue to digital printing PrintCo also had to re-think the existing revenue model and sales approach. Previously, the company mainly sold equipment that was seen by its customers as an initial investment, whereas the new product was used in industrial flow processes where costs per unit und reliability were important sales factors.

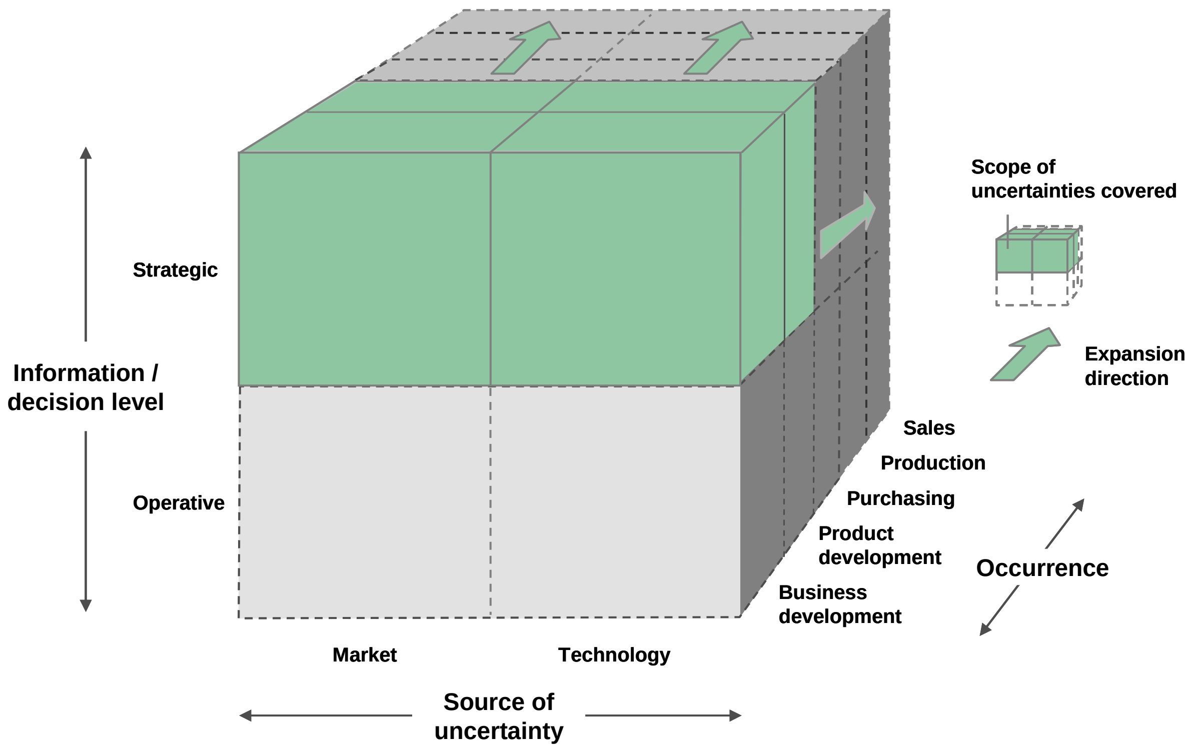


Figure 7-1: Expansion of uncertainties covered

Finally, the model showed how to handle and resolve uncertainties in a structured way in order to increase the learning effect, to generate optimal solutions and to integrate market and technology decision-making. The implementation shows that an integration of different functions within a company and the dealing with risk and uncertainty also strongly relies on the risk perception of individuals and teams and on the motivation of cross-functional work. Following this logic, interdisciplinary research between engineering and psychology seems highly relevant from the perspective of the discussed study in order to further advance the field of product development.

8 Bibliography

Abetti, P. (2000). "Critical Success Factors for Radical Technological Innovation: A Five Case Study." Creativity and Innovation Management, Vol. 9, No.4, pp. 208–221.

Abetti, P. and Stuart, R. W. (1988). "Evaluating New Product Risk." Research Technology Management, Vol. 31, No.3, pp. 40-43.

Adams, A. (1962). "New Product Risk Strategy in Small Firms." The Business Graduate, Vol. Spring, pp. 64-67.

Adams, M. and Boike, D. (2004). "PDMA Foundation’s Comparative Performance Assessment Study (CPAS)." PDMA Visions, Vol. 28, No.3, pp. 26-29.

Adelson, B. (1989). "Cognitive Research: Uncovering how Designers design; Cognitive Modeling: Explaining and predicting how Designers design " Research in Engineering Design, Vol. 1, No.1, pp. 35-42.

Akao, Y. (2004). Quality Function Deployment: Integrating Customer Requirements Into Product Design. Portland, OR, Productivity Press.

Andreasen, M. M. (1991). "Design Methodology." Journal of Engineering Design, Vol. 2, No.4, pp. 321 - 335.

Andreasen, M. M. and Hein, L. (1987). Integrated Product Development. London, IFS Publications Ltd.

Andrew, J. P. and Sirkin, H. L. (2007). Payback: Reaping the Rewards of Innovation. Boston, MA, Mcgraw-Hill Professional.

Ansoff, I. (1962). Corporate Strategy: An Analytic Approach to Business Policy for Growth and Expansion, McGraw-Hill.

Becker, J. and Kahn, D. (2005). Der Prozess im Fokus. In: Prozessmanagement: Ein Leitfaden zur prozessorientierten Organisationsgestaltung. Becker, J., Kugeler, M. and Rosemann, M. Berlin, Springer, pp. 665.

Benbasat, I., Goldstein, D. and Mead, M. (1987). "The Case Research Strategy in Studies of Information Systems." MIS Quarterly, Vol. 11, No.3, pp. 369-386.

Bernard, R. (1999). Early Evaluation of Product Properties within the Integrated Product Development. Aachen, Shaker.

Bichlmaier, C. (2000). Methoden zur flexiblen Gestaltung von integrierten Entwicklungsprozessen. München, Verlag Herbert Utz.

Birkhofer, H. and Jänsch, J. (2003). Interaction between Individuals: Summary of Discussion. In: Human Behaviour in Design - Individuals, Teams, Tools. Lindemann, U. Berlin, Springer, pp. 195-202.

Björk, E. and Ottosson, S. (2007). "Aspects of consideration in product development research." Journal of Engineering Design, Vol. 18, No.3, pp. 195-207.

Black, F. and Scholes, M. (1973). "The Pricing of Options and Corporate Liabilities." The Journal of Political Economy, Vol. 81, No.3, pp. 637-654.

Blessing, L., Chakrabarti, A. and Wallace, K. (1998). An Overview of Descriptive Studies in Relation to a General Design Research Methodology. In: Designers–The Key to Successful Product Development. Frankenberger, E., Badke.Schaub, P. and Birkhofer, H. Berlin, Springer, pp. 42-56.

Boehm, B., Egyed, A., Kwan, J., Port, D., Shah, A. and Madachy, R. (1998). "Using the WinWin Spiral Model: A Case Study." IEEE Computer, Vol. 31, No.7, pp. 33-44.

Boehm, B. W. (1988). "A Spiral Model of Software Development and Enhancement." IEEE Computer, Vol. 21, No.5, pp. 61-72.

Boutellier, R., Gassmann, O. and von Zedtwitz, M. (2000). Managing Global Innovation. Berlin Heidelberg, Springer.

Bowman, E. H. and Hurry, D. (1993). "Strategy through the Option Lens: An Integrated View of Resource Investments and the Incremental-Choice Process." The Academy of Management Review, Vol. 18, No.4, pp. 760-782.

Braunschmidt, I. (2005). Technologieinduzierte Innovationen: Wege des innerbetrieblichen Technologie-Transfers in innovative Anwendungen. Wiesbaden, Deutscher Universitätsverlag.

Brittain, J. and Sitkin, S. B. (1990). "Facts, Figures, and Organizational Decisions: Carter Racing and Quantitative Analysis in the Organizational Behavior Classroom." Journal of Management Education, Vol. 14, No.2, pp. 62-81.

Brown, S. L. and Eisenhardt, K. M. (1995). "Product Development: Past Research, Present Findings, and Future Directions." The Academy of Management Review, Vol. 20, No.2, pp. 343-378.

Brunner, G. F. (2001). "The Tao of Innovation " Research Technology Management, Vol. 44, No.1, pp. 45-51.

Carlile, P. R. and Rebentisch, E. S. (2003). "Into the Black Box: The Knowledge Transformation Cycle." Management Science, Vol. 49, No.9, pp. 1180-1195.

Christensen, C. (1997). The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail, Harvard Business School Press Book.

Christensen, C. M., Kaufman, S. P. and Shih, W. C. (2008). "Innovation Killers: How Financial Tools Destroy Your Capacity to Do New Things " Harvard Business Review, Vol. 86, No.1, pp. 98-105.

Clough, N. (2007). Introducing a new Family of GORE™ ePTFE Fibers, W. L. Gore & Associates, Inc.

Cohen, W. M. and Levinthal , D. A. (1990). "Absorptive Capacity: A New Perspective on Learning and Innovation." Administrative Science Quarterly, Vol. 35, No.1, pp. 128-152.

Cooper, R. G. (1979). "The Dimensions of Industrial New Product Success and Failure." Journal of Marketing, Vol. 43, No.3, pp. 93-103.

Cooper, R. G. (1994). "Third-Generation New Product Processes." Journal of Product Innovation Management, Vol. 11, No.1, pp. 3-14.

Cooper, R. G. (2001). Winning at New Products: Accelerating the Process from Idea to Launch. Cambridge, Perseus Books Group.

Cooper, R. G. (2005). "Your NPD Portfolio may be harmful to your Business's Health " PDMA Visions, Vol. 28, No.3.

Cooper, R. G. (2007). "Managing Technology Development Projects." IEEE Engineering Management Review, Vol. 35, No.1, pp. 67-75.

Cooper, R. G., Edgett, S. J. and Kleinschmidt, E. J. (2002a). "Optimizing the Stage-Gate Process: What the Best-Practice Companies Do—I." Research Technology Management, Vol. 45, No.5, pp. 21-28.

Cooper, R. G., Edgett, S. J. and Kleinschmidt, E. J. (2002b). "Optimizing the Stage-Gate Process: What the Best-Practice Companies Do—II." Research Technology Management, Vol. 45, No.6, pp. 43-50.

Cooper, R. G. and Kleinschmidt, E. J. (1991). "New product processes at leading industrial firms." Industrial Marketing Management, Vol. 20, No.2, pp. 137-147.

Cooper, R. G. and Kleinschmidt, E. J. (1994). "Screening New Products for Potential Winners." IEEE Engineering Management Review, Vol. 22, No.4, pp. 23-30.

Copeland, T. and Antikarov, V. (2003). Real Options: A Practitioner's Guide. New York, NY, Texere.

Copeland, T., Koller, T. and Murrin, J. (2000). Valuation Measuring and Managing the Value of Companies, John Wiley & Sons.

Copeland, T. and Tufano, P. (2004). "A real-world way to manage real options." Harvard Business Review, Vol. 82, No.3, pp. 90-00.

Corning (2006). Corning 2006 Annual Report & 2007 Proxy Statement, Corning Inc.

Day, G. S. (2007). "Is It Real? Can We Win? Is It Worth Doing?: Managing Risk and Reward in an Innovation Portfolio." Harvard Business Review, Vol. 85, No.12, pp. 110-120.

DIN EN ISO 8402 (1995). Qualitätsmanagement - Begriffe Berlin, Beuth.

Ditzer, R. (2005). "Faszination Toyota." Japan aktuell, Vol., No.2, pp. 5-10.

Dörner, D. (2007). Die Logik des Misslingens: Strategisches Denken in komplexen Situationen. Reinbek, Rowohlt.

Dörner, D. and Schaub, H. (1994). "Errors in planning and decision-making and the nature of human information processing." Applied Psychology: An International Review, Vol. 43, No.4, pp. 433-453.

Dougherty, D. (1992). "Interpretive Barriers to Successful Product Innovation in Large Firms." Organization Science, Vol. 3, No.2, pp. 179-202.

Dougherty, D. and Hardy, C. (1996). "Sustained product innovation in large, mature Organizations: Overcoming Innovation-to-Organization Problems." Academy of Management Journal Vol. 39, No.5, pp. 1120-1153.

Duffy, A. H. B., Andreasen, M. M. and O'Donnell, F. J. (1999). Design Co-ordination. Proceedings of the 12th International Conference on Engineering Design, München, Technische Universität München.

Duncan, R. B. (1972). "Characteristics of Organizational Environments and Perceived Environmental Uncertainty." Administrative Science Quarterly, Vol. 17, No.3, pp. 313-327.

Dwyer, L. and Mellor, R. (1991). "Organizational Environment, New Product Process Activities, and Project Outcomes " Journal of Product Innovation Management Vol. 8, No.1, pp. 39-48.

Ehrlenspiel, K. (1999). Komplexe Bedingungen beim Entwickeln und Konstruieren erfordern eine Anpassung des Vorgehens. In: Prof. Dr.-Ing. E.h. Dr.-Ing. Wolfgang Beitz zum Gedenken - Sein Wirken und Schaffen. Pahl, G. Berlin, Springer, pp. S. 225-240.

Ehrlenspiel, K. (2003). On the Importance of the Unconscious and the Cognitive Economy in Design. In: Human Behaviour in Design - Individuals, Teams, Tools. Lindemann, U. Berlin, Springer, pp. 25-41.

Ehrlenspiel, K. (2007). Integrierte Produktentwicklung Denkabläufe, Methodeneinsatz, Zusammenarbeit. Munich, Carl Hanser.

Ehrlenspiel, K., Kiewert, A. and Lindemann, U. (2007). Cost-Efficient Design. Berlin, Springer.

Eisenhardt, K. M. and Graebner, M. E. (2007). "Theory Building from Cases: Opportunities and Challenges." Academy of Management Journal, Vol. 50, No.1, pp. 25-32.

Ettlie, J., Bridges, W. and O'Keefe, R. (1984). "Organization Strategy and Structural Differences for Radical versus Incremental Innovation." Management Science, Vol. 30, No.6, pp. 682-695.

Ettlie, J. and Elsenbach, J. (2007). "Modified Stage-Gates Regimes in New Product Development." Journal of Product Innovation Management, Vol. 24, No.1, pp. 20–33.

Euromonitor (2005). The World Market for Packaged Food. London, Euromonitor International.

Eversheim, W., Bochtler, W. and L., L. (1995). Simultaneous Engineering: Erfahrungen aus der Industrie für die Industrie. Berlin, Springer.

FiberOpticsWeeklyUpdate (2003). Fiber sales give Corning needed boost. Fiber Optics Weekly Update. April 25.

Finch, W. (2006). Integrated Product and Process Design. Cambridge, MA, Center of Innovation in Product Development, Massachusetts Institute of Technology.

Finger, S. and Dixon, J. R. (1989b). "A Review of Research in Mechanical Engineering Design. Part I: Descriptive, prescriptive, and computer-based Models of Design Processes." Research in Engineering Design, Vol. 1, No.1, pp. 51-67.

Ford, D. N. and Sobek, D. K. (2005). "Adapting real options to new product development by modeling the second Toyota paradox." IEEE Transactions on Engineering Management, Vol. 52, No.2, pp. 175 - 185.

Fox, J. (2001). "Nokia's secret code." Fortune, Vol. May, No.161-174.

Funke, J. (2003). Problemlösendes Denken. Stuttgart, Kohlhammer.

Gaitanides, M., Scholz, R. and Vrohlings, A. (1994). Prozeßmanagement. Konzepte, Umsetzungen und Erfahrungen des Reengineering. München, Hanser.

Gausemeier, J. (2003). "Strategiekompetenz und Agilität - Strategische Erfolgspositionen des Mittelstands." ZWF - Zeitschrift für wirtschaftlichen Fabrikbetrieb, Vol., pp. 530-534.

Gausemeier, J., Fink, A. and Riepe, B. (1998). "Szenariobasiertes Technologiemanagement." ZWF - Zeitschrift für wirtschaftlichen Fabrikbetrieb, Vol. 93, No.4, pp. 139-142.

Gausemeier, J., Lindemann, U., Braun, T., Orlik, L. and Vienenkötter, A. (2004). "Ein Vorgehensmodell zur strategischen Produkt- und Prozessplanung in kleinen und mittleren Unternehmen." Konstruktion 2004, Vol. 3, pp. 65-70.

Gausemeier, J., Lindemann, U., Reinhart, G. and Wiendahl, H.-P. (2000). Kooperatives Produktengineering: Ein neues Selbstverständnis des ingenieurmäßigen Wirkens. Paderborn, Heinz Nixdorf Instutut.

Gausemeier, J., Lindemann, U. and Schuh, G. (2004). Planung der Produkte und Fertigungssysteme für die Märkte von morgen: Ein praktischer Leitfaden für mittelständische Unternehmen des Maschinen- und Anlagenbaus. Frankfurt, VDMA Verlag.

Gerhard, E. (1998). Entwickeln und Konstruieren mit System. Grafenau, Expert-Verlag.

Gerwin, D. and Susman, G. (1996). "Special Issue on Concurrent Engineering - Guest Editorial." IEEE Transactions on Engineering Management, Vol. 43, No.3, pp. 118-123.

Giapoulis, A. (1996). Modelle für effektive Konstruktionsprozesse. Fakultät für Maschinenwesen. München, Technische Universität München. Dissertation.

Grant, R. M. (1996). "Prospering in Dynamically-Competitive Environments: Organizational Capability as Knowledge Integration." Organization Science, Vol. 7, No.4, pp. 375-387.

Gupta, A. K. and Wilemon, D. (1996). "Changing patterns in industrial R&D management " Journal of Product Innovation Management Vol. 13, No.6, pp. 497-511.

Hacker, W. (2002). Denken in der Produktentwicklung. Psychologische Unterstützung der frühen Phasen. Zürich, Rainer Hampp Verlag.

Haddad, C. J. (1996). "Operationalizing the Concept of Concurrent Engineering: A Casestudy from the US Auto Industry." IEEE Transactions on Engineering Management, Vol. 43, No.2, pp. 124-132.

Hamel, G. (2007). The Future of Management Boston, MA, Harvard Business School Press.

Hammer, M. and Champy, J. (2003). Business Reengineering Die Radikalkur für das Unternehmen. Frankfurt, Campus.

Hauschildt, J. and Gemünden, H. G. (1999). Promotoren: Champions der Innovation. Wiesbaden, Gabler Verlag.

Herstatt, C., Stockstrom, C., Tschirky, A. and Nagahira, A. (2005). Management of Technology and Innovation in Japan. Berlin, Springer.

Herstatt, C. and Verworn, B. (2003). Bedeutung und Charakteristika der frühen Phasen des Innovationsprozesses. In: Management der frühen Innovationsphasen. Herstatt, C. and Verworn, B. Wiesbaden, Gabler, pp.

Herstatt, C. and Verworn, B. (2003). Prozessgestaltung der frühen Phasen. In: Management der frühen Innovationsphasen. Herstatt, C. and Verworn, B. Wiesbaden, Gabler, pp.

Howell, J. M. and Higgings, C. A. (1990). "Champions of Technological Innovation." Administrative Science Quarterly, Vol. 35, No.2, pp. 317-341.

Hull, J. C. (2000). Options, Futures, and other Derivatives. Upper Saddle River, NJ, Prentice-Hall.

International Photo Marketing Association (2005). Transitioning to digital: Industry trends report notes increases in camera sales and prints. Photo Marketing. 80.

Jetter, A. (2005). Produktplanung im Fuzzy Front End - Handlungsunterstützungssysteme auf Basis der Fuzzy Cognitive Maps. Wiesbaden, Deutscher Universitäts-Verlag.

Jorion, P. (2001). Value at Risk: The new Bechmark for Managing Financial Risk. New York, McGraw-Hill.

Jung, C. (2006). Anforderungsklärung in interdisziplinärer Entwicklungsumgebung. München, Verlag Dr. Hut.

Kester, W. C. (1984). "Today's Options for Tomorrow's Growth." Harvard Business Review, Vol. 62, No.2, pp. 153-160.

Khurana, A. and Rosenthal, S. R. (1997). "Integrating the fuzzy front end of new product development." Sloan Management Review, Vol. 38, No.2, pp. 103-120.

Khurana, A. and Rosenthal, S. R. (1998). "Towards Holistic 'Front Ends' in New Product Development." Journal of Product Innovation Management, Vol. 15, No.2, pp. 57-74.

Kim, J. and Wilemon, D. (2002). "Focusing the Fuzzy Front-end in New Product Development." R&D Management, Vol. 32, No.4, pp. 269-279.

Kipphan, H. (2000). Handbuch der Printmedien : Technologien und Produktionsverfahren. Berlin, Springer.

Kleinschmidt, E. J., Geschka, H. and Cooper, R. G. (1996). Erfolgsfaktor Markt: Produktinnovationen am Markt und Kunden ausrichten. Berlin, Springer.

Koen, P. (2003). Tools and Techniques for Managing the Front End of Innovation:

Highlights from the May 2003 Cambridge Conference. . May 2003 Cambridge Conference Visions XXVII. Cambridge.

Koen, P., Ajamian, G., Boyce, S., Clamen, A., Fisher, E., Fountoulakis, S., Johnson, A., Puri, P. and Seibert, R. (2002). Fuzzy Front End: Effective Methods, Tools, and Techniques. In: The PDMA Toolbook for New Product Development. Belliveau, P., Griffin, A. and Somermeyer, S. New York, John Wiley & Sons, Inc., pp. 2-35.

Koen, P., Ajamian, G., Burkart, R., Clamen, A., Davidson, J., D'Amore, R., Elkins, C., Herald, K., Incorvia, M., Johnson, A., Karol, R., Seibert, R., Slavejkov, A. and Wagner, K. (2001). "Providing Clarity and a Common Language to the "Fuzzy Front End" " Research Technology Management, Vol. 44, No.2, pp. 46-55.

Kotler, P. (2000). Marketing Management: Ana. Upper Saddle River, NJ, Prentice-Hall, Inc.

Krishnan, V. (1996). "Managing the Simultaneous Execution of Coupled Phases in Concurrent Product Development." IEEE Transactions on Engineering Management, Vol. 43, No.2, pp. 210-217.

Krishnan, V. and Ulrich, K. T. (2001). "Product Development Decisions: A Review of the Literature." Management Science, Vol. 47, No.1, pp. 1-21.

Leslie, K. J. and Michaels, M. P. (2000). "The Real Power of Real Options." The McKinsey Quarterly, Vol., No.3, pp. 97-108.

Lindemann, U. (2003). Human Behaviour in Design - Individuals, Teams, Tools. Berlin, Springer.

Lindemann, U. (2005). Methodische Entwicklung technischer Produkte. Berlin, Heidelberg, Springer.

Lindemann, U. (2006). Methoden der Produktentwicklung. München, Technische Universität München, Lehrstuhl für Produktentwicklung.

Lindemann, U., Bichlmaier, C., Stetter, R. and Viertlböck, M. (1999). "Integrierte Produktentwicklung in der industriellen Anwendung." Konstruktion Vol. 9, pp. 30-34.

Lindemann, U. and Kleedörfer, R. (1997). Erfolgreiche Produkte durch Integrierte Produktentwicklung. In: Mit Schwung zum Aufschwung - Information - Inspiration - Innovation. Reinhart, G. Landsberg/Lech, Verlag Moderne Industrie, pp. 115-136.

Lindemann, U., Kleedörfer, R. and Gerst, M. (1998). The Development Department and Engineering Change Management. In: Designers–The Key to Successful Product Development. Frankenberger, E., Badke.Schaub, P. and Birkhofer, H. Berlin, Springer, pp. 169-182.

Lindemann, U. and Maurer, M. (2006). Entwicklung und Strukturplanung individualisierter Produkte. In: Individualisierte Produkte: Komplexität beherrschen in Entwicklung und Produktion Lindemann, U., Reichwald, R. and Zäh, M. Berlin, Springer, pp. 41-62.

Lindemann, U., Stetter, R. and Viertlböck, M. (2001). "A Pragmatic Approach for Supporting Integrated Product Development." Journal of Integrated Design and Process Science Vol. 5, No.2, pp. 39 - 51.

Lynn, G. S. (1993). Understanding Products and Markets for Radical Innovations. Rensselaer Polytechnic Institute. Troy, New York, Rensselaer Polytechnic Institute**:** 385.

Lynn, G. S. and Akgün, A. E. (1998). "Innovation strategies under uncertainty: a contingency approach for new product development." Engineering Management Journal, Vol. 10, No.3, pp. 11-17.

Lynn, G. S., Morone, J. G. and Paulson, A. S. (1996). "Marketing and discontinuous innovation: The probe and learn process." California Management Review, Vol. 38, No.3, pp. 8-37.

Marxt, C. and Hacklin, F. (2005). "Design, Product Development, Innovation: all the same in the End? A short Discussion on Terminology." Journal of Engineering Design, Vol. 16, No.4, pp. 413-421.

McCutcheon, D. M. and Meredith, J. R. (1993). "Conducting Case Study Research in Operations Management." Journal of Operations Management, Vol. 11, No.3, pp. 239-256.

McDermott, C. M. and O'Connor, G. C. (2002). "Managing Radical Innovation: An Overview of Emergent Strategy Issues." Journal of Product Innovation Management, Vol. 19, No.6, pp. 424-438.

Meerkamm, H., Heynen, C. and Schweiger, W. (1999). Integration von Berechnungen in den frühen Entwurfsprozess. Verkürzte Entwicklungsprozesse durch Integration von Gestaltung und Berechnung : Potentiale und Erfahrungen, Stuttgart, VDI-Verlag.

Mikkola, J. H. (2003). "Modularity, Component Outsourcing, and inter-firm Learning." R&D Management, Vol. 33, No.4, pp. 439-454.

Milliken, F. (1987). "Three Types of Perceived Uncertainty about the Environment: State, Effect, and Response Uncertainty." The Academy of Management Review, Vol. 12, No.1, pp. 133-143.

Möller, N. (2008). Bestimmung der Wirtschaftlichkeit wandlungsfähiger Produktionssysteme. München, Herbert Utz Verlag.

Myers, S. C. (1977). "Determinants of Corporate Borrowing." Journal of Financial Economics Vol. 5, No.2, pp. 147-175.

Newton, D. P., Paxson, D. A. and Martin Widdicks, M. (2004). "Real R&D options." International Journal of Management Reviews, Vol. 5-6, No.2, pp. 113–130.

Nokia. (2007a). "Story of Nokia." Extracted on 18.06.2007 from www.nokia.com/A4303001.

Nokia. (2007b). "Financials: Quarterly and annual Information." Extracted on 18.06.2007 from www.nokia.com/A4399348.

Ohno, T. (1988). Toyota Production System: Beyond Large-Scale Production New York, NY, Productivity Press.

Pahl, G., Beitz, W., Feldhusen, J. and Grote, K. H. (2007). Engineering Design. A Systematic Approach. Berlin, Springer.

Pennings, E. and Lint, O. (1995). "The Option Value of Advanced R & D " European Journal of Operational Research Vol. 103, No.1, pp. 83-94.

Peterson, R. S., Owens, P. D., Tetlockc, P. E., Fand, E. T. and Martoranae, P. (1998). "Group Dynamics in Top Management Teams: Groupthink, Vigilance, and Alternative Models of Organizational Failure and Success." Organizational Behavior and Human Decision Processes, Vol. 73, No.2-3, pp. 272-305.

Project Management Institute (2004). A Guide to the Project Management Body of Knowledge. Newtown Square, PA.

Putz-Osterloh, W. (1981). "Über die Beziehung zwischen Testintelligenz und Problemlöseerfolg." Zeitschrift für Psychologie, Vol. 189, pp. 79-100.

Rigby, D. (2001). "Management Tools and Techniques: A Survey." California Management Review, Vol. 43, No.2, pp. 139.

Salomo, S., Gemünden, H. G. and Billing, F. (2003). Dynamisches Schnittstellenmanagement radikaler Innovationsvorhaben. In: Management der frühen Innovationsphasen. Herstatt, C. and Verworn, B. Wiesbaden, Gabler, pp. 161-194.

Salomo, S. J., Weise, J. and Gemünden, H. G. (2007). "NPD Planning Activities and Innovation Performance: The Mediating Role of Process Management and the Moderating Effect of Product Innovativeness." Journal of Product Innovation Management, Vol. 24, No.4, pp. 285-302.

Santiago, L. P. and Bifano, T. G. (2005). "Management of R&D Projects Under Uncertainty: A Multidimensional Approach to Managerial Flexibility." IEEE Transactions on Engineering Management, Vol. 52, No.2, pp. 269-280.

Schaub, H. (1993). Modellierung der Handlungsorganisation. Bern, Huber.

Schmickl, C. and Kieser, A. (2008). "How much do Specialists have to learn from each other when they jointly develop Radical Product Innovations?" Research policy, Vol. 37, No.3, pp. 473-491.

Schrader, S., Riggs, W. M. and Smith, R. P. (1993). "Choice over Uncertainty and Ambiguity in Technical Problem Solving." Journal of Engineering and Technology Management, Vol. 10, No.1-2, pp. 73-99.

Schwankl, L. (2002). Analyse und Dokumentation in den frühen Phasen der Produktentwicklung. München, Verlag Dr. Hut.

Seidel, M. and Stahl, M. (2001). Risikomanagement von Innovationen bei BMW. In: High-Risk-Projekte. Quantensprünge in der Entwicklung erfolgreich managen. Gassmann, O., Kobe, C. and Voit, E. Berlin, Springer, pp.

Sekolec, R., Kunz, A. and Meier, M. (2003). Methodology for Product Structuring in the early Stages of the Design Process. ICED 03 - International Conference on Engineering Design Stockholm, The Design Society.

Siegel, S. (1957). "Nonparametric Statistics." The American Statistician, Vol. 11, No.3, pp. 13-19.

Siggelkow, N. (2007). "Persuasion with Case Studies." Academy of Management Journal, Vol. 50, No.1, pp. 20-24.

Simon, H. A. (1996). The Sciences of the Artificial. Boston, MA, The MIT Press.

Sitkin, S. B. and Weingart, L. R. (1995). "Determinants of Risky Decision-Making Behavior: A Test of the Mediating Role of Risk Perceptions and Propensity." The Academy of Management Journal, Vol. 38, No.6, pp. 1573-1592.

Smit, H. T. J. and Ankum, L. A. (1993). "A Real Options and Game-Theoretic Approach to Corporate Investment Strategy under Competition " Financial Management, Vol. 22, No.3, pp. 241-250.

Smit, H. T. J. and Trigeorgis, L. (2007). "Strategic Options and Games in Analysing Dynamic Technology Investments " Long Range Planning, Vol. 40, No.1, pp. 84-114.

Smith, P. G. and Merrit, G. M. (2002). Proactive Risk Management: Controlling Uncertainty in Product Development. New York, NY, Productivity Press.

Smith, P. G. and Reinertsen, D. G. (1992). "Shortening the Product Development Cycle," Research-Technology Management, May-June, 1992, pp. 44-49." Research Technology Management, Vol. 35, No.3, pp. 44-49.

Smith, R. P. and Morrow, J. A. (1999). "Product Development Process Modeling " Design Studies Vol. 20, No.3, pp. 237-261.

Snyder, C. (2003). Paper Prototyping: The Fast and EasyWay to Design and Refine User Interfaces. Amsterdam, Morgan Kaufmann.

Sobek, D. K., Ward, A. C. and Liker, J. K. (1999). "Toyota's Principles of Set-Based Concurrent Engineering." MIT Sloan Management Review, Vol. 40, No.2, pp. 67-83.

Sörensen, D. (2006). The Automotive Development Process: A Real Options Analysis. Wiesbaden, Deutscher Universitäts-Verlag.

Stevens, S. S. (1964). "On the Theory of Scales of Measurement." Science, Vol. 103, No.2684, pp. 677-680.

Sudhoff, W. (2007). Methodik zur Bewertung standortübergreifender Mobilität in der Produktion. München, Herbert Utz Verlag.

Susman, G. and Evered, R. (1978). "An Assessment of the Scientific Merits of Action Research." Administrative Science Quarterly, Vol. 23, No.4, pp. 582-603.

Swink, M. L. (1998). "A Tutorial on Implementing Concurrent Engineering in New Product Development Programs." Journal of Operations Management, Vol. 16, No.1, pp. 103-116.

Tatikonda, M. V. and Rosenthal, S. R. (2000). "Technology novelty, project complexity, and product developmentproject execution success: a deeper look at task uncertainty in productinnovation." IEEE Transactions on Engineering Management, Vol. 47, No.1, pp. 74-87.

Thomke, S. and Fujimoto, T. (2000). "The Effect of “Front-loading” Problem-solving on Product Development Performance." Journal of Product Innovation Management, Vol. 17, No.2, pp. 128-142.

Thomson Financial Datastream. (2007). "Thomson ONE Analytics " Extracted on 10.08.2007 from www.datastream.com.

Tripsas, M. and Gavetti, G. (2000). "Capabilities, Cognition, and Inertia: Evidence from Digital Imaging." Strategic Management Journal, Vol. 21, No.10-11, pp. 1147 - 1161.

Ullman, D. (2003). The Mechanical Design Process. New York, McGraw-Hill.

Ulrich, K. T. and Eppinger, S. D. (2007). Product Design and Development. New York, McGraw-Hill.

Ulrich, K. T. and Seering, W. P. (1989). "Synthesis of Schematic Descriptions in Mechanical Design." Research in Engineering Design, Vol. 1, pp. 3-18.

VDI Richtlinie 2221 (1993). Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte. Düsseldorf, VDI-Verlag.

VDI/VDE Richtlinie 3694 (2005). System Requirement/Specification for Planning and Design of Automation Systems. Düsseldorf, VDI-Verlag.

Verworn, B. and Herstatt, C. (2003). Prozessgestaltung der frühen Phasen. In: Management der fühen Innovationsphasen. Herstatt, C. and Verworn, B. Wiesbaden, Gabler, pp. 195-214.

Veryzer, R. W. (1998). "Discontinuous Innovation and the New Product Development Process." Journal of Product Innovation Management, Vol. 15, No.4, pp. 304-321.

Ward, A. C., Liker, J. K., Cristiano, C. C. and Sobek, D. K. (1995). "The Second Toyota paradox: How delaying Decisions can make Cars faster." MIT Sloan Management Review, Vol. 36, No.3, pp. 43-61.

Wittmann, W. (1959). Unternehmung und unvollkommene Information. Unternehmerische Vorrausicht - Ungewissheit und Planung. Köln, Westdeutscher Verlag.

Wood, S. C. and Brown, G. S. (1998). "Commercializing Nascent Technology: The Case of Laser Diodes at Sony." Journal of Product Innovation Management, Vol. 15, No.2, pp. 167-183.

Yin, R. (2003). Case study research: Design and methods. Thousand Oaks, Sage.

Zhang, Q. and Doll, W. (2001). "The fuzzy front end and success of new product development." European Journal of Innovation Management, Vol. 4, No.2, pp. 95-112.

Zimbardo, P. G. and Gerrig, R. J. (2004). Psychologie. Munich Pearson Education.

Zirger, B. J. and Maidique, M. A. (1990). "A Model of New Product Development: An Empirical Test." Management Science, Vol. 36, No.7, pp. 867-883.

9 List of Dissertations

Lehrstuhl für Produktentwicklung
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Dissertations under supervision of

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- Prof. Dr.-Ing. K. Ehrlenspiel
- Prof. Dr.-Ing. U. Lindemann

D1 COLLIN, H.:
Entwicklung eines Einwalzenkalanders nach einer systematischen Konstruktionsmethode. München: TU, Diss. 1969.

D2 OTT, J.:
Untersuchungen und Vorrichtungen zum Offen-End-Spinnen.
München: TU, Diss. 1971.

D3 STEINWACHS, H.:
Informationsgewinnung an bandförmigen Produkten für die Konstruktion der Produktmaschine.
München: TU, Diss. 1971.

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Entwicklung eines Rehabilitationsgerätes für Schwerstkörperbehinderte.
München: TU, Diss. 1972.

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Die Entwicklung eines Maschinensystems zur Verarbeitung von chemischen Endlosfasern.
München: TU, Diss. 1974.

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Entwurf und Optimierung eines Getriebesystems für einen Rotationsquerschneider mit allgemeingültigen Methoden.
München: TU, Diss. 1974.

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Die Vereinfachung von Geräten zur Konstanthaltung physikalischer Größen.
München: TU, Diss. 1976.

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Beitrag zum konstruktionsmethodischen Vorgehen durchgeführt am Beispiel eines Hochleistungsschalter-Antriebs.
München: TU, Diss. 1976.

D9 SCHÄFER, J.:
Die Anwendung des methodischen Konstruierens auf verfahrenstechnische Aufgabenstellungen.
München: TU, Diss. 1977.

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Extruder mit Feststoffpumpe – Ein Beitrag zum Methodischen Konstruieren.
München: TU, Diss. 1978.

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Längencodierer mit Hilfsbewegung.
München: TU, Diss. 1979.

D12 KIEWERT, A.:
Systematische Erarbeitung von Hilfsmitteln zum kostenarmen Konstruieren.
München: TU, Diss. 1979.

D13 LINDEMANN, U.:
Systemtechnische Betrachtung des Konstruktionsprozesses unter besonderer Berücksichtigung der Herstellkostenbeeinflussung beim Festlegen der Gestalt.
Düsseldorf: VDI-Verlag 1980. (Fortschritt-Berichte der VDI-Zeitschriften Reihe 1, Nr. 60).
Zugl. München: TU, Diss. 1980.

D14 NJOYA, G.:
Untersuchungen zur Kinematik im Wälzlager bei synchron umlaufenden Innen- und Außenringen.
Hannover: Universität, Diss. 1980.

D15 HENKEL, G.:
Theoretische und experimentelle Untersuchungen ebener konzentrisch gewellter Kreisringmembranen.
Hannover: Universität, Diss. 1980.

D16 BALKEN, J.:
Systematische Entwicklung von Gleichlaufgelenken.
München: TU, Diss. 1981.

D17 PETRA, H.:
Systematik, Erweiterung und Einschränkung von Lastausgleichslösungen für Standgetriebe mit zwei Leistungswegen – Ein Beitrag zum methodischen Konstruieren.
München: TU, Diss. 1981.

D18 BAUMANN, G.:
Ein Kosteninformationssystem für die Gestaltungsphase im Betriebsmittelbau.
München: TU, Diss. 1982.

D19 FISCHER, D.:
Kostenanalyse von Stirnzahnrädern. Erarbeitung und Vergleich von Hilfsmitteln zur Kostenfrüherkennung.
München: TU, Diss. 1983.

D20 AUGUSTIN, W.:
Sicherheitstechnik und Konstruktionsmethodiken – Sicherheitsgerechtes Konstruieren.
Dortmund: Bundesanstalt für Arbeitsschutz 1985. Zugl. München: TU, Diss. 1984.

D21 RUTZ, A.:
Konstruieren als gedanklicher Prozess.
München: TU, Diss. 1985.

D22 SAUERMANN, H. J.:
Eine Produktkostenplanung für Unternehmen des Maschinenbaues.
München: TU, Diss. 1986.

D23 HAFNER, J.:
Entscheidungshilfen für das kostengünstige Konstruieren von Schweiß- und Gussgehäusen.
München: TU, Diss. 1987.

D24 JOHN, T.:
Systematische Entwicklung von homokinetischen Wellenkupplungen.
München: TU, Diss. 1987.

D25 FIGEL, K.:
Optimieren beim Konstruieren.
München: Hanser 1988. Zugl. München: TU, Diss. 1988 u. d. T.: Figel, K.: Integration automatisierter Optimierungsverfahren in den rechnerunterstützten Konstruktionsprozess.

Reihe Konstruktionstechnik München

D26 TROPSCHUH, P. F.:
Rechnerunterstützung für das Projektieren mit Hilfe eines wissensbasierten Systems.
München: Hanser 1989. (Konstruktionstechnik München, Band 1). Zugl. München: TU, Diss. 1988 u. d. T.: Tropschuh, P. F.: Rechnerunterstützung für das Projektieren am Beispiel Schiffsgetriebe.

D27 PICKEL, H.:
Kostenmodelle als Hilfsmittel zum Kostengünstigen Konstruieren.
München: Hanser 1989. (Konstruktionstechnik München, Band 2). Zugl. München: TU, Diss. 1988.

D28 KITTSTEINER, H.-J.:
Die Auswahl und Gestaltung von kostengünstigen Welle-Nabe-Verbindungen.
München: Hanser 1990. (Konstruktionstechnik München, Band 3). Zugl. München: TU, Diss. 1989.

D29 HILLEBRAND, A.:
Ein Kosteninformationssystem für die Neukonstruktion mit der Möglichkeit zum Anschluss an ein CAD-System.
München: Hanser 1991. (Konstruktionstechnik München, Band 4). Zugl. München: TU, Diss. 1990.

D30 DYLLA, N.:
Denk- und Handlungsabläufe beim Konstruieren.
München: Hanser 1991. (Konstruktionstechnik München, Band 5). Zugl. München: TU, Diss. 1990.

D31 MÜLLER, R.
Datenbankgestützte Teileverwaltung und Wiederholteilsuche.
München: Hanser 1991. (Konstruktionstechnik München, Band 6). Zugl. München: TU, Diss. 1990.

D32 NEESE, J.:
Methodik einer wissensbasierten Schadenanalyse am Beispiel Wälzlagerungen.
München: Hanser 1991. (Konstruktionstechnik München, Band 7). Zugl. München: TU, Diss. 1991.

D33 SCHAAL, S.:
Integrierte Wissensverarbeitung mit CAD – Am Beispiel der konstruktionsbegleitenden Kalkulation.
München: Hanser 1992. (Konstruktionstechnik München, Band 8). Zugl. München: TU, Diss. 1991.

D34 BRAUNSPERGER, M.:
Qualitätssicherung im Entwicklungsablauf – Konzept einer präventiven Qualitätssicherung für die Automobilindustrie.
München: Hanser 1993. (Konstruktionstechnik München, Band 9). Zugl. München: TU, Diss. 1992.

D35 FEICHTER, E.:
Systematischer Entwicklungsprozess am Beispiel von elastischen Radialversatzkupplungen.
München: Hanser 1994. (Konstruktionstechnik München, Band 10). Zugl. München: TU, Diss. 1992.

D36 WEINBRENNER, V.:
Produktlogik als Hilfsmittel zum Automatisieren von Varianten- und Anpassungskonstruktionen.
München: Hanser 1994. (Konstruktionstechnik München, Band 11). Zugl. München: TU, Diss. 1993.

D37 WACH, J. J.:
Problemspezifische Hilfsmittel für die Integrierte Produktentwicklung.
München: Hanser 1994. (Konstruktionstechnik München, Band 12). Zugl. München: TU, Diss. 1993.

D38 LENK, E.:
Zur Problematik der technischen Bewertung.
München: Hanser 1994. (Konstruktionstechnik München, Band 13). Zugl. München: TU, Diss. 1993.

D39 STUFFER, R.:
Planung und Steuerung der Integrierten Produktentwicklung.
München: Hanser 1994. (Konstruktionstechnik München, Band 14). Zugl. München: TU, Diss. 1993.

D40 SCHIEBELER, R.:
Kostengünstig Konstruieren mit einer rechnergestützten Konstruktionsberatung.
München: Hanser 1994. (Konstruktionstechnik München, Band 15). Zugl. München: TU, Diss. 1993.

D41 BRUCKNER, J.:
Kostengünstige Wärmebehandlung durch Entscheidungsunterstützung in Konstruktion und Härterei.
München: Hanser 1994. (Konstruktionstechnik München, Band 16). Zugl. München: TU, Diss. 1993.

D42 WELLNIAK, R.:
Das Produktmodell im rechnerintegrierten Konstruktionsarbeitsplatz.
München: Hanser 1994. (Konstruktionstechnik München, Band 17). Zugl. München: TU, Diss. 1994.

D43 SCHLÜTER, A.:
Gestaltung von Schnappverbindungen für montagegerechte Produkte.
München: Hanser 1994. (Konstruktionstechnik München, Band 18). Zugl. München: TU, Diss. 1994.

D44 WOLFRAM, M.:
Feature-basiertes Konstruieren und Kalkulieren.
München: Hanser 1994. (Konstruktionstechnik München, Band 19). Zugl. München: TU, Diss. 1994.

D45 STOLZ, P.:
Aufbau technischer Informationssysteme in Konstruktion und Entwicklung am Beispiel eines elektronischen Zeichnungsarchives.
München: Hanser 1994. (Konstruktionstechnik München, Band 20). Zugl. München: TU, Diss. 1994.

D46 STOLL, G.:
Montagegerechte Produkte mit feature-basiertem CAD.
München: Hanser 1994. (Konstruktionstechnik München, Band 21). Zugl. München: TU, Diss. 1994.

D47 STEINER, J. M.:
Rechnergestütztes Kostensenken im praktischen Einsatz.
Aachen: Shaker 1996. (Konstruktionstechnik München, Band 22). Zugl. München: TU, Diss. 1995.

D48 HUBER, T.:
Senken von Montagezeiten und -kosten im Getriebebau.
München: Hanser 1995. (Konstruktionstechnik München, Band 23). Zugl. München: TU, Diss. 1995.

D49 DANNER, S.:
Ganzheitliches Anforderungsmanagement für marktorientierte Entwicklungsprozesse.
Aachen: Shaker 1996. (Konstruktionstechnik München, Band 24). Zugl. München: TU, Diss. 1996.

D50 MERAT, P.:
Rechnergestützte Auftragsabwicklung an einem Praxisbeispiel.
Aachen: Shaker 1996. (Konstruktionstechnik München, Band 25). Zugl. München: TU, Diss. 1996 u. d. T.: MERAT, P.: Rechnergestütztes Produktleitsystem

D51 AMBROSY, S.:
Methoden und Werkzeuge für die integrierte Produktentwicklung.
Aachen: Shaker 1997. (Konstruktionstechnik München, Band 26). Zugl. München: TU, Diss. 1996.

D52 GIAPOULIS, A.:
Modelle für effektive Konstruktionsprozesse.
Aachen: Shaker 1998. (Konstruktionstechnik München, Band 27). Zugl. München: TU, Diss. 1996.

D53 STEINMEIER, E.:
Realisierung eines systemtechnischen Produktmodells – Einsatz in der Pkw-Entwicklung
Aachen: Shaker 1998. (Konstruktionstechnik München, Band 28). Zugl. München: TU, Diss. 1998.

D54 KLEEDÖRFER, R.:
Prozess- und Änderungsmanagement der Integrierten Produktentwicklung.
Aachen: Shaker 1998. (Konstruktionstechnik München, Band 29). Zugl. München: TU, Diss. 1998.

D55 GÜNTHER, J.:
Individuelle Einflüsse auf den Konstruktionsprozess.
Aachen: Shaker 1998. (Konstruktionstechnik München, Band 30). Zugl. München: TU, Diss. 1998.

D56 BIERSACK, H.:
Methode für Krafteinleitungsstellenkonstruktion in Blechstrukturen.
München: TU, Diss. 1998.

D57 IRLINGER, R.:
Methoden und Werkzeuge zur nachvollziehbaren Dokumentation in der Produktentwicklung.
Aachen: Shaker 1998. (Konstruktionstechnik München, Band 31). Zugl. München: TU, Diss. 1999.

D58 EILETZ, R.:
Zielkonfliktmanagement bei der Entwicklung komplexer Produkte – am Bsp. PKW-Entwicklung.
Aachen: Shaker 1999. (Konstruktionstechnik München, Band 32). Zugl. München: TU, Diss. 1999.

D59 STÖSSER, R.:
Zielkostenmanagement in integrierten Produkterstellungsprozessen.
Aachen: Shaker 1999. (Konstruktionstechnik München, Band 33). Zugl. München: TU, Diss. 1999.

D60 PHLEPS, U.:
Recyclinggerechte Produktdefinition – Methodische Unterstützung für Upgrading und Verwertung.
Aachen: Shaker 1999. (Konstruktionstechnik München, Band 34). Zugl. München: TU, Diss. 1999.

D61 BERNARD, R.:
Early Evaluation of Product Properties within the Integrated Product Development.
Aachen: Shaker 1999. (Konstruktionstechnik München, Band 35). Zugl. München: TU, Diss. 1999.

D62 ZANKER, W.:
Situative Anpassung und Neukombination von Entwicklungsmethoden.
Aachen: Shaker 1999. (Konstruktionstechnik München, Band 36). Zugl. München: TU, Diss. 1999.

Reihe Produktentwicklung München

D63 ALLMANSBERGER, G.:
Erweiterung der Konstruktionsmethodik zur Unterstützung von Änderungsprozessen in der Produktentwicklung.
München: Dr. Hut 2001. (Produktentwicklung München, Band 37). Zugl. München: TU, Diss. 2000.

D64 ASSMANN, G.:
Gestaltung von Änderungsprozessen in der Produktentwicklung.
München: Utz 2000. (Produktentwicklung München, Band 38). Zugl. München: TU, Diss. 2000.

D65 BICHLMAIER, C.:
Methoden zur flexiblen Gestaltung von integrierten Entwicklungsprozessen.
München: Utz 2000. (Produktentwicklung München, Band 39). Zugl. München: TU, Diss. 2000.

D66 DEMERS, M. T.
Methoden zur dynamischen Planung und Steuerung von Produktentwicklungsprozessen.
München: Dr. Hut 2000. (Produktentwicklung München, Band 40). Zugl. München: TU, Diss. 2000.

D67 STETTER, R.:
Method Implementation in Integrated Product Development.
München: Dr. Hut 2000. (Produktentwicklung München, Band 41). Zugl. München: TU, Diss. 2000.

D68 VIERTLBÖCK, M.:
Modell der Methoden- und Hilfsmitteleinführung im Bereich der Produktentwicklung.
München: Dr. Hut 2000. (Produktentwicklung München, Band 42). Zugl. München: TU, Diss. 2000.

D69 COLLIN, H.:
Management von Produkt-Informationen in kleinen und mittelständischen Unternehmen.
München: Dr. Hut 2001. (Produktentwicklung München, Band 43). Zugl. München: TU, Diss. 2001.

D70 REISCHL, C.:
Simulation von Produktkosten in der Entwicklungsphase.
München: Dr. Hut 2001. (Produktentwicklung München, Band 44). Zugl. München: TU, Diss. 2001.

D71 GAUL, H.-D.:
Verteilte Produktentwicklung - Perspektiven und Modell zur Optimierung.
München: Dr. Hut 2001. (Produktentwicklung München, Band 45). Zugl. München: TU, Diss. 2001.

D72 GIERHARDT, H.:
Global verteilte Produktentwicklungsprojekte – Ein Vorgehensmodell auf der operativen Ebene.
München: Dr. Hut 2002. (Produktentwicklung München, Band 46). Zugl. München: TU, Diss. 2001.

D73 SCHOEN, S.:
Gestaltung und Unterstützung von Community of Practice.
München: Utz 2000. (Produktentwicklung München, Band 47). Zugl. München: TU, Diss. 2000.

D74 BENDER, B.:
Zielorientiertes Kooperationsmanagement.
München: Dr. Hut 2001. (Produktentwicklung München, Band 48). Zugl. München: TU, Diss. 2001.

D75 SCHWANKL, L.:
Analyse und Dokumentation in den frühen Phasen der Produktentwicklung.
München: Dr. Hut 2002. (Produktentwicklung München, Band 49). Zugl. München: TU, Diss. 2002.

D76 WULF, J.:
Elementarmethoden zur Lösungssuche.
München: Dr. Hut 2002. (Produktentwicklung München, Band 50). Zugl. München: TU, Diss. 2002.

D77 MÖRTL, M.:
Entwicklungsmanagement für langlebige, upgradinggerechte Produkte.
München: Dr. Hut 2002. (Produktentwicklung München, Band 51). Zugl. München: TU, Diss. 2002.

D78 GERST, M.:
Strategische Produktentscheidungen in der integrierten Produktentwicklung.
München: Dr. Hut 2002. (Produktentwicklung München, Band 52). Zugl. München: TU, Diss. 2002.

D79 AMFT, M.:
Phasenübergreifende bidirektionale Integration von Gestaltung und Berechnung.
München: Dr. Hut 2003. (Produktentwicklung München, Band 53). Zugl. München: TU, Diss. 2002.

D80 FÖRSTER, M.:
Variantenmanagement nach Fusionen in Unternehmen des Anlagen- und Maschinenbaus.
München: TU, Diss. 2003.

D81 GRAMANN, J.:
Problemmodelle und Bionik als Methode.
München: Dr. Hut 2004. (Produktentwicklung München, Band 55). Zugl. München: TU, Diss. 2004.

D82 PULM, U.:
Eine systemtheoretische Betrachtung der Produktentwicklung.
München: Dr. Hut 2004. (Produktentwicklung München, Band 56). Zugl. München: TU, Diss. 2004.

D83 HUTTERER, P.:
Reflexive Dialoge und Denkbausteine für die methodische Produktentwicklung.
München: Dr. Hut 2005. (Produktentwicklung München, Band 57). Zugl. München: TU, Diss. 2005.

D84 FUCHS, D.:
Konstruktionsprinzipien für die Problemanalyse in der Produktentwicklung.
München: Dr. Hut 2006. (Produktentwicklung München, Band 58). Zugl. München: TU, Diss. 2005.

D85 PACHE, M.:
Sketching for Conceptual Design.
München: Dr. Hut 2005. (Produktentwicklung München, Band 59). Zugl. München: TU, Diss. 2005.

D86 BRAUN, T.:
Methodische Unterstützung der strategischen Produktplanung in einem mittelständisch geprägten Umfeld.
München: Dr. Hut 2005. (Produktentwicklung München, Band 60). Zugl. München: TU, Diss. 2005.

D87 JUNG, C.:
Anforderungsklärung in interdisziplinärer Entwicklungsumgebung.
München: Dr. Hut 2006. (Produktentwicklung München, Band 61). Zugl. München: TU, Diss. 2006.

D88 HEßLING, T.:
Einführung der Integrierten Produktpolitik in kleinen und mittelständischen Unternehmen.
München: Dr. Hut 2006. (Produktentwicklung München, Band 62). Zugl. München: TU, Diss. 2006.

D89 STRICKER, H.:
Bionik in der Produktentwicklung unter der Berücksichtigung menschlichen Verhaltens.
München: Dr. Hut 2006. (Produktentwicklung München, Band 63). Zugl. München: TU, Diss. 2006.

D90 NIßL, A.:
Modell zur Integration der Zielkostenverfolgung in den Produktentwicklungsprozess.
München: Dr. Hut 2006. (Produktentwicklung München, Band 64). Zugl. München: TU, Diss. 2006.

D91 MÜLLER, F.:
Intuitive digitale Geometriemodellierung in frühen Entwicklungsphasen.
München: Dr. Hut 2007. (Produktentwicklung München, Band 65). Zugl. München: TU, Diss. 2006.

D92 ERDELL, E.:
Methodenanwendung in der Hochbauplanung – Ergebnisse einer Schwachstellenanalyse.
München: Dr. Hut 2006. (Produktentwicklung München, Band 66). Zugl. München: TU, Diss. 2006.

D93 GAHR, A.:
Pfadkostenrechnung individualisierter Produkte.
München: Dr. Hut 2006. (Produktentwicklung München, Band 67). Zugl. München: TU, Diss. 2006.

D94 RENNER, I.:
Methodische Unterstützung funktionsorientierter Baukastenentwicklung am Beispiel Automobil.
München: Dr. Hut 2007 (Reihe Produktentwicklung) Zugl. München: TU, Diss. 2007.

D95 PONN, J.:
Situative Unterstützung der methodischen Konzeptentwicklung technischer Produkte.
München: Dr. Hut 2007 (Reihe Produktentwicklung) Zugl. München: TU, Diss. 2007.

D96 HERFELD, U.:
Matrix-basierte Verknüpfung von Komponenten und Funktionen zur Integration von Konstruktion und numerischer Simulation.
München: Dr. Hut 2007. (Produktentwicklung München, Band 70). Zugl. München: TU, Diss. 2007.

D97 SCHNEIDER, S.:
Model for the evaluation of engineering design methods.
TU München: 2007. (als Dissertation eingereicht)

D98 FELGEN, L.:
Systemorientierte Qualitätssicherung für mechatronische Produkte.
München: Dr. Hut 2007 (Reihe Produktentwicklung) Zugl. München: TU, Diss. 2007.

D99 GRIEB, J.:
Auswahl von Werkzeugen und Methoden für verteilte Produktentwicklungsprozesse.
München: Dr. Hut 2007 (Reihe Produktentwicklung) Zugl. München: TU, Diss. 2007.

D100 MAURER, M.:
Structural Awareness in Complex Product Design.
München: Dr. Hut 2007 (Reihe Produktentwicklung) Zugl. München: TU, Diss. 2007.

D101 BAUMBERGER, C.:
Methoden zur kundenspezifischen Produktdefinition bei individualisierten Produkten .
München: Dr. Hut 2007 (Reihe Produktentwicklung) Zugl. München: TU, Diss. 2007.

D102 KEIJZER, W.:
Wandlungsfähigkeit von Entwicklungsnetzwerken – ein Modell am Beispiel der Automobilindustrie.
München: Dr. Hut 2007 (Reihe Produktentwicklung) Zugl. München: TU, Diss. 2007.