MASTER

Radical new project management for developing radical new product applications

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Radical New Project Management for Developing Radical New Product Applications

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Abstract

By bringing innovative new products to the market, firms aim to gain sustainable advantage. Radical innovations are highly desired for they have the potential to open up avenues of profitable new business. However, they are difficult to manage and very risky. The question is: What can be done to manage these innovations properly?

Two contrasting views exist regarding managing radical innovation projects. First, several authors suggest radical new projects typically involve trial-and-error. Because radical new product applications often do not fit existing market demarcation lines or product categories, customer preference is difficult to forecast and market size and profitability are hard to estimate at best. On the other hand, other authors suggest managing project flexibility is well possible and can seriously reduce project costs. Drawing on real options theory, they suggest that R&D projects can be managed in a linear way and outcomes optimized by quantifying uncertainty.

Based on the above, we wondered: Can radical new product applications be managed in a linear way or is an ad hoc approach paramount? We explored, based on a literature review and case research, the degree to which real options approach can be used and extended to management of radical innovations.

Based on a case study from Philips regarding new lighting technology, we found that innovation management requires a mix of the two approaches identified above. The early search for a useful application is a type of deliberated trial-and-error approach simply because risks cannot be calculated. After this, real options come into sight as developments of technology, market and the risks involved become more specific and can be estimated within boundaries. Hence real options theory can be used but with some modifications based on different distributions of uncertainties and levels of control. The streams seem to complement rather than substitute. According to the findings of our case study, we developed a conceptual framework for managing radical product applications consisting of a pre-radical R&D phase, a radical R&D phase, and an incremental R&D phase. The radical R&D phase is characterized by an iterative behavior of subsequent radical innovation R&D projects which are selected by senior management which is an additional source of option value and is a critical real option for managing radical new projects. As the R&D projects develop through the different phases and stages the uncertainty is resolved and the level of control is increased.

The current work extends previous findings regarding managing radical innovations, particularly explaining how ad hoc and real options approaches complement rather than compete. The results are highly useful for managers in companies facing these types of projects.

Management summary

To assure sustainable competitive advantage, firms need to bring innovative new products to the market (*Veryzer, 1998*). Radical innovations are highly desired as they have the potential to provide higher levels of value compared to existing products (*Griffin, 1997, Benedetto, 1999*). However, managing radical innovations is a difficult and risky process (*Cooper, 1990*). The question is: What can be done to manage these innovations properly?

Two juxtaposing views for managing innovations co-exist. First, several authors suggest radical new projects typically involve trial-and-error (*e.g., O'Connor, 1998; Chandy and Tellis, 1998*). Because radical innovations are often causing substantial changes in the market place, estimating market potential and likely market acceptance of these types of innovations is proven to be very difficult (*Lynn et al., 1996*). Moreover, when the technology is still in embryonic stage unexpected problems may emerge requiring exceptional technological efforts and creativity (*Stevens, 1999*). On the other hand, *Huchzermeier and Loch* (*2001*) suggest managing project flexibility is well possible and can seriously reduce project costs. Drawing on real options theory, they suggest that R&D projects can be managed in a linear way and outcomes optimized by quantifying uncertainty. Of course, when possible such approach will provide much more control to managers when confronting innovation risk and uncertainty and thus would be preferable to ad hoc approaches.

The objective of this thesis is to find out which view is correct under conditions of radical new technology. Can radical new technology and conversion to product applications be managed in a linear way, as suggested by *Huchzermeier and Loch* (*2001*), or is an ad hoc approach paramount? We explore the degree to which real options approach can be used and extended to management of radical innovations.

Based on a case study from Philips Research and Philips Lighting regarding new lighting technology, we found a mix of these two approaches; they coexist and alternate. The early search of a useful application is a type of deliberated trial-and-error approach. After this, real options theory can be used but with some modifications based on different distributions of uncertainties and levels of control. Our results show that the streams seem to complement rather than substitute. Divergent findings may be explained by lack of sensitivity to or differentiation of radical vs. incremental innovation projects. Furthermore, real options literature use synonymous definitions uncertainty and risk and lacking specifying the level of project control, which determine the degree to which real options approach can be used and extended to management of radical innovations.

Early stages in the (pre) radical R&D project are characterized by very high uncertainty and require much flexibility. This flexibility will stimulate creativity, encourage outstanding technological efforts and fuel new opportunities. In these early phases of the full R&D lifecycle managerial flexibility loses its value because market input, such as market requirements and payoff, is not available and technical drivers are unclear and hard to manage since the technology is still in the embryonic stage. As the radical R&D project develops through the different phases and stages the uncertainty will resolve and less flexibility is needed, while the value of managerial flexibility will generally increase as uncertainties become quantifiable at higher levels of control and higher investments are needed.

Based on the findings of our case study, we developed a conceptual framework for managing radical product applications consisting of (1) a pre-radical R&D phase, (2) a radical R&D phase, and (3) an incremental R&D phase. In the pre-radical R&D project phase new applications for a novel technology or material are identified. This is a convergent process which leads to a single or a few most interesting applications. Based on the opportunity identification radical R&D projects are executed which focus on an application. Identifying and selecting the first application of a technology is an important source of option value and is a critical real option when managing radical new projects. Because of high failure rates, many radical R&D projects are abandoned. This explains the iterative behavior of subsequent radical innovation R&D projects. After launching a radical innovation to the market, incremental R&D projects are executed delivering continuations and extensions of the radical product on the market.

We contribute to the literature by reconciling the debate on the use of ad hoc/trial-and-error and real options approaches. We extend the soft real options stream that has focused on R&D project portfolio management to R(technology)&D(product application) project management. By doing this we close the gap between the hard and soft real options approach. We also extend current work on real options approach for managing (incremental product applications to) radical new product applications.

The contribution to practice includes new insights on how radical new product applications should be managed in R&D based companies. Our radical new project management process is highly usable for managers in companies facing these types of projects.

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After working several years at Philips Research Eindhoven, I decided beginning 2005 to study part-time Innovation Management at Eindhoven University of Technology. The main reasons to start studying again were to obtain a M.Sc. degree, to combine my technical background in Chemistry and Physics with knowledge in Industrial Engineering, to gain insights on how to innovate inventions, and last but not least because I enjoy studying. This acknowledgement section I would like to use to thank all who have helped me during my study and beyond.

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Ties van Bommel

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AFS:	Automotive Front lighting System
AIL:	Automotive Interior Lighting
CCD:	Color Conversion Device
CRT:	Cathode Ray Tubes
DCF:	Discounted Cash Flow
DL:	Display Lighting
DPS:	Double Plain Switching
ECD:	Electro Chromic Devices
FFS:	Fringe Field Switching
GL:	General Lighting
GRIN:	Gradient Index
IPS:	In Plain Switching
LC:	Liquid Crystal
LCD:	Liquid Crystal Display
LCG:	Liquid Crystal Gel
LED:	Light Emitting Diode
MDE:	Mechanical Deforming Element
MEMS:	Micro Electro Mechanical System
MME:	Mechanical Moving Element
MU:	Market uncertainty
NPD:	New Product Development
NPV:	Net Present Value
OEM:	Original Equipment Manufacturer
OLED:	Organic Light Emitting Diode
PDLC:	Polymer Dispersed Liquid Crystal
RBT:	Roll Blind Technology
RO:	Real Options
ROA:	Real Options Analysis
RS:	Replicated Structures
R&D:	Research and Development
SF-SPD:	Surface Force Suspended Particle Devices
SL:	Spot Lighting
SLCG:	Structured Liquid Crystal Gel
SPD:	Suspended Particle Devices
SPD-LC:	Suspended Particle Devices stabilized in Liquid Crystal
SSL:	Solid State Lighting
TU:	Technical uncertainty
VF:	Video Flash

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1. Introduction

1.1 Background and problem definition

By bringing innovative new products to the market, firms aim to gain sustainable advantage (*Veryzer*, *1998*). Radical innovations are highly desired for they have the potential to create new profitable lines of business (*Griffin, 1997; Benedetto, 1999*). However, managing radical innovations is a difficult and risky process (*Cooper, 1990*). The question is: What can be done to manage these innovations properly?

Two juxtaposing views co-exist. On the one hand, several authors suggest radical new projects typically involve trial-and-error (*e.g., O'Connor, 1998; Chandy and Tellis, 1998*). This view advocates an ad hoc approach because radical new product applications often serve an entirely new market and therefore customer preference is difficult to forecast and market size and profitability are hard to estimate (*Lynn et al., 1996, 1997*).

On the other hand, *Huchzermeier and Loch* (*2001*) suggest managing project flexibility is well possible and can seriously reduce project costs. Drawing on real options theory, they suggest that R&D projects can be managed in a linear way and outcomes optimized by quantifying uncertainty. They use a formal, systematic methodology having defined procedures for doing development.

If *Huchzermeier and Loch* (*1999, 2001*) are right their approach would provide managers with much more control. However, recent empirical findings suggest that – contrary to the authors' opinion — it may be less suitable for radical innovation. For instance, *Santiago* (*2008*) reports that the model seems to be more suitable for managing projects at the later stages of the full R&D lifecycle.

Thus in the literature several competing perspectives exist and it is unclear how useful these approaches are for managing radical innovations. Consequently, the question remains which approach is more appropriate.

1.2 Research questions

The purpose of this thesis is to find out which view is correct under conditions of radical new technology. Can radical new technology and conversion to product applications be managed in a linear way, as suggested by *Huchzermeier and Loch* (*2001*) or is an ad hoc approach paramount (*e.g. O'Connor, 1998*)? We explore the degree to which real options approach can be used and extended to management of radical innovations.

We begin with a literature review with a discussion of the relevant streams of research / conceptualizations. We address whether they are substitutes or complements and how useful these approaches are for managing radical innovation.

Next, we research limitations in the approach of *Huchzermeier and Loch* (*2001*) and look for modifications to fit conditions of radical innovation products.

In order to clarify our research question we define radical innovation as innovation which concerns exploration using new methods or practices and involves entirely new products, whereas incremental innovation refers to exploitation using continuations of existing methods or practices and involves refining or expanding existing products (*Mohr et al., 2001*).

Research questions:

- Can radical new product applications be managed in a linear way, as suggested by *Huchzermeier and Loch* (*2001*) or is an ad hoc approach paramount?
- More specifically, can we complement and modify *Huchzermeier and Loch's* (*2001*) approach to also address radical innovation project conditions?

1.3 Objectives

The objectives of the thesis are the following.

First, to clarify if radical new product applications can be managed in a linear way, as suggested by *Huchzermeier and Loch* (*1999, 2001*) or is an ad hoc/trial-and-error approach paramount (*e.g., O'Connor, 1998; Moorman and Minor, 1995, 1998*).

Second, to develop a conceptual framework for managing radical new R&D projects which provides better descriptions on how to manage radical new product applications.

Objectives:

- To clarify if radical new product applications can be managed in a linear way, as suggested by *Huchzermeier and Loch* (*2001*) or is an ad hoc/trial-and-error approach paramount?
- To develop a conceptual framework for radical new R&D projects which provides better descriptions on how to manage radical new product applications.

1.4 Methodology

First, we present a literature review on both perspectives, i.e. real options approach and ad hoc approach, to get a good understanding of the state of art in this domain. We will describe the real options stream and focus on models for managing R&D projects introduced by *Huchzermeier and Loch* (*1999, 2001*), *Huchzermeier* (*2009*), and further developments of the concept (*e.g., Santiago and Bifano, 2005; Santiago and Vakili, 2005; Rese and Baier, 2007; Santiago, 2008*). Then, we will study the contrasting view which describes projects conducted by a trial-and-error/ad hoc approach. We will compare the juxtaposing views and indicate limitations of the existing literature. Specifically, the limitations of the hard real options stream will be assessed.

Secondly, to answer our research question we use a case from Phillips regarding radical new lighting technology. The motivation for choosing a case study concerning multiple related R&D projects developing same radical technology within a single firm is that such approach provides the possibility to explore a total trajectory of R&D projects. We describe the new technology and illustrate how early on search of a useful application is a type of deliberated trial-and-error approach. After this, real options theory can be used but with some modifications based on different distributions of uncertainties. Additional considerations and uncertainties are also identified and included. The case study is based on several R&D projects working on the new lighting technology which were executed over the last seven years – 2003 to 2010 –. The author of this master thesis participated as a researcher in many of the projects. In order to increase the objectiveness of the qualitative analysis, the input of the author is supported by project proposals, progress reports and published documents including patent applications and (scientific) articles. In addition, we briefly refer to other R&D projects in / innovations of Philips to strengthen our findings.

Although the approach of this study is descriptive, we will make prescriptive statements to increase the relevance of our work.

Third, based on the literature review and case research we develop a conceptual framework of radical new project management for developing radical new product applications.

Methodology:

- Literature review on real options approach and trial-and-error approach for managing R&D projects studying both streams.
- Case study from Philips on radical innovation R&D projects to clarify if radical new product applications can be managed in a linear way or if an ad hoc approach is paramount.
- Constructing conceptual framework for radical new project management for developing radical new product applications based on the literature review and case research.

1.5 Contribution to literature and practice

We contribute to the literature in three important ways.

First, we reconcile the debate on use of ad hoc/trial-and-error (*e.g. O'Connor, 1998*) and real options approaches (*e.g. Huchzermeier and Loch, 2001*).

Second, we extend soft real options stream that has focused on organization strategy including R&D project portfolio management (*e.g., MacMillan and McGrath, 2002*) to engineering management in particular R(technology)& D(product technology) project management (*e.g., Santiago and Bifano, 2005*). By doing this we close the gap between soft and hard real options approaches.

Third, we extend the work regarding real options theory and innovation project management for managing radical new product applications. Current work (*e.g., Huchzermeier and Loch, 2001*) is more geared towards incremental new products, as will be explained.

Contribution to literature:

- Reconcile the debate on use of trial-and-error and real options approaches.
- Extend soft real options stream that has focused on R&D project portfolio management to R&D project management closing the gap between hard and soft real options approach.
- Extend current work on real options approach for managing radical new product applications.

Our contribution to practice includes new insights on how to manage radical new product applications. Based on case research we developed a conceptual framework. Our radical new R&D innovation management process is highly usable for managers in companies facing these types of projects.

Contribution to practice:

- Provide conceptual framework for managing radical new product applications.

1.6 Findings

Our results show that for radical innovation and radical product applications a mix of the two approaches is most useful. Based on a case study from Philips regarding new lighting technology, we found that the truth is a mix of these two approaches. The early search of a useful application is a type of deliberated trial-and-error approach. After this, real options theory can be used but with some modifications based on different distributions of uncertainties and levels of control. Our results show that the streams seem to complement rather than substitute. Divergent findings may be explained by lack of sensitivity to or differentiation of radical vs. incremental innovation projects. Furthermore, real options literature use synonymous definitions uncertainty and risk and lacking specifying the level of project control, which determine the degree to which real options approach can be used and extended to management of radical innovations.

We developed a conceptual framework for managing radical product applications next, consisting of (1) a pre-radical R&D phase, (2) a radical R&D phase, and (3) an incremental R&D phase. In the pre-radical R&D project phase new applications for a novel technology or material are identified. This is a convergent process which should lead to a single or a few most interesting applications. Based on the opportunity identification radical R&D projects are executed which focus on an application. The choice of which application to focus on first, is a "real option of select action" approach. Because of high failure rates, many radical R&D projects are abandoned. This explains iterative behavior regarding subsequent radical innovation R&D projects. After launching a radical innovation to the market, incremental R&D projects are executed delivering continuations and extensions of the radical product on the market. When the radical new technology develops further the first successful product applications will help obtain a better understanding of how to attack the market and product alternatives further (i.e. bowling alley idea in which after launching a first product to the market many other derived products will follow, *Moore, 2006*).

Findings:

- Radical new product applications should be managed by using a mix of an ad hoc and a real options approach.
- Both literature streams seem to complement rather than substitute.
- Further, the *Huchzermeier and Loch* (*2001*) approach needs some adaptations to extend it to management of radical innovations, not only regarding assumed variability distributions but also in terms of use of real options and managerial flexibility.
- Conceptual framework of radical new project management for developing radical new product applications.

1.7 Structure of the thesis

The remainder of this thesis is divided into five chapters. Chapter two describes managing R&D projects. In this part we describe managing R&D projects by using a real options and a trial-and-error approach and limitations of both approaches will be studied. In chapter three, we present a case from Philips Research and Philips Lighting regarding radical innovation R&D projects developing a new lighting technology. In chapter four, we capture and discuss our findings from the literature review and case study, and in chapter five we develop a real options based model for managing radical innovation R&D projects by using findings of the previous chapters. Finally, in chapter six we will present our main findings, draw conclusions from it and show the implications and limitations of our work which is a call for further research.

Structure:

1. Introduction
2. Managing R&D projects - Literature review
3. Case Study - Empirical study
4. Discussion of case findings - Results and discussion of case material
5. Construction of a conceptual framework for developing radical new product applications - Results and discussion
6. Conclusion

2. Managing R&D projects

In this section, we will review the real options (RO) approach to manage R&D projects that overcomes the limitations of traditional static project management tools, for instance it provides linear project management in which the course of an R&D project is steered from start to finish based on real time information (section 2.1). Specifically, we will discuss the models introduced by Huchzermeier and Loch (1999, 2001), Huchzermeier (2009), and further developments of the concept (e.g., Santiago and Bifano, 2005; Santiago and Vakili, 2005; Rese and Baier, 2007; Santiago 2008). We will then (section 2.2) discuss a contrasting view which describes projects conducted by a trial-and-error approach (e.g., O'Connor, 1998). Next, we will compare both approaches (section 2.3) and end with addressing limitations of the hard real options approach (section 2.4) as suggested by Huchzermeier and Loch (2001) as this approach – according to the authors' opinion – would be favorable for managing radical innovations because it would provide managers with much more control and enhances NPD success.

2.1 The real options paradigm

In order to assure a profitable sustainable future business, high-tech companies invest heavily in research and development (R&D) (*e.g., Griffin, 1997; Ollila, 2000*). Characterized by high technological and market uncertainty (*Rese and Baier, 2007*) investments in R&D projects are risky, because payoffs are unsure while investments are substantial and irreversible (*Huchzermeier and Loch, 2001*). For this reason it is key to manage R&D projects in an appropriate way (*Cooper, 1990*). However, it is difficult to assess R&D investments because technology and project characteristics such as lead time, cost and product performance of a project are difficult to estimate in time and market characteristics including market requirements and payoff are hard to forecast (*Lynn et al., 1996*).

Most R&D based companies use traditional Discounted-Cash-Flow (DCF) methods such as Net Present Value (NPV) to valuate their R&D projects (*e.g., Miller and Chan 2002; Boute et al., 2004*). However these DCF methods show significant limitations which might be catastrophic in making choices about R&D project investments (*e.g., Herath and Park, 1999*). These calculations do not take into account managerial flexibility and assume passive management of the project (*MacMillan et al., 2006*). For instance, DCF methods do not take into account that a project may be abandoned before finishing if intermediate results are disappointing (*Faulkner, 1996*). As a result many projects in a company's R&D project portfolio are undervalued (*Trang et al., 2002*).

Generally these static approaches are overly simplistic. In order to illustrate this, Figure 1 and Table 1 (*Faulkner, 1996*) present a simple example of four different valuations of a project: (a) most likely outcome, (b) most likely outcome including market uncertainty, (c) NPV analysis which assumes introduction of the product including all uncertainties, and (d) so-called real options analysis (ROA) which assumes that the R&D project is managed actively (*Santiago and Vakili, 2005*). Cost, uncertainties (i.e. probabilities) and possible returns are shown in Figure 1 and used in the calculations for the different valuations as shown in Table 1. When executing the project an initial investment in R&D of $6M is needed followed by an investment for commercialization of the product of $15M. The possible return of the project varies between -$60M and $60M dependent on the R&D and market outcome.

(a) The most likely outcome calculates the value of a project based on the scenario which has the highest probability against the possibility of investing that money somewhere else at an established interest or discount rate. This calculation is most oversimplified because it neglects other possible outcomes. This valuation method gives a negative value of $11.4M (most likely outcome is a good result with a return of $10M after two years).

(b) The most likely outcome calculation is improved by including market uncertainty, but still does not consider other possible outcomes. This valuation method still gives a negative value of $9.0M (R&D outcome is good and the range of possible returns is $10M or $20M having a probability of 0.7 and 0.3, respectively).

(c) The standard Net Present Value (NPV) of a project calculates the value of a project against the possibility of investing that money somewhere else at an established interest or discount rate under the assumption of commitment to commercialization and including all uncertainties. Still it is not financially beneficial to undertake the R&D project as a negative result of $5.4M is obtained with this valuation methodology.

d) The real options analysis shows a positive outcome (i.e. result of +$2.2M), because it takes into account managerial flexibility. The commercialization phase is only started in case the R&D project has an excellent outcome and therefore it is financially beneficial to start the R&D project.

Table 1: *Real options analysis vs. traditional analysis tools.*

	2007	2008	2009	result
most likely outcome	-$6M	-$15M/(1.12) =-$13.4M	$\$10M/(1.12)^2$ =$8.0M	-$11.4M
most likely outcome incl. MU	-$6M	-$15M/(1.12) =-$13.4M	$[(0.3)(\$20M)+(0.7)(\$10M)]/(1.12)^2$ =$10.4M	-$9.0M
NPV analysis	-$6M	-$15M/(1.12) =-$13.4M	(0.3)[(0.8)($60M)+(0.2)($15M)] (0.6)[(0.3)($20M)+(0.7)($10M)] (0.1)[(0.1)(-$15M)+(0.9)(-$60M)]=$14M $(1.12)^2$	-$5.4M
RO analysis	-$6M	(0.3)(-$15M/1.12) =-$4.0M	(0.3)(0.8)($60M)+(0.2)($15M)=$12.2M $(1.12)^2$	+$2.2M

The simplified example illustrates that discounted cash-flow (DCF) methods such as Net Present Value (NPV) calculations show limitations (e.g., *Herath and Park, 1999; Bowman and Moskowitz, 2001; Boute et al., 2004*). As a consequence, these methods lead to risk-averse investments (*Kester, 1984; Loch and Bode-Greuel, 2001; Fredberg, 2007*), while risky projects generally generate the highest profits (*Fredberg, 2007*). However, it should be noticed that in the example of *Faulkner* (*1996*) uncertainty is quantified whereas only in case of risks probabilities are known and measurable as described in the Finance literature (*Knight, 1921*).

In short, real options overcome limitations of DCF methods as they limit the downside of a R&D project because real options approach provides the possibility to adjust the course of a project such as to abandon the project if intermediate results are disappointing. The example further aims for the use of real options thinking to R&D valuation (*Faulkner, 1996*). Although in practice its use is still limited, there will be a shift from static approaches to a dynamic paradigm of real options for R&D management (*Trigeorgis, 1996*). In the next paragraph the real options theory is further explained.

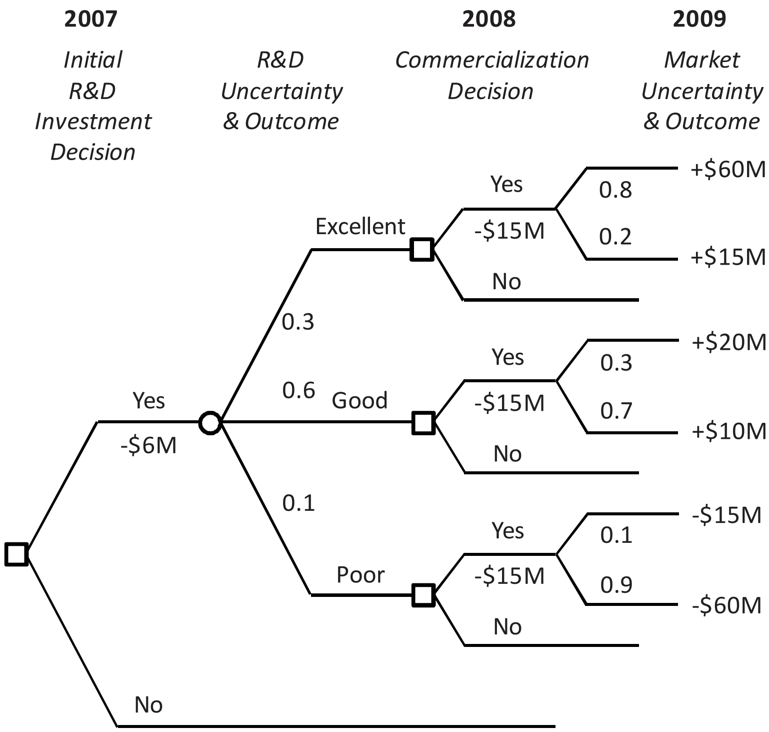


Figure 1: *Real options analysis vs. traditional analysis tools (adapted from: Faulkner, 1996)***.**

2.1.1 Real options theory

The concept of options originates from Finance (*Myers, 1977*) and is extended to a variety of application areas and topics (*Lander and Pinches, 1998; Miller and Chan, 2002*) including to R&D projects (*e.g., Faulkner, 1996; Morris et al., 1991; Barnett, 2005; Baker and Adu-Bonnah, 2008; Oriani and Sobrero, 2008; Levardy and Browning, 2009*) supply chain management, e.g. investments in sourcing, manufacturing and distribution activities (*Tong and Reuer, 2007; Nembhard et al., 2005*), acquisitions (*Eckhause et al., 2009*), technology licensing (*Ziedonis, 2007*), environmental investments of firms (*Cortazar et al., 1998*), or other kind of projects (*Gil, 2009; Driouchi et al., 2009*). Literature on options for non-financial applications denotes the concept real options (*Fredberg, 2007*). Real options provide the right, but not the obligation, to make a future investment or to take an action in future (*Amram and Kulatilaka, 1999*). Thus the owner of a real option has the opportunity, but not the obligation, to exercise the option (*Fredberg, 2007*).

Definition of real option:

The right, but not the obligation, to make a future investment or to take an action in future (*Amram and Kulatilaka, 1999*).

Although the use of real options in management is rather difficult (*Trigeorgis, 1996; Amram and Kulatilaka, 1999*), the theory is used in many scientific papers (*Lander and Pinches, 1998*) including R&D management. Real options approach can be used as a strategic decision making tool to make choices about future R&D investments or other managerial actions based on newly arrived information (*Huchzermeier and Loch*, *2001*). It has developed in a specific stream in the literature (*Eden, 2009*).

First we explain the basic concepts. R&D projects have the potential to open up avenues of profitable new business. However, per definition, if something has a potential, it also has a downside. Real options approach limits the downside and thus improves the upside potential of a project. It captures the value of managerial flexibility (*Trang et al., 2002*), because during an R&D project new information can be repeatedly gathered, and based on this new information a gated decision can be made (*Huchzermeier and Loch, 2001*). A high level of flexibility means that management has many chances to alter the course of a project in order to maximize gains *(Trang et al., 2002*).

There are several types of real options which can be categorized into three groups (Table 2): (1) learning options, (2) insurance options, and (3) growth options (*Hommel and Pritch, 1999; Rese and Baier, 2007*).

Table 2: *Types of real options (Huchzermeier and Loch, 2001; Loch and Bode-Greuel, 2001; Borissiouk and Peli, 2002; Rese and Baier, 2007).*

Category	**Type of RO**	**Definition**
learning options	defer	possibility to postpone the investment until more information has become available
	time-to-build	possibility to make staged investments
insurance options	contract	possibility to decrease the scale of the investment
	switch	possibility to change the mode of operation of an
	shut down and restart	possibility to stop the investment and restart again
	abandon	possibility to proceed further or whether to stop the investment
	improve	possibility to improve product performance or correct its targeting to market needs
growth options	expand	possibility to increase the scale of the investment
	innovate	possibility to acquire new knowledge or skills through (current/new) investments

(1) learning options refer to real options which are used before the investment is made and include the defer option and the time-to-build option (*Rese and Baier, 2007*).

(2) insurance options correspond to options used to react to negative changes in the R&D project, and contain the option to contract, option to shut down and restart, option to abandon, option to switch, and option to improve (*Huchzermeier and Loch, 2001; Rese and Baier, 2007*).

(3) growth options refer to options used for future investments and include the option to expand and the innovate option (e.g., *Loch and Bode-Greuel, 2001*).

Real options studies can be classified into different ways. Several studies categorize real options literature in the two sub-streams: soft real options and hard real options (*e.g., Natarayan, 2006; Fredberg, 2007*). Both sub-streams will be further described in the sections here below and summarized by Table 3.

2.1.1.1 Soft real options approach

Next to the standard real options of R&D projects a related but different sub-stream exists, using a more implicit concept of real options. Soft real options approach involves a qualitative orientation towards the real options theory and is focused on performance and antecedents of options. This stream takes the ideas from real options and makes qualitative assessments avoiding the use of complex mathematics (*Fredberg, 2007*). Proponents of soft real options analysis argue that it is beneficial to use the real options approach for initial decision making and strategic purposes, while its use is rather difficult for exact valuation of projects (*Lander and Pinches, 1998*). Several studies on the soft real options stream are published in the literature (e.g., *Natarajan, 2006; Fredberg, 2007*) and are applied to disciplines such as international business (*Lee and Makhija, 2009; Eden, 2009; Cuypers and Martin, 2010; Xu et al., 2010*), marketing (*Rese and Roemer, 2004; Adams, 2004*), information systems (*Benaroch, 2002*), organization management (*Kogut and Kulatilaka, 2001*), but mainly on organization strategy (*McGrath, 1997, 1999; McMillan and McGrath, 2000A, 2000B, 2002; McGrath and Nerkar, 2004; Vassolo et al., 2004; MacMillan et al., 2006; Li et al., 2007*). The softer use of real options is often applied in empirical studies (*Natarayan, 2006*). For instance, *MacMillan and McGrath* (*2002*) provided a model to map R&D projects along the two types of uncertainty and based on the mapping senior management can strategically decide which projects to execute (Figure 2).

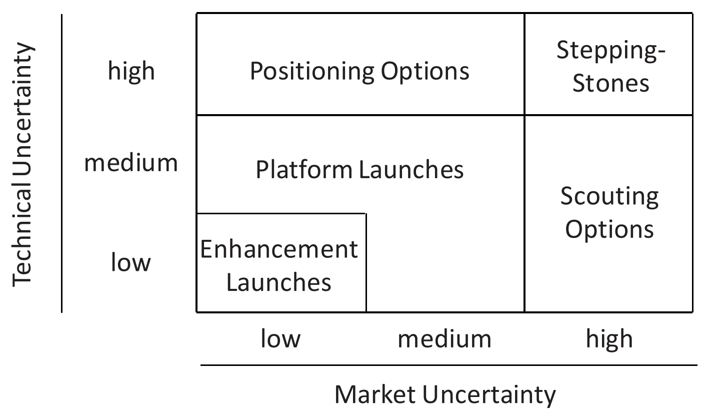


Figure 2: *Categorization scheme for mapping R&D projects.*

In another article, *McGrath and Nerkar* (*2004*) studied if R&D investments of pharmaceutical firms show similarities with real options reasoning. Based on patent mapping methodology they found that real options reasoning can be used as a strategic tool by large pharmaceutical firms and that investment decisions are guided by opportunities and experience (*McGrath and Nerkar, 2004*). Also other studies focused on real options reasoning describing methodologies (*MacMillan et al., 2006*), processes (*McGrath and MacMillan, 2000*), theories and propositions (*McGrath, 1997, 1999*) for investment analysis and decisions. Although many papers show the advantage and the easy practical application of this soft stream, it is not yet widely embraced by firms, because traditional decision making and management tools such as NPV are well-known and wide-spread (*Fredberg, 2007*). Several soft real options studies look at applications in R&D and NPD, but also these applications or topics show limited practical use or the concept is rather unconsciously applied. Literature on the softer use of real options is still immature and developing (*Li et al., 2007*).

2.1.1.2 Hard real options approach

An alternative sub-stream concerns the hard real options approach, characterized by mathematical modeling (*Fredberg, 2007*, *Natarajan, 2006*). Hard real options approach uses quantitative methods for understanding innovation decisions (*Lander and Pinches, 1998*), and its papers are often conceptual, lacking empirical tests. Most quantitative models are based on complicated mathematics such as Monte Carlo simulations and stochastic optimizations (*Cobb and Charnes, 2007*). The harder use of real options theory is published in many scientific papers (*Miller and Chan, 2002; Natarajan, 2006*) including studies on disciplines such as marketing (*Haenlein et al., 2006*), entrepreneurship (*O'Brien et al., 2003*), and economics (*Chen and Tokinaga, 2004; Richards and Patterson, 2004; Cobb and Charnes, 2007*), but mainly on engineering management (*Ford and Sobek, 2005; Santiago and Bifano, 2005; Rese and Baier, 2007; Santiago, 2008; Bekkum et al., 2009; Silva and Santiago, 2009*), management science (*Huchzermeier and Loch, 1999, 2001; Bollen, 1999; Cortazar et al., 1998; Santiago and Vakili, 2005*) and operations research (*Pennings and Lint, 1997, 2000; Trang et al., 2002*).

Table 3: *Overview of soft vs. hard real options stream (Natarajan, 2006; Fredberg, 2007).*

	Category	
	Soft real options	***Hard real options***
type of study	empirical	modeling
focus of study	phenomenon testing in empirical setting	methodology application & mathematically modeling
mainly applied discipline	Strategy	Management Science Operations Research
application topics	include R&D and NPD	include R&D and NPD
application in practice / reason	little / traditional concepts well-known & wide-spread	little / complex mathematics and assumptions
state-of-art	application to management of innovation	application of quantitative method in empirical study

Most mathematical models are based on assumptions which decrease rather than increase the accuracy of these calculations and understanding (*Fredberg, 2007*). These drawbacks explain the rather limited use of hard real options theory in practice (*Lander and Pinches, 1998*). In the same way, to our knowledge little research has been done on case studies about hard real options management showing empirical evidence of this stream. Nevertheless *Rese and Baier* (*2007*) showed a hard real options approach which can be easily used to model simple real options. They developed a quantitative method based on standard spreadsheet software for modeling real options. By using the computer-assisted decision tool the real options to continue, to abandon, and to improve within an R&D project were evaluated. They proved the applicability of hard real options theory in an empirical setting and called for new research in this area and stress the complexity of underlying assumptions. Also hard real options approach is applied in the research and development and new product development literature, but practical use in R&D and NPD is also very limited. Literature on hard real options is still far from established and is developing. An overview of both soft and hard real options is given in Table 3.

2.1.2 Real options approach of Huchzermeier and Loch

In this section we will review the real options based models introduced by Huchzermeier and Loch (1999, 2001), Huchzermeier (2009), and further developments of the concept (e.g., Santiago and Bifano, 2005; Santiago and Vakili, 2005; Rese and Baier, 2007; Santiago 2008). Their methodology assumes that R&D projects can be managed in a linear way and outcomes optimized by quantifying uncertainty (Huchzermeier and Loch, 2001). By surveying this stream we can explore the degree to which this real options approach can be used and extended to management of radical innovations.

Huchzermeier and Loch (*1999, 2001*) developed a hard real options based model of an R&D project. In their conceptualization of an R&D project, *Huchzermeier and Loch* (*1999, 2001*) consider a project determined by two sources of uncertainty: (a) technical uncertainty and (b) market uncertainty (*Huchzermeier, 2009*).

The technical uncertainty can be defined as “skepticism about whether the technology will function as promised or be available when expected by the company providing it” (*Mohr et al., 2001*) and is characterized by the three interacting drivers of project management (*Meredith and Mantel, 2006*), namely (1) product performance, (2) product development cost and (3) time-to-market or schedule (*Huchzermeier and Loch, 2001*).

Definition of technical uncertainty: “Skepticism about whether the technology will function as promised or be available when expected by the company providing it” (*Mohr et al., 2001*).

Market uncertainty refers to “ambiguity about the type and extent of customer needs that can be satisfied by a particular technology, arising from customer fear, uncertainty, and doubt about the needs or problems a new technology will address and meet” (*Mohr et al., 2001*) and is characterized by (4) market performance requirements and (5) market payoff (*Huchzermeier and Loch, 2001*).

Definition of market uncertainty: “Ambiguity about the type and extent of customer needs that can be satisfied by a particular technology, arising from customer fear, uncertainty, and doubt about the needs or problems a new technology will address and meet” (*Mohr et al., 2001*).

The value of an R&D project (V) is thus related to the two sources of uncertainty and determined by the five drivers of an R&D project and can be captured by the following equation (*Huchzermeier and Loch, 2001*):

V = f (performance, cost, time, market requirements, market payoff)

The five drivers of an R&D project distinguished by *Huchzermeier and Loch* (*1999, 2001*) are characterized by uncertainty and vary according to a distribution around a mean value. The five types of variability are listed together with their definitions here below (*Huchzermeier and Loch, 2001*) and their interactions are shown in the conceptual framework depicted in Figure 3.

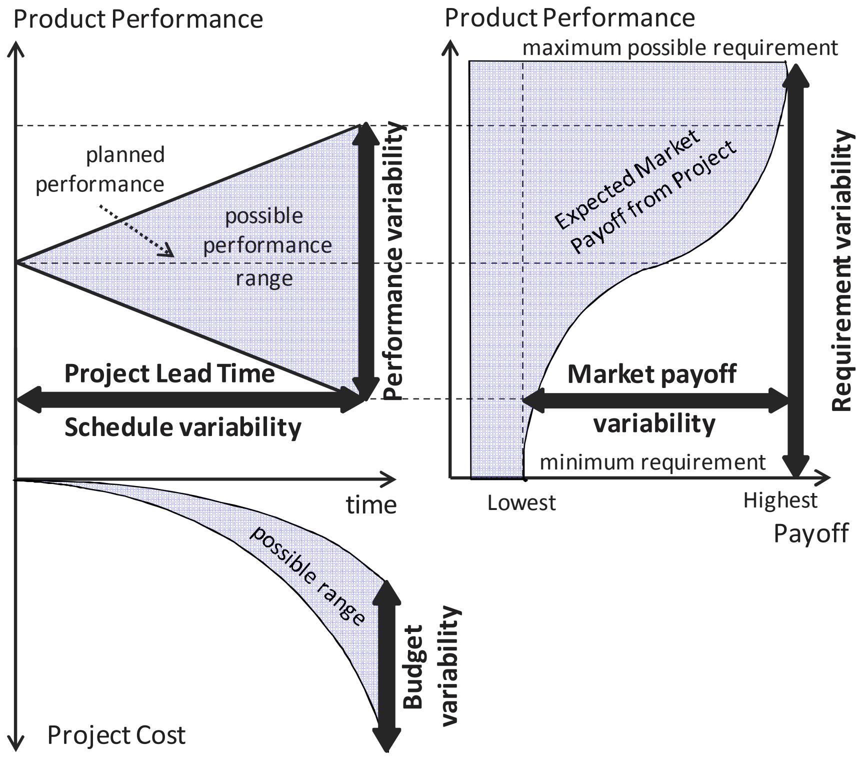


Figure 3: *Five types of operational uncertainty and their dependence (Huchzermeier and Loch, 1999, 2001).*

1.) Product performance variability: refers to uncertainty in the performance of the product being developed in the R&D project.

2.) Product development cost variability: corresponds to the uncertainty in the cost of the R&D project which develops the product.

3.) Product development schedule variability: refers to the uncertainty in the start and duration of the R&D project developing the new product.

4.) Market requirement variability: refers to the uncertainty about the required product performance level by the market.

5.) Market payoff variability: corresponds to the uncertainty about the payoff by the market, i.e. price and sales forecasts.

The model of *Huchzermeier and Loch* (*1999, 2001*) presented above can be simplified as shown in Figure 4 (*Huchzermeier*, *2009*). *Huchzermeier and Loch* (*2001*) conceptualize the R&D project as involving and proceeding in discrete stages. Furthermore, the performance of the product developed is subject to technical uncertainty, which leads to a drift in product performance over time. According to the model (*Huchzermeier and Loch*, *1999*, *2001; Huchzermeier*, *2009*) management has three possible real options after completing each stage: (1) the option to abandon, (2) to continue or (3) the real option of corrective action, i.e. improvement. These are discussed briefly below.

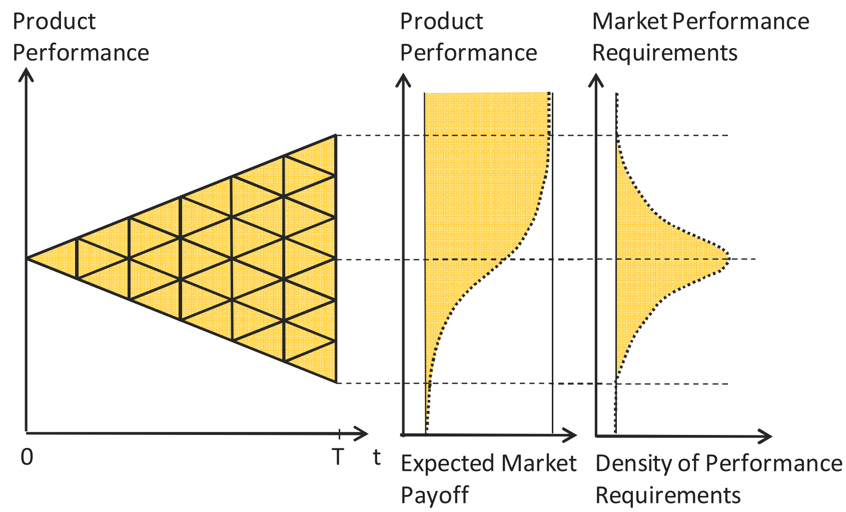


Figure 4: *Simplified conceptual framework of Huchzermeier and Loch (Huchzermeier, 2009).*

The real option of improvement was introduced by *Huchzermeier and Loch* (*1999, 2001*) in the same paper and is schematically explained in Figure 5. *Huchzermeier and Loch* (*2001*) define the real option of improvement as "midcourse actions during R&D projects to improve the performance of the product or to correct its targeting to market needs."

> *Definition of real option of improvement:*
>
> Midcourse actions during R&D projects to improve the performance of the product or to correct its targeting to market needs (*Huchzermeier and Loch, 2001*).

A change in product performance level over two periods is shown in Figure 5 for a transition without improvement and a transition with improvement. As can be seen from the illustration, the real option of improvement leads to an upwards shift in product performance. Thus improvement implies moving the product performance up, but is of course costly and should only be considered when investing that money is financially beneficial such that an increase in expected market payoff outweighs the additional costs of improvement (*Huchzermeier and Loch*, *1999*). Thus because the expected market payoff is determined by the product performance level and market needs, it is worthwhile to actively manage the project. The decision whether to invest or not should be based on the latest information update. During execution of the R&D project management can gather new information about uncertain project and market characteristics and according to the collected information, management can decide whether to continue the project or change its course of action by abandonment or improvement (*Huchzermeier and Loch, 2001*).

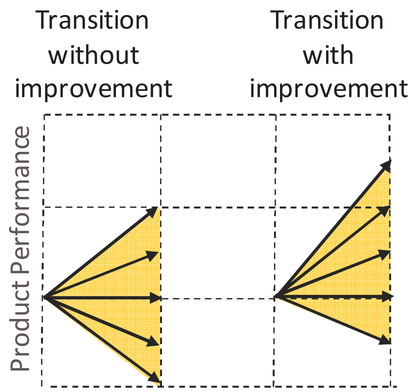


Figure 5: *Schematic illustration of real option of improvement (Huchzermeier and Loch, 2001)*.

In real options literature managerial flexibility is defined as the ability to alter the course of a project in response to the most recent gathered information about project progress and market characteristics (*Huchzermeier and Loch, 2001*).

> *Definition of managerial flexibility:*
>
> The ability to alter the course of a project in response to the most recent gathered information about project progress and market characteristics (*Huchzermeier and Loch*, *1999, 2001*).

Managerial flexibility can create real option value (*Huchzermeier and Loch, 1999*) which is the value added by actively managing the R&D project instead of passive management (*Santiago and Vakili, 2005*). This flexibility can be valuable in optimizing project value and future financial returns as shown here above. For instance, by controlling performance level of the product one can optimize project value or market payoff. The five drivers of an R&D project and their variability determine the project value and thus the value of managerial flexibility.

> *Definition of real option value:*
>
> Value added to uncertain R&D projects by creating real options through actively managing the project (*Huchzermeier and Loch, 2001*)

> *Definition of value of managerial flexibility:*
>
> Value added to uncertain R&D projects when the R&D project is actively managed versus when it is under passive project management (*Santiago and Vakili, 2005*)

According to *Santiago and Vakili* (*2005*), the value of managerial flexibility in R&D projects is self-evident, but estimating this value is still rather unclear. *Huchzermeier and Loch* (*2001*) have addressed this question and tried to evaluate flexibility in R&D. It is important to address this question because it provides qualitative insights on how R&D projects should be managed (*Huchzermeier and Loch, 2001; Santiago, 2008*). Real options theory has shown that higher uncertainty increases the value of managerial flexibility or real option value (*Dixit and Pindyck, 1994; Roberts and Weitzman, 1981*).

Relationship between uncertainty and value of managerial flexibility according to the real options theory: Higher uncertainty increases the value of managerial flexibility (*Dixit and Pindyck, 1994; Roberts and Weitzman, 1981*)

Several papers have been published which studied the relationship between uncertainty and the value of managerial flexibility (*Rese and Baier, 2007*). However, until the publication of *Huchzermeier and Loch* in *2001* the relationship between different types of uncertainty and the value of managerial flexibility was not distinguished (*Rese and Baier, 2007*). *Huchzermeier and Loch* (*2001*) proposed different types of uncertainty, i.e. uncertainty in market payoff, budget, performance, market requirements and schedule, and studied the impact of these different sources of uncertainty on the value of managerial flexibility. They found that the real options theory is not always valid for the different types of uncertainty (*Huchzermeier and Loch, 2001*). In agreement with standard real options theory their model revealed that (1) increased variability in market payoffs and (2) budgets enhances the option value of managerial flexibility. In case of (1) a higher variability in the market payoff, an increase or decrease in product performance has a higher impact on the payoff. Therefore managerial flexibility has more value in case of increased variability in market payoff (*Huchzermeier and Loch, 2001*). In case of (2) increased variability in budget, the conceptualization of *Huchzermeier and Loch* (*2001*) shows that a budget overrun is more likely and will make a subsequent future budget overrun also more likely and therefore the option value of managerial flexibility increases since it is more important to counteract budget runs.

However, increased variability in (3) performance and (4) market requirements may have the effect of reducing the value of managerial flexibility and does not correspond to established real options theory (*Huchzermeier and Loch, 2001*). In case of (3) a higher variability in performance, the expected payoff function will flatten and therefore decreases the value of managerial flexibility (*Huchzermeier and Loch, 2001*). In case of (4) higher variability in market requirements, part of the market requirements range are outside the reachable performance range and will reduce the payoff variability such that managerial flexibility loses its value (*Huchzermeier and Loch, 2001*).

Huchzermeier and Loch (*2001*) also found that (5) increased variability in time-to-market (schedule) will always decrease the value of managerial flexibility which is contrary to the established literature (*Dixit and Pindyck, 1994; Roberts and Weitzman, 1981*). The explanation of *Huchzermeier and Loch* (*2001*) is that if the delay is very large active project management is not worth much, while small delays can be compensated by active management.

The findings of *Huchzermeier and Loch* (*2001*) suggest that management should repeatedly gather information on all sources of uncertainty and not use a trial-and-error approach (*Rese and Baier, 2007*). This is consistent with literature on market orientation that advocates that current market information can help the firm develop better products meeting latent customer needs while paying attention to current and emerging competition (see e.g., *Li and Calantone, 1998*).

Relationships between different types of uncertainty and the value of managerial flexibility (*Huchzermeier and Loch, 2001*)*:*

1. Increased variability in market payoffs enhances the option value of managerial flexibility.
2. Increased variability in budgets enhances the option value of managerial flexibility.
3. Increased variability in performance may have the effect of reducing the value of managerial flexibility.
4. Increased variability in market requirements may have the effect of reducing the value of managerial flexibility.
5. Increased variability in time-to-market or schedule will have the effect of reducing the value of managerial flexibility.

The seminal paper of *Huchzermeier and Loch* (*2001*) had a significant impact on the R&D management literature and is referenced in more than 50 scientific papers. Nevertheless, as pointed out before, few articles have been published criticizing this work or extending it (*Santiago and Vakili, 2005; Santiago and Bifan, 2005; Baier and Rese, 2007; Santiago, 2008; Silva and Santiago, 2009*). *Santiago and Vakili* (*2005*), provide an important critique. Focusing on (1) the influence of an increase in uncertainty on increases of the value of an R&D project and (2) the impact of increased uncertainty on the value of management flexibility, they found intriguing contradictory results (*Santiago and Vakili, 2005*). Focusing on market payoff variability, product performance variability, and market requirement variability, their results reveal that one cannot make a general statement on the relationship between product performance variability or market requirement variability and the value of managerial flexibility (and project value). They show, for instance, that in some cases, the value of flexibility (and project value) will increase, while in others it will decrease. It depends on the conditions at hand, e.g. by varying the continuation cost in the model of *Huchzermeier and Loch* (*2001*). As modeled by *Santiago and Vakili* (*2005*), in case of a decrease in continuation cost, increased variability in performance may decrease the option value. However, in case of an increase in continuation cost, increased variability in performance may increase the option value. In another example they show that under specific conditions increasing variability in market uncertainty will lead to an increase in project value, while at even higher market requirement uncertainties, the project value decreases. The examples of *Santiago and Vakili* (*2005*) clearly show that the impact on project value and real option value is case dependent.

Table 4 summarizes the findings of the established real options literature, findings of *Huchzermeier and Loch* (*2001*) and the results of *Santiago and Vakili* (*2005*).

In summary, if *Huchzermeier and Loch* (*1999, 2001*) are right their results indicate that management should not perform an ad hoc approach, but a real options approach using formal, systematic methodology having defined procedures for doing development. Even in case of radical innovation one should monitor the different sources of uncertainty at regular intervals and act accordingly. This approach would provide managers with much more control (*Huchzermeier and Loch, 1999, 2001*). However, as described above, recent empirical findings suggest that –

contrary to the authors' opinion — this approach may be less suitable for radical innovation. For instance, *Santiago* (*2008*) state that the model seems to be more suitable for managing projects where development activities dominate those of research. In the next section we will review the juxtaposing approach of trial-and-error.

Table 4: *Literature overview on impact of uncertainty on (the value of) managerial flexibility (Dixit and Pindyck, 1994; Huchzermeier and Loch, 1999, 2001; Santiago and Vakili, 2005).*

<table>
<tr><th rowspan="2">uncertainty X</th><th colspan="3">more variability in X will</th></tr>
<tr><th>real options institution</th><th>Huchzermeier and Loch (2001)</th><th>Santiago and Vakili (2005)</th></tr>
<tr><td>market payoff variability</td><td rowspan="5">increase the value of managerial flexibility (MF)</td><td>increase the value of MF</td><td>increase project value or value of flexibility</td></tr>
<tr><td>budget variability</td><td>increase the value of MF</td><td>-</td></tr>
<tr><td>performance variability</td><td>may reduce the value of MF</td><td>no general statement about project value and the value of</td></tr>
<tr><td>market requirement variability</td><td>may reduce the value of MF</td><td>no general statement about project value and the value of</td></tr>
<tr><td>schedule variability</td><td>reduce the value of MF</td><td>-</td></tr>
</table>

2.2 Trial-and-error approach

Several authors suggest that highly uncertain R&D projects should be managed on an ad hoc basis which involves trial-and-error (*e.g.*, *Lynn et al.*, *1996, 1997; O'Connor*, *1998; Chandy and Tellis, 1998; Moorman and Minor, 1995, 1998; Thomke, 1998; Terwiesch and Xu*, *2008; Lindkvist*, *2008*). They argue that radical innovation is uncertain and creative and cannot be planned systematically or via application of mathematical formulas. Trial-and-error projects are characterized by many different projects which have an unclear path to a project's goal or have a project's goal which is still vague. A schematic representation of this unsystematic stream is depicted in Figure 6. The illustration shows the space of new concepts in terms of technologies and applications as a function of project duration. After exploring a first application, a new application is searched and researched. According to this approach a wide range of concepts are briefly studied in a disorganized way and patterns occur in different directions (*O'Connor*, *1998*). The process involves variation and adaptation.

An ad hoc approach is suggested because highly uncertain product innovations often do not fit existing market demarcation lines or product categories, and therefore customer preference is difficult to forecast and market size and profitability are hard to estimate at best (*O'Connor*, *1998; Chandy and Tellis*, *1998*). A number of articles discuss managing R&D projects on an ad hoc basis, along the lines of (1) improvisation methods (*Moorman and Minor*, *1995*, *1998*), (2) probe-and-learn techniques (*Lynn et al.*, *1996*) or (3) other trial-and-error project approaches (*Terwiesch and Xu*, *2008; Lindkvist*, *2008; O'Connor*, *1998; Thomke*, *1998*).

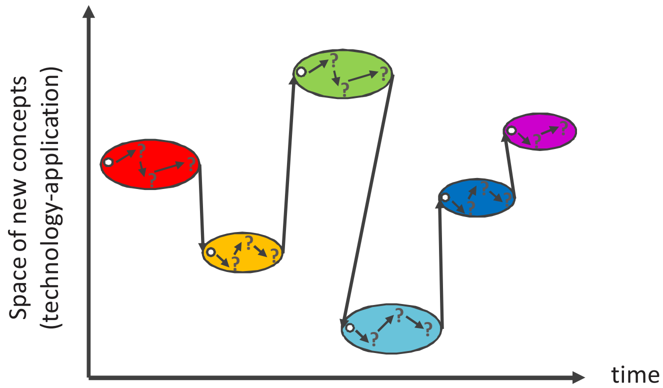


Figure 6: *Schematic illustration of trial-and-error approach.*

A first sub-stream within the trial-and-error methodology is (1) improvisation (*O'Connor*, *1998*). This type of ad hoc basis approach assumes that technology and market converge in time and thus initial market strategies which have been laid down are not appropriate anymore at a certain point in time such that a firms strategy should be adapted in time as well (*Moorman and Minor, 1995; Moorman and Minor, 1998*). Improvisation involves creation of new actions and strategies which are outside current plans and routines and can be executed at different levels from individual to organizational (collective) improvisation (*Moorman and Minor*, *1998*). This stream of thinking might have special value especially in fast-changing environments (*Moorman and Minor*, *1998*). *Moorman and Minor* (*1998*) suggest that strategy implementation along with innovation by anticipating on real-time information creates more possibilities for organizations. Their results show improvisation is a substitute for planning and that this NPD strategy generates effective products and processes.

Related to trial-and-error, but more systematic is *Lynn et al.'s* (*1996*, *1997*) view of (2) probe-and-learn for managing discontinuous innovations. It draws on experiential learning approaches. A case study based on four successful discontinuous innovations revealed that use of conventional new product development and in specific market research techniques proved to be of limited utility, showed striking results and even pointed the company in a wrong direction (*Lynn et al.*, *1996*). They conclude that the process for developing discontinuous innovations is fundamentally different than the conventional new product development (NPD) processes. The process is far more experimental and far less analytic (*Lynn et al.*, *1996*). For this reason they suggest a trial-and-error approach in which early versions of product are introduced to an initial market, i.e. probing. Based on the market feedback one can decide to improve the immature product or target another plausible market segment or application, i.e. learning. This iterative process is often referred to in the literature as probe-and-learn process.

(3) Other trial-and-error approaches argue that R&D projects may be seen as experiments in order to come up with creative solutions (*Lindkvist*, *2008; Thomke*, *1998*). This adaptive-learning process will reveal or at least give an indication what works or not (*Lindkvist*, *2008*). Based on a set of alternatives generated by such trials, one may select a solution for further experimentation. This trial-and-error process which treats projects as trials or experiments may result through a series of iterations in a successful solution to a specific project problem. This type of approach is especially suitable for R&D projects characterized by high uncertainty (*Lindkvist*, *2008*). Thus by

treating projects as experiments or trials, through a series of projects (iterations), one may find the right technology-application combination targeted for the right market (*Lindkvist, 2008*). This ad hoc solution is suggested to be a successful process for developing new product applications characterized by high market and technology uncertainty. A special type of this approach is to conduct experimental projects under open innovation conditions (*Chesbrough, 2003, 2004*) over corporate boundaries or ultimately by innovation contests (*Terwiesch and Xu, 2008*).

2.3 Real options vs. trial-and-error approach

We can now juxtapose the real options vs. the trial-and-error approaches. Both approaches are rooted in different perspectives on innovation management. The first stream sees the world as absolute and planable, while the trial-and-error stream uses a more dynamic and evolutionary view. Although the first view is desirable, it is an illusion that it can be attained under all conditions. As a compromise soft real options emerged (Figure 7).

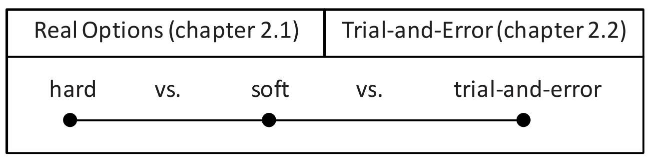


Figure 7: *Real options vs. trial-and-error approach.*

Some argue that an ad hoc approach involves extreme flexibility which is very expensive (*Huchzermeier and Loch, 2001*); the long term risky gambling or trial-and-error strategies are unlikely to pay off as high wins are negatively effected or compensated by high losses (*Huchzermeier and Loch, 1999*). Several disadvantages of trial-and-error have been identified in the literature.

First, trial-and-error projects such as probe-and-learning techniques are often executed in series (*Lynn et al., 1996*) and this methodology is rather time consuming (*Loch et al., 2001b*), while real options provides planning advantages such as strategic planning of activities in parallel to reduce time-to-market (*Childs et al., 1998*).

Second, performance improvement received less attention in trial-and-error projects (*Lynn et al., 1996*), while performance improvement is key in real options even in the early stages of real options approach managed R&D projects (*Huchzermeier and Loch, 1999, 2001*).

A third disadvantage is that many trial-and-error projects do not have strict budget constraints, which may result in budget overruns, or are over budgeted and those investments being made may lose value (*Chandy and Tellis, 1998*).

In other words, from a technical point of view, trial-and-error approach is difficult to plan in terms of costs, performance and time. Opponents of the ad hoc approach for R&D projects conclude that companies cannot afford such high flexibility (*Huchzermeier and Loch, 2001*). Strict management of product performance, project development duration and costs is needed to optimize market-project payoff (*Huchzermeier and Loch, 1999, 2001*).

As most trial-and-error projects are focused on studying technical feasibility of the concept the market part gets less attention (*O'Connor, 1998*). For instance, trial-and-error R&D projects do not include regular planned market information updates, i.e. continuous market learning (*Day, 1994*), which are according to real options stream needed to decrease market uncertainty (*Huchzermeier, 2009*). For this reason in trial-and-error projects market requirements are not (well) known (*Lynn et al., 1996*).

In addition, coordination of uncertain and complex R&D projects is key (*Mimh et al., 2003*), however, this is rather omitted in trial-and-error projects (*O'Connor, 1998*). For instance, risk management is hardly used in ad hoc projects.

Another drawback of trial-and-error approach is that this methodology is not standard and generalizable, while management of R&D based companies would like to use standard project management tools. They would like to have control over the projects being executed. In the same way, evaluation of projects executed by a trial-and-error approach is rather difficult, while for example project value using real options approach can be calculated to select projects (*Huchzermeier and Loch, 1999, 2001; Huchzermeier, 2009; Loch et al., 2001a; Loch and Kavadias, 2002*).

Hence several disadvantages of an ad hoc approach exist. However, also the real options approach has disadvantages. These are discussed in the next section. Specifically, the limitations of the hard real options stream of *Huchzermeier and Loch* (*1999, 2001*) will be assessed.

2.4 Limitations of Huchzermeier and Loch

The insightful model introduced by *Huchzermeier and Loch* (*1999, 2001*) attracted academic attention (*Santiago, 2008*) and is improved by several scholars (*e.g., Santiago and Vakili, 2005; Santiago and Bifano, 2005; Rese and Baier, 2007; Silva and Santiago, 2009*). For instance, *Santiago and Vakili* (*2005*) found case dependent correlations between different types of uncertainty and the value of managerial flexibility. The real options approach described by *Huchzermeier and Loch* (*2001*) has also several other limitations, which we outline next.

Although the contribution of *Huchzermeier and Loch* (*2001*) is significant to the literature, their publication shows several limitations:

(1) Their conceptualization addresses incremental innovation and not radical innovation; from their examples it is clear that the application is a given and uncertainties CAN be estimated.

(2) They do not describe the real option of select action that management can take; In accordance with previous observation they do not recognize or consider the possibility that – particularly for a new technology — the search for useful application is a major issue, and a critical element in the process (*Gruber et al., 2008; Baron and Ensley, 2006*).

(3) Consequently, they also do not address the iterative behavior of subsequent R&D projects and product network effects; their conceptualization is limited by a single individual project, while R&D projects are linked with each other and show patterns of iteration (*Levardy and Browning, 2009*).

(4) They do not differentiate between uncertainty and risk; in their approach uncertainty is synonymous with risk, while in Finance literature two clearly separated constructs are used (*Knight, 1921; Epstein and Schneider, 2008*).

(5) They do not place the use of real options and managerial flexibility in context with the level of control; in their approach they do not formulate the use of real options and the value of managerial flexibility according to the level of project control.

The five limitations identified will deliberately be described in the following individual sections. Each limitation will raise different questions which will be addressed by means of several case examples in the next chapter.

2.4.1 Incremental innovation

A first limitation of the article of *Huchzermeier and Loch* (*2001*) is that their conceptualization is suitable for incremental innovation and not radical innovation.

(1.) Their conceptualization addresses incremental innovation and not radical innovation,

- from their examples it is clear that the application is a given and uncertainties CAN be estimated.

In order to explain this statement we will briefly define innovation and the different types of innovations. Innovations are a result of the innovation process which is defined as "the combined activities leading to new, marketable products and services and/or new production and delivery systems" (*Burgelman et al., 2004*).

Definition of innovation process:

"The combined activities leading to new, marketable products and services and/or new production and delivery systems" (Burgelman et al., 2004)

The innovation process starts at the fuzzy front end which can be defined as the zone between when the opportunity is known and when a serious effort on the development begins (*Smith and Reinertsen, 1998*).

Definition of fuzzy front end:

The zone between when the opportunity is known and when a serious effort on the development begins (*Smith and Reinertsen, 1998*).

An innovation is successful if it returns investments made in R&D and commercialization plus some additional returns. Innovations can be classified into two broad categories which we call incremental and radical innovations. Incremental innovation concerns exploitation (*Leifer et al., 2000*), i.e. continuations of existing methods or practices (*Mohr et al., 2001*) and involves refining or expanding existing products or services (*Burgelman et al., 2004*).

> *Definition of incremental innovation:*
>
> Innovation which concerns exploitation using continuations of existing methods or practices and involves refining or expanding existing products or services (*Mohr et al., 2001*).

Radical innovation relates to exploration (*Leifer et al., 2000*), i.e. using new methods and practices (*Mohr et al., 2001*) and involves entirely new products or services (*Burgelman et al., 2004*).

> *Definition of radical innovation:*
>
> Innovation which concerns exploration using new methods or practices and involves entirely new products or services (*Mohr et al., 2001*).

In this master thesis we will focus on technological product innovations, i.e. new products which are technology based. Examples of radical product innovations were the first Computerized Tomography and Magnetic Resonance Imaging systems in the field of medical imaging modalities (*O'Connor, 1998*), first personal computers in the area of computing and mobile phones in mobile communications (*Leifer, 2000*). A more recent example of a radical product innovation in the area of consumer lighting for atmosphere creation is Philips LivingColors. Subsequent extensions of all these products are incremental product innovations.

Huchzermeier and Loch (*2001*) suggest that R&D projects can be managed in a linear way (*Cooper, 1990, 2004a, 2004b, 2004c; Day, 1994*) and outcomes optimized by quantifying uncertainty are well possible (*Huchzermeier and Loch, 1999*). Other authors argue that the quantitative model is not applicable for radical R&D projects (*e.g., O'Connor, 1998*). They state that the path to a radical R&D project's goal is rather unclear and not linear. Many authors agree that the performance, cost, schedule, market requirements and also the project payoff characteristics of an incremental product innovation can be reasonably estimated based on information of the existing standard products (*e.g., Santiago, 2008*). However, the five drivers of an R&D project identified by *Huchzermeier and Loch* (*2001*) are difficult to quantify for radical innovations. These findings are supported by the literature. *Santiago* (*2008*) concludes that the concept introduced by *Huchzermeier and Loch* (*1999, 2001*) and further developed by *Santiago and Vakili* (*2005*), *Santiago and Bifano* (*2005*) and *Silva and Santiago* (*2009*) seems to be better applicable for later stages in the R&D lifecycle. In addition, as observed in the literature and discussed here above, scholars have criticized the use of hard real options (*e.g. Fredberg, 2007*). Effective use of quantitative models is limited by poor estimations (inputs) and assumptions (*Bowman and Moskowitz, 2001*). Because radical new product applications often do not fit existing market demarcation lines or product categories, customer requirements are difficult to forecast and market size and profitability are hard to estimate at best (*Lynn et al., 1996*). If estimations of radical R&D projects are used, than the results from the decision support model (*Huchzermeier and Loch, 1999, 2001; Santiago and Vakili, 2005; Santiago and Bifano, 2005*) will be incorrect (*Bowman and Moskowitz, 2001*). This may explain why such models are not applicable for radical R&D projects. Even for incremental innovations the use of quantitative models in practice is limited since estimations are still uncertain although relatively much more certain than for radical innovations (*Lander and Pinches, 1998*). Based on the limitation addressed here above, the author of the thesis states that literature on real options for R&D projects lacks a conceptual framework for radical innovation R&D projects.

2.4.2 Project selection

A second limitation of the article of *Huchzermeier and Loch* (*2001*) is that the authors omit the selection of a new product application which management should undertake.

> (2.) They do not describe the real option of select action that management can take,
>
> - In accordance with previous observation they do not recognize or consider the possibility that – particularly for a new technology — the search for useful application is a major issue, and critical element in the process (*Gruber et al., 2008; Baron and Ensley, 2006*)

Huchzermeier and Loch (*2001*) as well as the literature which elaborates on their conceptual framework (*Huchzermeier and Loch, 1999; Santiago and Vakili, 2005; Santiago and Bifano, 2005; Santiago, 2008*) do not recognize or consider the possibility that – particularly for a new technology — the search for a useful application is a major issue, and critical element in the process (*Baron and Ensley, 2006*). A new technology can serve different markets and can be used for several applications. Thus before starting an R&D project there should be at least one application in one segment identified in which the new technology can be used (*Gruber et al., 2008*). The targeted initial application-segment combination functions as an overview in which each application is characterized by project and market uncertainties. Defining these characteristics prior to the start of the project reduces the uncertainty and variability of the project. It is key to identify for a new technology several applications and segments in a specific market. By identifying more than one application and/or market segment, management is able to select the most attractive opportunity. Particularly for radical product innovations, a new technology can serve several applications and segments in a specific market (*Moore, 2006*). Successful introduction of a radical product innovation to the market may enhance NPD success as many other derived applications/segments may follow according to the bowling alley idea of *Moore* (2006). *Huchzermeier and Loch* (2001) do not describe this opportunity identification phase (*Gruber et al., 2008; Baron and Ensley, 2006*).

2.4.3 Iteration and network effects

A third limitation of the article of *Huchzermeier and Loch* (*2001*) is that the authors do not describe the iterative nature and behavior of R&D projects. Their models show a focus on product project management rather than innovation project management.

Most R&D projects generate one or multiple subsequent R&D projects (*Levardy and Browning, 2009*). A subsequent project may be a project in which the same new technology is being researched but targeted for a new application. Because R&D projects are not single individual projects, but linked projects, this will impact the technological and market uncertainty, and the value of a project. For this reason it is valuable to map these interrelated projects as they show network effects (*Lee and O'Connor, 2003*).

(3.) Consequently, they also do not address the iterative behavior of subsequent R&D projects and product network effects,

- their conceptualization is limited by a single individual project, while R&D projects are linked with each other and show patterns of iteration (*Levardy and Browning, 2009; Green et al., 1995*)

2.4.4 Risk vs. uncertainty

A fourth limitation of the article of *Huchzermeier and Loch* (*2001*) is that the authors use risk and uncertainty interchangeably.

(4.) they do not differentiate between uncertainty and risk,

- in their approach uncertainty is synonymous with risk, while in Finance literature two clearly separated constructs are used (*Knight, 1921; Epstein and Schneider, 2008*)

The real options literature also does not differentiate between the two terms (*e.g. Huchzermeier and Loch, 1999, 2001; Huchzermeier, 2009; Santiago and Bifano, 2005; Santiago and Vakili, 2005; Rese and Baier, 2007; Santiago, 2008, Silva and Santiago, 2009*), while in Finance literature two clearly separated constructs are being used (*Knight, 1921; Epstein and Schneider, 2008*). *Knight* (*1921*) was one of the first who described this distinction. According to *Knight* (*1921*) risk is measurable/calculated uncertainty, whereas uncertainty is non-quantitative thus immeasurable uncertainty. In case of risk the probabilities are know, while in case of uncertainty they are unknown.

Definition of risk (Knight, 1921):

Measurable/calculated uncertainty where probabilities are known.

Definition of uncertainty (Knight, 1921):

Immeasurable uncertainty where probabilities are unknown.

Huchzermeier and Loch (*2001*) use different types of uncertainty as input for the conceptual model. However, actually they use operational risks as input.

2.4.5 Level of project control

A fifth limitation of the article of *Huchzermeier and Loch* (*2001*) is that the authors do not use their definitions in combination with the level of control.

(5.) they do not place the use of real options and managerial flexibility in context with the level of control,

- in their approach they do not formulate the use of real options and the value of managerial flexibility according to the level of project control

The use of real options depends on the level of project control. For instance, if there is almost no control, the real option of improvement (*Huchzermeier and Loch, 1999, 2001*) cannot be used. In this situation real options types as abandonment and continue are more often applied. In the same way the level of control will influence managerial flexibility and the real option value. In addition, the use of the different types of real options varies in time (*Katzy, 2003; Rese and Baier, 2007*).

3. Case study

This chapter presents a case study from Philips (Research and Lighting) regarding new lighting technology. Case research is used to answer our research question whether radical new technology and conversion to product applications can be managed in a linear way as suggested by Huchzermeier and Loch (2001) or if a deliberated trial-and-error approach is paramount (e.g., O'Connor, 1998). First, we define the methodological considerations of our study (section 3.1), and after a case company description (section 3.2), an introduction to projects and project management at Philips Research is given (section 3.3). We will describe the new lighting technology and delineate the different R&D projects and their trajectory (section 3.4). The projects involve trial-and-error as more systematic real options like approaches. The former dominate the beginning of the radical new technology for application development whereas the latter are more used or resembled in later stages.

3.1 Methodological considerations

In this master thesis we present a case study concerning multiple R&D projects regarding a new lighting technology within Philips. All these projects were developing the same radical new technology. The motivation for choosing multiple related projects is that such a case study provides the possibility to explore a total trajectory of R&D projects. A case study is defined in the literature as "an empirical enquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" and "relies on multiple sources of evidence" (*Yin, 1984*). Our case study provides insights to develop ideas on resolving/addressing limitations of the conceptualization of *Huchzermeier and Loch* (*2001*) identified in section 2.4. The case study includes participative research, because the author of this master thesis took part in many of the R&D projects. Advantages of this approach include deeper understanding of subjects, situations and organizational context. For instance, the author of this master thesis is familiar with the technology, concepts, projects, terminology, et cetera. Based on a richer understanding, evaluation and interpretation of information, the research methodology generally results in a higher chance to develop/design theories/solutions to existing problems and make substantial practical recommendations. Disadvantages of this research methodology include constraints in terms of reliability or generality of findings and the methodology may be exposed to biases when used incorrectly (*Soy*, *1997*). For this reason we use case research as an exploratory tool to study the R&D projects within Philips and apply suggested methods and techniques reported in the literature for organizing and conducting the case research successfully (*Yin, 1984; Graziano and Raulin, 1997; Soy, 1997*). To guarantee the objectiveness of our study we will use a systematic/structured way of working and exercise the following five steps: (1) properly determine and define our research questions, (2) demarcate our case sample, (3) describe our data collection approach, (4) illustrate our data analysis method, and (5) point out our way of reporting. We discuss these issues in more detail next:

(1) In this master thesis we will investigate whether radical new technology and conversion to product applications can be managed in a linear way, as suggested by *Huchzermeier and Loch*

(*2001*) or if an ad hoc approach is paramount (*e.g. O'Connor, 1998*). More specifically, we explore the degree to which real options approach can be used and extended to management of radical innovations. Both research questions are explained in more detail in chapter 1. The projects within the R&D of Philips apply as they meet the criterion of radical defined as "innovation which concerns exploration using new methods or practices and involves entirely new products or services." Further, it concerns a major new technology (LEDs combined with electro-optical elements) with adequate variation in types of projects and success and failures.

(2) Within Research and Lighting there are many projects related to LED lighting. In this case study we considered all the projects which were related to the radical new lighting technology (i.e. projects which developed electro-optical elements for LED lighting). All other projects on LED lighting were not considered. In total seven projects will be discussed, which to a large extent happened sequentially. The R&D projects were executed at Research and Lighting over the last seven years, i.e. 2003 to 2010. To further define our case sample we will give a case company description (section 3.2), describe project and project management at Philips Research, as most of the case projects are executed at Research (section 3.3), and illustrate the new lighting technology (section 3.4.1).

(3) We will collect our data by using multiple sources of evidence (*Yin, 1984*). We rely mainly on formal project proposals, progress reports, patent applications and (scientific) articles. Much of this information is included in this chapter and the appendices for evidence. R&D project proposals of Research were directly copied, while project information of Lighting was based on project progress documents. In addition, we will use information and illustrations originating from invention disclosures and published patent applications. Furthermore, we use information from technical scientific publications and information from books describing the new lighting technology. Finally, insights were obtained by interviewing project members. This supplemented and helped validate observations and interpretations of the author.

(4) Data is analyzed by the author of this master thesis and evaluated together with both supervisors. Furthermore, results were summarized and presented to a set of three former project members for review. Based on their feedback only small changes were necessary, for instance the help the researchers got finding an application area. A client from Lighting got to hear about another technology intended for another market who was not aware of the technology described in the case study. After he was informed about the technology described in the thesis the project of car lighting (executed in 2005) started.

(5) All R&D projects and their trajectory are summarized in section 3.4. This provides a brief overview of all findings and the interpretation. These findings will be discussed in chapter 4 and relationships with the literature are highlighted.

3.2 Case company description

Philips Electronics, headquartered in Amsterdam, The Netherlands, is a diversified Health and Wellbeing company which is focused on improving people's health and wellbeing through timely innovations. Philips is a world leader in healthcare, lifestyle and lighting, and integrates technologies and designs into people-centric solutions. Philips' brand promise is "sense and simplicity" which encapsulates the company's commitment to deliver advanced products and solutions that are designed to meet the needs of their customers (designed around you) and are easy to experience. The values of the company are to delight customers, to deliver on commitments, to develop people, and to depend on each other. Figure 8 shows the organizational structure of Philips Electronics.

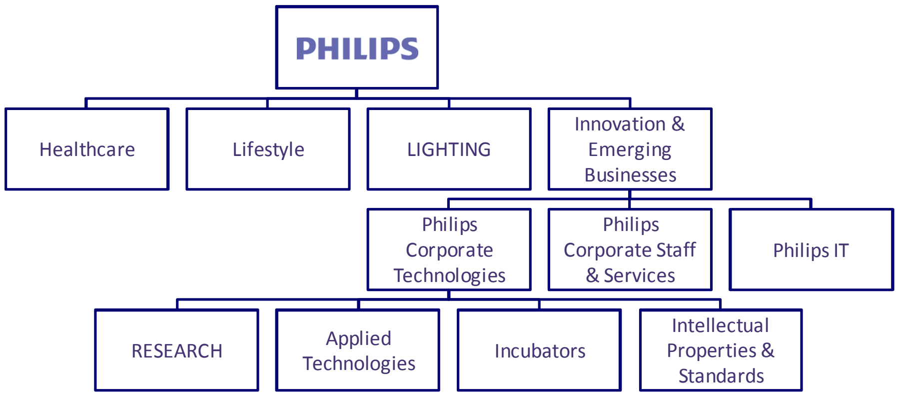


Figure 8: *Organizational structure of Philips (Philips annual report 2009).*

Philips has approximately 120,000 employees in more than 60 countries worldwide and had a turnover of 23 billion euro in 2009. Philips Electronics is organized in three sectors, namely Healthcare, Lifestyle and Lighting. An additional separate entity is Corporate Technologies which includes Philips Research, Philips Applied Technologies, Philips Intellectual Properties & Standards and Incubators. Philips owns about 50,000 registered patents and invests a large amount of its sales in research and development, namely 1.6 billion euro in 2009 which is 7% of its sales *(Philips annual report, 2009)*. Philips is heavily involved in R&D projects. However, there is severe pressure within the firm for more results driven R&D, i.e. leading to marketable products. Yet, the firm has produced many patents over the years and thus is very suitable as a case study for our topic.

Philips Research executes research for the three Philips sectors and undertakes projects in strategic growth areas. It has research sites in Eindhoven (The Netherlands), Redhill (Great Britain), Aachen and Hamburg (Germany), Briarcliff (United States), Shanghai (China) and Bangalore (India). Figure 9 depicts the organizational structure of Philips Research.

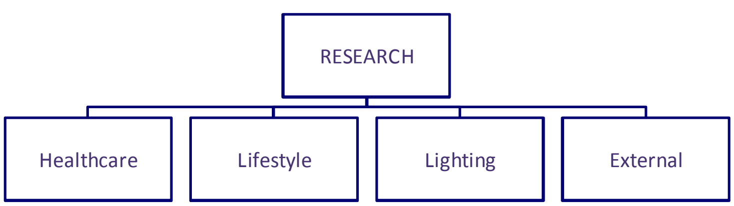


Figure 9: *Organizational structure of Philips Research.*

About 2,000 researchers of various disciplines are working worldwide on new technologies and applications in the area of Healthcare, Lifestyle (i.e. consumer electronics, domestic appliances and personal care) and Lighting. Nowadays, Philips Research operates via a combination of open and closed innovation strategy in order to bring more innovations to the market.

Philips Lighting is global leader in the lighting market. Philips Lighting is in terms of employees the largest sector of Philips Electronics (approximately 50,000 employees) and has a turnover of 7 billion euro (*Philips annual report, 2009*). The division is structured in the business units Lamps, Professional Luminaires, Consumer Luminaires, Lighting Electronics, Automotive and Lumileds (Figure 10). Philips Lighting's products include mature lighting products such as incandescent lamps, halogen lamps, fluorescent lamps, fixtures, lighting electronics, ballasts, automotive lamps, to innovative Solid State Lighting light solutions. Research is the driving force behind these innovations. In 2009 Philips spent 351 million euro on R&D in the area of Lighting (*Philips annual report, 2009*). Besides research executed at Philips Research, Philips Lighting has a separate centralized R&D organization (pre-development) and most business units within Lighting have their own development department.

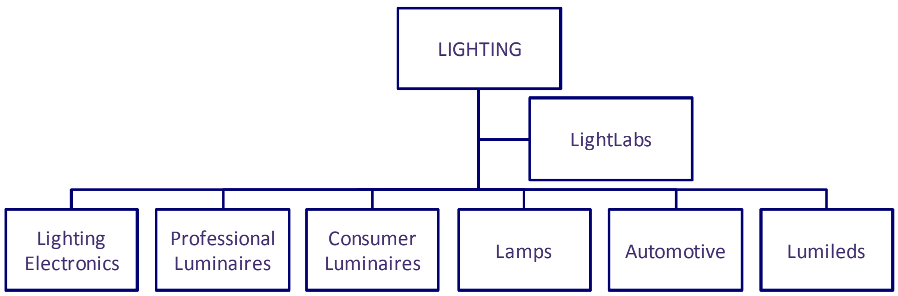


Figure 10: *Organizational structure of Philips Lighting.*

The lighting industry is changing enormously and will continue to change for years to come. It is facing a massive shift from conventional lighting towards Solid State Lighting including inorganic Light Emitting Diodes (LEDs), Organic Light Emitting Diodes (OLEDs) and Lasers. Solid State Lighting (SSL) is a semi-conductor-based technology which is completely different from technologies used in conventional light sources which dominated the lighting market in the last century. Another global trend in the lighting industry, which is embraced by Philips as well, is the transition from selling lighting components to delivering lighting solutions. This has also been made possible by the rapid developments and potential of LEDs as they are small, have a long lifetime, offer amazing efficiency, are dynamically tunable in light level (dimming) and dynamics in color and color temperature can be obtained.

In the following section, we first describe what kind of projects are conducted, typical trajectories of R&D projects, and we give a brief overview on project management executed at Philips Research.

3.3 Projects and project management

There is a large variety in research projects at Philips Research. As a consequence, different project management methods/tools exist and are being used. An overview of this is documented in a project management handbook of Philips Research (*Aalders, 2009*) which we briefly summarize in this section together with additional information gathered by the author of this thesis.

Just like projects in development, research projects differ in terms of their constraints (*Meredith and Mantel, 2006*): Product performance (i.e. functionality and quality), cost (i.e. resources and materials), and time (i.e. duration and schedule).

Most projects at Philips Research are executed for one of the Philips sectors. This implies that many of the products being developed in projects are related to the business of one of the Philips sectors (Healthcare, Lifestyle and Lighting). Projects may also be directed towards one of the innovation themes which were defined by the Philips Innovation Board and are potential growth areas for Philips. Cost of the projects is mainly dependent on the number of team members (fulltime-equivalents, FTEs). Each FTE is about 200 K€ which includes salary, accommodation, materials, services and overhead costs. Typical project size is between 2-5 FTEs (0.5-1M€) in which most project members have one or two different projects and projects may have members of different disciplines (multidisciplinary teams). Projects are directly financed by one of the Philips sectors (so-called Contract Research projects) or paid by Philips Research organization (so-called Company Research projects) financed by the Board of Management of Royal Philips. Of course, research activities in Philips may also be executed for external parties or funded by external investors (other companies or subsidized by the government). Projects usually start in January and finish in December and have a duration of 1 year and can be extended for several years. Extended projects are often re-shaped each year while many abandoned projects deliver subsequent similar projects directed towards new markets, segments and/or applications. In other words, the project may change over time due to new gained technology knowledge and market insights (both including new opportunities) although market insights / requirements are often still vague in this stage of the full R&D lifecycle. For instance, a new technology may not meet the required performance or market/application appears not to be attractive anymore. In these cases one may study a new technology or target current technology for a new market/application. Completely new ideas for new projects are often generated in brainstorm sessions, so-called deep dive studies, Friday afternoon experiments or just originate from an ordinary R&D project executed by engineers and scientists.

Other important characteristics which are typical for research projects include:

- Technology/market orientation: technology vs. society/people focus
- Product newness: extensions to existing products vs. entirely new products
- Time orientation: shorter-term vs. longer-term focused projects
- Uncertainty: high-uncertainty vs. (relatively) low uncertainty projects

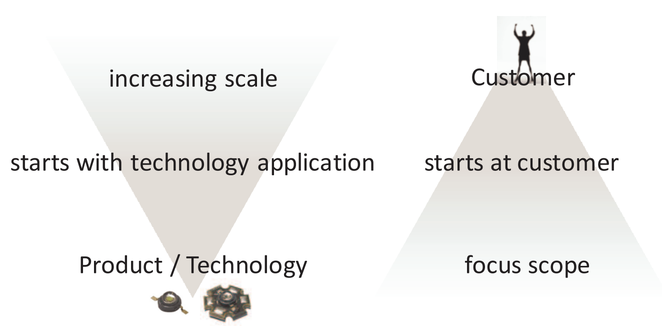


Figure 11: *Technology vs. customer focus.*

Most of the technology projects undertaken at Philips Research have a technology orientation although there is a changing nature to move to a customer focus (Figure 11). Research projects usually study new technological opportunities targeted for an existing or new market as is illustrated in Figure 12. This means that the product newness is high compared with development projects. Nevertheless, the level of newness of research projects also varies substantially. Research for extensions to existing products have a high level of newness (so-called incremental product innovations), but new products based on new technology have an even higher degree of newness (so-called radical product innovations). Projects on incremental product innovations are often relatively short-term oriented, with a time horizon of 1-3 years. Time to market of radical product innovations projects are often relatively long-term oriented, with a time horizon of 3-10 years. All characteristics are interlinked with each other. For instance, research regarding new technology for a new product type are often long-term oriented and have a high uncertainty, while extensions of existing products based on mature technology are executed with a more short-term orientation and the risk is relatively low. Research projects at Philips Research are going through several phases which includes project planning, project execution, transfer of results, review/evaluation and project closure.

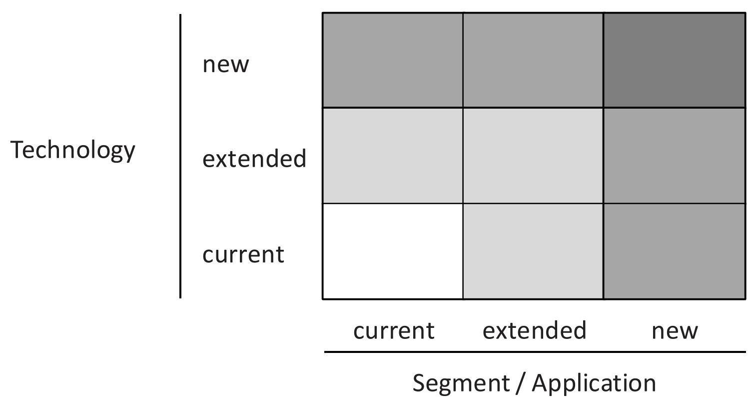


Figure 12: *Maturity of technology vs. market newness (e.g., Christensen, 2004).*

Philips Research has implemented different project management tools including a web-portal which contains project management facilities for submitting new projects, project portfolio management and publication of project output such as invention disclosures, reports and publications (*Aalders, 2009*). Other examples include databases to collect and manage project team information in general or other information systems to archive project results.

Proposed projects should have clear objectives and intermediate milestones. However, it is difficult to define accurate and measurable project output, such as the performance of a new technology, during the project proposal phase due to the uncertainty inherent to research projects. For this reason decision points are suggested (so-called gates) to overcome the limitations of definability of milestones. At a decision point, one decides to continue the current project, redirect or abandon it. Intermediate decision points are proposed as well and are valuable tools for uncertain projects. However, up till now they are not often (fully) applied, although this is changing. A standard decision point used at Philips Research is the decision at the end of the year to abandon or continue a project. Other formalized tools to archive and communicate project progress are project progress reporting documents and project reviews (typically twice or four times a year).

Research projects are characterized by high uncertainty and complexity. In order to deal with this high uncertainty and complexity one may use risk assessments, identify project success factors and try to manage expectations of project stakeholders. Further, application of strict project management methods is often not the best way to enhance research project success. Due to the variety of research projects it is difficult to prescribe a single project management methodology. In addition, research projects, compared to development projects, are relatively difficult to control. For instance, it is very difficult or not possible to control the generation of inventions. Even more important, too strict project management methods may limit the creativity in research projects. The creativity of the researchers is often one of the key ingredients for research project success. This means that the success of research projects is dependent on the skills of the researchers involved. Research should hire the best researchers available. Another factor for research project success is an innovative environment/climate. Research should be executed in a creative stimulating environment and project conditions should be flexible. Taken into account these aspects, the project leader should decide which research project methods and tools to use.

Program managers at Philips Research execute project portfolio management. Each year about 350 projects are undertaken which are sub-divided into a number of programs (*Aalders, 2009*). Portfolio management assesses the risks and potential rewards of projects. The R&D projects executed are based on a balanced portfolio. For instance, balance between short-term and longer-term oriented projects, smaller and larger projects and type of projects (for the Philips sectors). Furthermore, resource constraints are taken into account. In addition, the portfolio should match with the maturity of the business and related innovation requirements. Types of innovation pursued are defined by: improved product, new to category, new to Philips, new to the world. Maturity in market lifecycle characteristics is defined by: decline, mature, growing, and emerging. Defining all projects by both definitions for the year to come results in a 4x4 matrix, which can be used for project evaluation and selection (Figure 13).

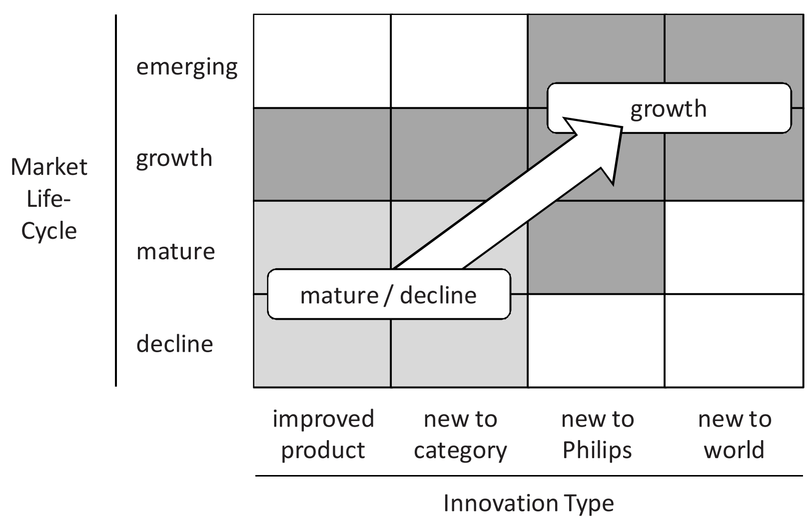


Figure 13: *Innovation portfolio balance matrix of Philips Research.*

On the diagonal from left below to right above one moves from incremental to radical innovation. Most of the time projects located in the incremental area are executed by Development, while projects located in the radical area are generally performed at Research. New projects are mainly generated by researchers, and evaluation and selection is performed by higher level management. This process is annually updated and during project execution a business rationale of many projects is defined. However due to the uncertainty of most research projects market forecasts are very difficult to estimate up front.

Research projects generate value in many different forms such as intellectual property and rights and project/ technology transfers. It is important to monitor the success of projects and one way of doing this is measuring the number of transfers to the business. The business impact of the transfer is defined as the business volume it has generated. In order to make estimates up front Philips Research has adopted the Net Present Value (NPV) approach (*Aalders, 2009*). NPV approach and its limitations are explained in detail in section 2.1.

Main conclusions about projects and project management at Philips Research:

- A variety of research projects are undertaken at Philips Research.
- Because of the variety of research projects, it is difficult to prescribe a single standard project management methodology.
- Too strict research project methodology limits creativity which is key for research project success.
- Research project success is dependent on the skills of the researchers and is enhanced by an innovative research environment.
- High uncertainty and complexity is inherent to research projects and therefore loose project management methodologies are preferred characterized with high flexibility.
- Project portfolio management is conducted at Philips Research in which a balanced project portfolio is selected based on an innovation matrix.
- Although desired, it is very difficult to predict research project success and to make market estimates in this research phase.
- Philips Research has adopted Net Present Value (NPV) approach to calculate future revenues generated by a new product.

Next, the new lighting technology will be explained and we will describe the separate phases of the R&D projects to provide an overview of the total projects regarding this new lighting technology.

3.4 Case project description

3.4.1 New lighting technology

Lighting is an essential ambience element in people's lives (*Hikmet and Van Bommel, 2006a*). People would like to be able to adjust the lighting conditions according to their activities in which they are engaged or desire lighting systems which autonomously adapt the lighting conditions depending on the activity of the user. Since the introduction of LED (Light Emitting Diode) lighting, it is possible to switch between colors and to obtain any desired color temperature from an LED light module. However, there are no easy-to-use solutions today for manipulating the collimation, shape and direction of a light beam. Therefore, scientists at Philips have developed simple electrically switchable (non-mechanical) flat optical elements for adjusting the collimation, shape and direction of a beam of light from an LED light source (*Hikmet and Van Bommel*, *2006b*). The non-mechanical elements are able to redirect light from a single spot and spread it out over precisely controlled areas (*Kraan et al., 2007; Hikmet et al., 2008a*).

In the beam collimation (size) control concept, the electrical beam forming technology can alter a collimated narrow beam into a broad beam and vice versa. Depending on the magnitude of the applied voltage, one can adapt the beam shape as is illustrated in Figure 14.

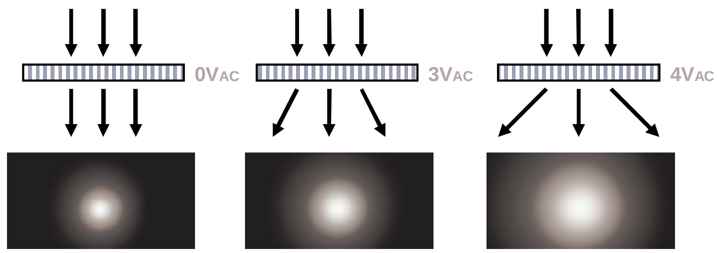


Figure 14: *Example of beam-shaping effect at different voltages.*

Pictures presented in Figure 15 show five white LED modules illuminating a wall (*Hikmet and Van Bommel*, *2006c*). In the lens-deactivated state the spots have a narrow collimation. Using software (e.g. DMX or DALI) and electronics one can individually control the voltage on the switchable elements and produce precise settings and change the beam angle continuously. Other beam control elements have been developed which alter the shape (e.g. from a spot into an asymmetrical shape) and direction (steering light from a first direction towards a second direction) of a beam of LED light.

Figure 15: *Photos of LED spots illuminating a wall. A) None of the optical elements in the activated state. B) Some of the elements in the activated state.*

Philips' beam-control technology uses advanced liquid crystal technology to manipulate the light from LEDs (Figure 16). Philips' innovative active beam control technology utilizes a unique mixture of the light scattering, refraction, diffraction, and reflection properties of liquid crystal materials. These materials are integrated into a thin transparent element (i.e. LC panel) that can be placed in front of LED modules and luminaires (Figure 17). The elements are highly transparent and do not use any polarizers or color filters commonly found in Liquid Crystal Displays (LCDs). Development of the radical new lighting technology has been made possible by both Philips' in-depth knowledge of liquid crystals (LCs) and its know-how in exploiting advanced LC effects, as well as by its knowledge of LED lighting and lighting applications (*Hikmet and Van Bommel, 2006b*).

The switchable flat optical elements can be used for a variety of applications. It can be used in standard lighting applications such as consumer luminaires for homes and professional luminaires for shops, museums, hotels and restaurants. It can also be used for more niche applications for example in the area of automotive and special lighting applications such as flash lights and toys (*Hikmet et al., 2007d*).

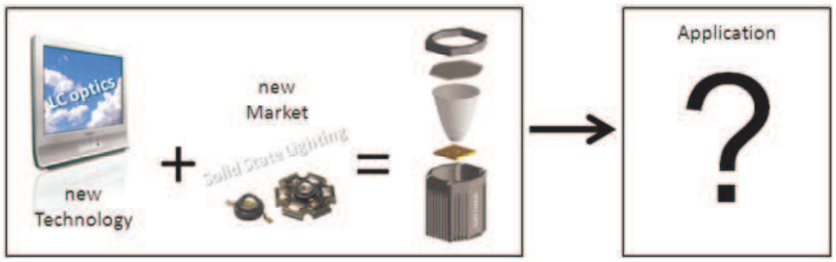


Figure 16: *Use of new technology (liquid crystal technology) for new market (Solid State Lighting) which can be used for many lighting applications.*

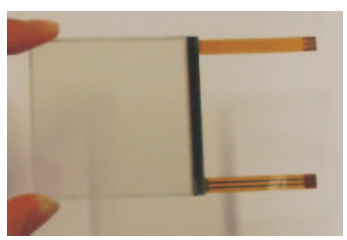


Figure 17: *Photo of an electro-optical element.*

In short, Philips' beam control technology (patents pending) offers: high-quality beam shaping (dynamic lighting); maintenance advantage (no mechanical moving parts); compactness (thin transparent panel can simply be placed in front of a luminaire so that the small form factor of LEDs is retained); and ease of operation (use of sensors or software). This new technology promises a whole new era of dynamic LED lighting which can be used for many different applications in many lighting segments.

3.4.2 General track and trajectory

This section describes a case study within Philips Research and Lighting regarding technology development of a new lighting concept. The projects used in the case study were executed over the last seven years – 2003 to 2010 – and the author of this master thesis participated as a researcher in many of the projects. We will go through the different projects executed in this time frame. The projects are divided over different phases: (A) pre-phase of developing the technology and inventory; (B) evaluation and selection phase of application; and (C) technology-application *development phase. Important stages in the different phases will be elaborately described as well and are denoted by sub-numbering style: (C2) iteration of technology-application development phase; (C3) abandon project; (C4) delay project; (D1) restart project; and (D2) project including commercialization activities.*

A) Pre-phase of developing the technology and inventory

The initial R&D project on electro-optical devices for LED light manipulation was executed in 2003. The aim of the project titled "Smart materials for beam and color control in lighting applications" was to develop smart optical materials for future light sources based on inorganic LEDs to control the beam collimation, shape, direction, color and color temperature of the light. The project description submitted late 2002 is given in Appendix A.

The project proposal refers to pioneering research on similar technology which was conducted more than a decade ago (i.e. beginning in the 1990s) but at that time targeted for tradition light sources such as halogen and high intensity discharge lamps. Technology research at that time was abandoned after a few years because such elements cannot be combined with traditional light sources since these lamps generate light in the infrared and ultraviolet which is disastrous for the switchable elements. Secondly, such light sources and systems are not compact and therefore large optical elements are needed which would be too costly. Thirdly, lighting hardware (such as electronic control units) and software (lighting control systems) were not available at that time. And last but not least, liquid crystal display technology was still in its pre-mature stage. The technology change from Cathode Ray Tubes (CRTs) to Liquid Crystal Displays (LCDs) started around 2000.

As described in the research project proposal (2002-364) LED light sources with a high efficiency and a very long lifetime were being studied at that time to be used for lighting applications. Before 2000, LEDs were used for indication lamps on electronic components, i.e. applications where high light output is not needed. However since about 2000, developed high power LEDs were introduced into the market in specific applications such as traffic lights. It was predicted that LEDs would soon (as from about 2000) be used for other lighting applications as they became even more efficient while costs of LEDs would substantially reduce each year. This would result in a technology change from traditional light sources such as incandescent lamps to inorganic LEDs which is going on at the moment.

LEDs do not face the disadvantages of the traditional light sources as described here above. LEDs do not produce light in the infrared and ultraviolet. They are compact light sources and heat generated by LEDs is transported to the back of the semiconductor lighting device. LEDs are very compact as the point light source is typically about 1 mm^2. This means that only small compact electro-optical elements are needed which reduces its costs significantly. Thirdly, due to the introduction of LEDs for lighting applications in 2000, infrastructure such as hardware and software became available which can be used for electro-optical elements as well. Finally, LCDs are phasing out CRTs, which started around 2000 and at the moment no CRTs are being sold anymore.

These trends justified the start of a project on the new lighting technology for inorganic LEDs. Project duration targeted was 1 year (and could be extended with 1 year) involving 3.5 FTEs. The

Research project “Smart materials for beam and color control in lighting applications” included two work packages.

The first work package involved working on the technology. New materials and new device technologies were identified. Besides work on advanced liquid crystal technology other beam-control technologies were studied as well. As described in the project proposal inorganic suspended particle devices (SPDs), micro electro mechanical systems (MEMS), mechanical microstructure devices or combinations thereof were investigated (*e.g., Van Bommel and Hikmet, 2006*).

A second work package includes definition of new products and lighting application using the new lighting technology. A summary of the project executed in 2003 is given in Table 5.

Table 5: *Summary Philips Research project executed in 2003.*

Summary Project 2003 (2002-364)	
Aim	Electro-optical devices for beam and color control for LED lighting applications
Work Packages	Research new materials and device technologies Definition of new products and lighting applications
Resources	3.5 FTE
Duration	1 year (Jan 2003 - Dec 2003)
Costs	~ 0.7 M€

Table 6: *Summary Philips Research project executed in 2004.*

Summary Project 2004 (2002-364 continued)	
Aim	Electro-optical devices for beam and color control for LED lighting applications
Work Packages	Research new materials and device technologies Definition of new lighting products applications and making demonstrators and prototypes
Resources	3 FTE
Duration	1 year (Jan 2004 - Dec 2004)
Costs	~ 0.6 M€

The research project “Smart materials for beam and color control in lighting applications” was continued in 2004. The research proposal generated late 2003 is given in Appendix B. Duration of the project was targeted for 1 year (and maybe extended with 1 year) involving 3 FTEs. The project proposal for 2004 was very similar to the proposal for 2003. Work on new materials and device technologies for beam-control was continued. Besides advanced liquid crystal technology, other technologies were studied as well. A summary of the project executed in 2004 is depicted in Table 6.

Uncertainty in the performance of the technology was still very high. Most research was exploratory and no in-depth technology research/development was undertaken. During these projects there was no focus on a single application. Furthermore, there was almost no involvement of business development and marketing where as a result market requirements and business potential were unknown.

B) Evaluation and selection phase of application

During the course of the project in 2003 and 2004 several beam manipulation technologies were identified and explored. A complete list of technologies identified is given in Table 7, and most of them were experimentally studied. Many of the technologies were suggested in invention disclosures during 2003, 2004 or beyond when explored in more detail. Not all of them could be protected by a patent application due to e.g. prior art or lack of inventive step. Patent applications are typically written about (half) a year after submitting an invention disclosure and it takes roughly 2 years before the application is published (i.e. it takes 2-3 years from invention disclosure submission to patent application publication).

In late 2004 it was decided to focus only on advanced liquid crystal technology and to undertake no research on mechanical, semi-mechanical and SPD like technologies for beam manipulation. No structured methods or tools have been used to assess the technologies. Evaluation and selection of the technologies was conducted by Researchers. Project proposal for 2005 was directed to advanced liquid crystal technology with a focus on LC gels.

In the same way first applications were identified. Some applications were still quite abstract such as lamps and luminaires (*e.g., Hikmet et al., 2006d*). Other applications were more specific such as Automotive Interior Lighting (AIL), Automotive Adaptive Front lighting System (AFS), and Automotive Rear Lighting (ARL). Project proposal for 2005 was mainly directed towards automotive lighting with a focus on Automotive Interior Lighting (*Hikmet et al., 2007a, 2007b, 2007c*). This decision was made by the researchers and confirmed/agreed on by higher level management.

Table 7: *Assessed technologies in 2003 and 2004 (excluding*) categorized in mechanical (m), semi-mechanical (s) and non-mechanical (n).*

Abbr.	**Name**	**Syste**		
		m	s	n
MME	Mechanical Moving Elements	x		
MDS	Mechanical Deformable Structures (*Hikmet and Van Bommel, 2009a*)	x		
RBT*	Roll Blind Technology (*Hikmet and Van Bommel, 2009b*)		x	
MEM	Micro Electro Mechanical System		x	
ECD	Electro Chromic Devices			x
SPD	Suspended Particle Devices (*e.g., Verhaegh et al., 2006*)			x
SF-	Surface Forced SPDs (*Van Bommel and Hikmet, 2006*)			x
SPD-	SPD stabilized in Liquid Crystals (*Hikmet, 2005a*)			x
PDLC	Polymer Dispersed Liquid Crystals (*e.g., Hikmet et al., 2006d*)			x
LCG	Liquid Crystal Gels (*e.g., Hikmet et al., 2006d*)			x
SLCG	Structured Liquid Crystal Gels (*e.g., Hikmet, 2006*)			x
LC-RS	LC with Replicated Structures (*e.g., Hoelen et al., 2005*)			x
GRIN	Gradient Index Liquid Crystals (*Hikmet and Ronda, 2007*)			x
LC-	LC Color Conversion Devices (*e.g., Hikmet, 2005b*)			x

During 2003 and 2004 various beam shaping technologies were identified and most were experimentally studied. Although the performance level of the individual technologies was not known, the advantages and disadvantages of all technologies became clear although not entirely. Information on market characteristics was hardly available at that time. Selection of application was not based on a market assessment. There was almost no involvement of marketing / business development.

C1) Technology-application development phase

Research project executed in 2005 named "Active beam manipulation of LEDs" was focused on applications for automotive lighting. Duration of the project was 1 year (Jan 2005 - Dec 2005) and the resources used were 3 FTE (about 0.6 M€). Previous projects were completely funded by Company Research, while for this project 2 FTE were funded with company money and 1 FTE was funded sponsored by Lighting (i.e. Contract Research). The project description submitted late 2004 is given in Appendix C.

The project included two main work packages. A first work package included research on advanced liquid crystal technology, i.e. new materials and devices, for beam manipulation of LED lighting. A second work package, closely linked to the first work package, was focused on development of advanced liquid crystal technology for the application automotive lighting. Several applications generated in the previous projects including Automotive Interior Lighting (AIL) (Figure 18), Automotive Adaptive Front lighting System (AFS) (Figure 19), and Automotive Rear Lighting (ARL) as described in the project proposal which was submitted late 2004, were investigated (*Hikmet et al., 2007a., 2007b, 2007c*). A summary of the R&D project is given in Table 8.

Figure 18: *Automotive Interior Lighting (Hikmet et al., 2007a, 2007b).*

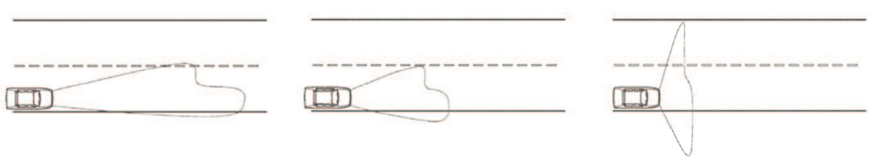


Figure 19: *Automotive Adaptive Front lighting System (Hikmet et al., 2007c).*

The main focus of the project activity was on Automotive Interior Lighting. In AIL electro-optical elements can be used in which a single light module can fulfill various functions such as entry light, reading light, and ambient lighting. In order to prevent dazzling of the driver and improve the illumination efficiency, asymmetrical beam shaping is preferred. Various LC materials and device configuration were studied in order to obtain such an effect. The automotive applications were identified in projects executed in 2003 and 2004. Nevertheless, during the course of the project a new application was identified, namely camera lighting (*Ronda and Hikmet, 2007*).

Table 8: *Summary Philips Research Project executed in 2005.*

Summary Project 2005 (2004-241)	
Aim	Active beam manipulation of LEDs targeted for automotive lighting (automotive interior lighting, AIL, and advanced automotive front lighting systems, AFS)
Work Packages	Research on new materials and device technologies. Work on automotive lighting applications AIL and AFS. Look into new applications
Resources	3 FTE
Duration	1 year (Jan 2005 - Dec 2005)
Costs	~ 0.6 M€

In the beginning of the (2005) project the performance level of the technology was still unknown. During the course of the project it became slightly more clear what performance level could be achieved if such components would be developed. In the same way, new product development costs and time to market were at that time unclear and undefined, but later on in the project estimates about the bill of material of the electro-optical elements were made based on prices of LCD displays. In the early stages of the R&D project there was no customer contact. As the project developed through different stages, prototypes were made and some of them were shown to potential customers and end-users during a few road shows and customer visits. In doing this, first customer insights and market requirements became available, although detailed market requirements were still unknown. The project focused on automotive lighting with beam-control functionality was finally stopped late 2005. The main reason for this was that the brief business case made by Philips Lighting at that time revealed that it was not attractive to continue R&D on this application because profits made by only selling the LEDs would be similar to selling the whole system.

C2) Iteration of technology-application development phase

Late 2005 two new research project proposals were submitted. At that time Philips Lighting considered the move into the camera flash market by manufacturing LED-based flash modules. Both projects focused on this application with beam-control. Duration of both projects was 1 year (Jan 2006 - Dec 2006) and the resources used for the research projects were 3 FTEs (about 0.6 M€). The project descriptions submitted late 2005 are given in Appendix D and E. The projects included two main work packages. First work package included research on advanced liquid crystal technology, i.e. new materials and devices, for beam manipulation of LED lighting for the application video flash (*Ronda and Hikmet, 2007*). A second work package includes making of demonstrators using the results of the first work package. A summary of the research project is given in Table 9.

Table 9: Summary Philips Research projects executed in 2006.

Summary Projects 2006 (2005-029 and 2004-241 continued)	
Aim	Active beam manipulation of LEDs + beam shaping targeted for video flash (digital still and video cameras)
Work Packages	Research on new materials and device technologies Work on camera flash with beam-control
Resources	3 FTE
Duration	1 year (Jan 2006 - Dec 2006)
Costs	~ 0.6 M€

Digital Still Cameras and Digital Video Cameras at that time used xenon light bulbs which generate enormous light output. Eventually LEDs will phase out xenon light bulbs for this application. In order to increase illumination performance and to extend the battery life of a camera, electro-optical elements can be used which adjust the shape and collimation of the light according to the zoom function of the camera (Figure 20).

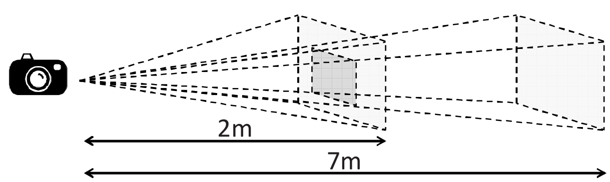


Figure 20: *Camera lighting with beam-control.*

Besides research activities at Philips Research, R&D activities were executed at Philips Lighting. The Lighting project on camera/video flash (VF) executed at pre-development in 2005/2006 named "LED video flash" was focused on module aspects and beam-control integration. Duration of the project was about 1.2 years and the resources used in the project were 4.5 FTE (about 1 M€). Main important aspects of the project are given in Appendix F. Table 10 lists a summary of the project executed at Philips Lighting.

Table 10: Summary Philips Lighting project executed in 2006.

Summary Project 2006 at Lighting	
Aim	Development of camera flash with beam width control
Work Packages	Electrical, optical and mechanical engineering on LED flash module
Resources	4.5 FTE
Duration	~ 1.2 years (mid 2005 – mid/end 2006)
Costs	~ 1 M€

During the project, technology research was mainly focused on gradient index (GRIN) liquid crystal (LC) technology. Previous projects identified advanced liquid crystal optics based on patterned electrode, double plain switching (DPS), and this sub-technology was selected as a potential candidate for camera flash applications (*e.g., Ronda and Hikmet, 2007*). DPS technology was experimentally studied mid-late 2005 and showed that it can diverge a beam of light of 10 degrees Full Width Half Maximum (FWHM) into 20 degrees FWHM. Experimentally results generated in 2006 showed that DPS technology can diverge a beam of 10˚ into a broad beam of 40˚ FWHM. Mid 2006 LC technology In Plain Switching (IPS) was identified (*e.g., Hikmet et al., 2008b*). Experiments showed that the performance in terms of beam spreading effect of the GRIN LC optics was substantially further improved. By using IPS LC cell configuration a beam of light of 10 degrees can be altered into a beam of 60 degrees FWHM. Late 2006 another new configuration was identified named Fringe Field Switching (FFS) (*Van Bommel et al., 2009*). This GRIN LC technology improves beam spreading and allows a larger degree of freedom in terms of patterned electrode design. Figure 21 illustrates the performance of the GRIN LC technologies identified/studied in the project executed in 2006 as a function of time. To this day no FFS cells are produced and experimentally studied.

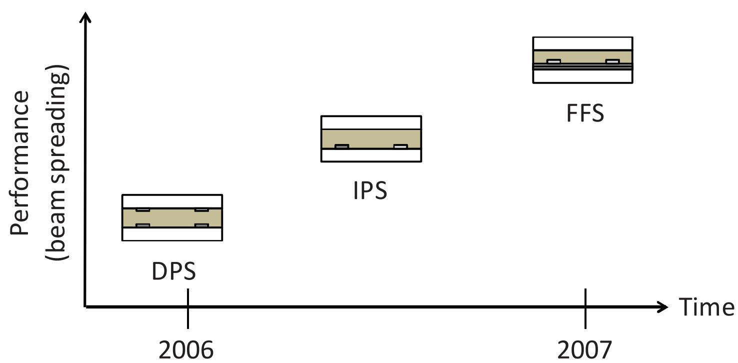
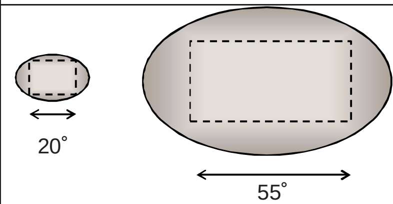
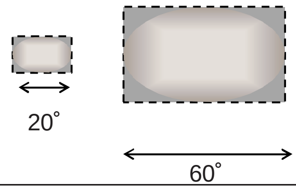


Figure 21: *Performance of the researched GRIN LC technologies identified in the project 2006: Double Plain Switching =DPS (2005), In Plain Switching = IPS (mid 2006), Fringe Field Switching = FFS (late 2006).*

Although most R&D effort was spent on GRIN technology development, sub-technologies PDLC and LC-RS were options also as these sub-technologies might serve the same application (*e.g., Paulussen and Tukker*, *2009*).

During the execution of the project in 2006 performance level required by the market became clear although uncertainty about market requirements was still high. Performance level needed was specified by customers through original equipment manufacturer (OEM) visits which were carried out by a project manager and a business developer at Lighting. With only a few customer visits market insights and specifications could be roughly visualized. Table 11 lists most of the market requirements gathered during the project in 2006.

Table 11: *Market requirements of camera flash with beam-control.*

Market requirements		
	must	***preferred***
beam	20˚ → 55˚ FWHM	20˚ → 60˚ FWHM
drawing		
uniformity	50%	corners as well
beam control	continuously	continuously
response	100ms	10ms
beam	horizontal and vertical	horizontal and vertical
aspect ratio	4:3 round	4:3 rectangular

C3) Abandon project

Late 2006 both Research and Lighting projects were abandoned. The main reason for this was that the market assessment made, including NPV calculations, indicated it was not attractive. Although OEMs liked the concept, the flash module was a commodity. By bringing this application to the market Philips would only dominate in a small part of the total supply chain. This means that EOMs would dictate the price and other contractual conditions. Although market specifications were mapped, there was still a high market uncertainty. In addition, the market was not yet ready for an LED based camera flash as xenon light sources would dominate the market over the next years because in terms of performance (amount of light, etc.) xenon was still outperforming LEDs for this application. Furthermore, there was still high uncertainty regarding the beam-shaping technology as the performance requirements for this application were extremely high (i.e. light distribution, color homogeneity and the like should be perfect for cameras). In addition, the infrastructure in the cameras at that time was not appropriate for Philips' VF module. A relatively large space was needed for the VF module in relation to the design which used the xenon light source. This means that OEMs have to make several changes in their camera design.

C4) Delay project

In 2007 and 2008 several R&D project proposals were submitted regarding the new lighting technology targeted for different applications including consumer luminaires such as LivingColors (proposals are not included in the appendices). All project proposals for 2007 and 2008 were rejected. Philips Lighting did not want to make new investments in beam-control technology for LEDs (no Contract Research). As a consequence Philips Research also did not make new investments in this radical new lighting technology (no Company Research).

In spite of abandonment of the project late 2006, main team members who worked on the technology over the last 3-4 years continued working on beam manipulation for about 0.1 FTE both during Friday afternoons, evenings and the weekend. Main activities were making demonstrators for Lighting or for other projects in Research.

One of the research projects executed during 2007/2008 studied retail lighting concepts and used the GRIN advanced liquid crystal technology in one of their concepts. The concept was named Reactive Spotlight and is an innovative yet simple way of drawing attention to goods on display (*Aarts and Van De Sluis, 2009*). As a customer approaches a product display, a sensor detects their presence and causes the lighting to alter from a broad-beam into a narrow-beam spotlight, thus placing extra emphasis on the product (Figure 22). Thus the Reactive Spotlight subtly attracts a customer to look at your best products on display (*Philips Lighting, 2008*).

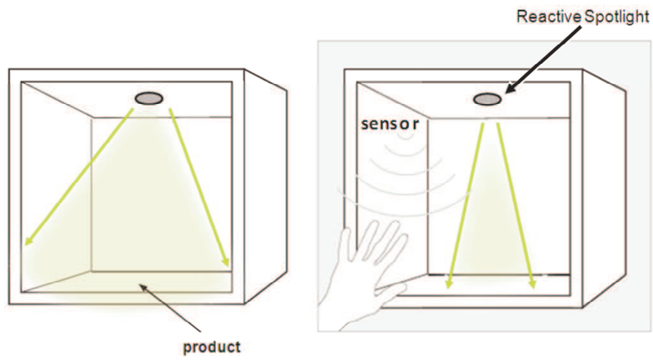


Figure 22: *Reactive Spotlight concept (Philips Lighting, 2008).*

In order to lower the uncertainty of manufacturability of the electro-optical elements, supply chain establishment of such components was realized. A manufacturer was found who was willing to produce the advanced liquid crystal technology.

Reactive Spotlight demonstrators were made and installed in Shop Lab which is one of the Experience Labs of Philips Research where customers of Philips Lighting are introduced to new lighting technologies and applications.

D1) Restart project

In 2007 and 2008, Philips Research and Lighting did not make new investments in R&D to develop the new lighting technology and applications. As a result no projects on the new lighting technology were executed. Yet, in 2009 a new beam-manipulation project was undertaken named "Electronic beam sweeping optics." The project was proposed and executed by other researchers employed at a different department in Philips Research. The project description submitted late 2008 is given in Appendix F.

Duration of the project was 1 year (Jan 2009 - Dec 2009) and the resources used for the project were 1 FTE (about 0.2 M€) which was funded by Company Research. Other project proposals for 2009 on the new lighting technology were not granted by Philips Lighting and Research. The "Electronic beam sweeping optics" project, which was selected by Research management to be executed, is focused on advanced liquid crystal technology, LC-RS, which was also identified by research projects conducted in 2003 and 2004. This sub-technology is able to steer the light from a first direction toward a second direction by applying a voltage on the LC element. However, research in previous years showed that this sub-technology had several limitations in terms of performance and manufacturability. In short, the technological and market uncertainty were substantially higher in relation to the other LC optics which had been studied and developed. Regardless of the higher market and technological uncertainties, Philips Research made an R&D

investment in the beam-steering project, while project proposals on other beam-manipulation technologies characterized by lower uncertainties were not approved. A possible explanation for this is that there is a tendency in Philips Research to explore rather advanced technologies and concepts while there is little focus on less immature concepts. Another possible explanation for executing this project and rejecting other proposals could be portfolio management such as balancing projects between research groups or resource constraints. A summary of the research project is given in Table 12.

Table 12: *Summary Philips Research Project executed in 2009.*

Summary Project 2009 (2008-268)	
Aim	Electro-optical beam sweeping (beam direction control) for main application office lighting
Work Packages	Developing electro-optical elements for beam direction control for application office lighting
Resources	1 FTE
Duration	1 year (Jan 2009 - Dec 2009)
Costs	~ 0.2 M€

Research in this R&D project was focused on general lighting, more specifically on office lighting. The concept of this project is schematically illustrated in Figure 23. The project studied advanced structures and materials which are even more complex than the structures briefly studied in the previous projects. The project was abandoned late 2009. Current performance of this LC technology does not meet LED luminaire / market requirements. Large R&D investments are needed to further develop this sub-technology, while the R&D outcome is highly uncertain. Mainly because of this, Philips Research and Lighting did not approve the new project proposal for 2010 to continue this project.

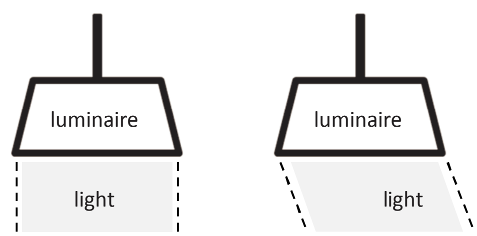


Figure 23: *Luminaire with beam steering.*

D2) Project including commercialization activities

In the same year (early 2009) a venture at Philips Lighting was started which embraced the Reactive Spotlight concept (leaflet of the Reactive Spotlight is given in Appendix I). The Reactive Spotlight is a niche application for the Retail Lighting segment. As the Philips Lighting venture is focused on the Retail market it would like to commercialize the Reactive Spotlight concept which can become a building block of the Lighting venture.

Activities in the venture on this concept include concept development, presentations to customers, sending demonstrators to customers, marketing activities such as sales estimates and business case, and product sample development. Product samples use LC GRIN DPS cells which were manufactured by a supplier which was found in 2007/2008 as described here above. The author of this thesis managed all activities regarding the Reactive Spotlight and was involved for about 0.3 FTE. For about 0.2 FTE other Philips Lighting employees were involved. A summary of the commercialization project which is still ongoing in 2010 is given in Table 13.

Table 13: *Summary Philips Lighting venture Project executed in 2009.*

Summary Commercialization Project 2009 at Philips Lighting	
Aim	Commercialization of Reactive Spotlight concept (reduce market uncertainty); Transfer concept from venture to Philips Lighting business
Work Packages	Concept development, presentations to customers, product marketing activities, and product sample development
Resources	~0.5 FTE
Duration	>1 year (Feb 2009 - still ongoing 2010)
Costs	~ 0.1 M€

By involving Lighting's customers through presentations, sending demonstrators and pilots, the performance level required by the market became known. The concept was presented to end-users, i.e. customers (retailers), installers, and other customers such as creative specifiers. Performance of first commercially produced elements was not good enough for bringing products to the market. Research on LC GRIN DPS technology was needed to improve the technology. This fact became known beginning 2009. However, the research project executed at that time was studying a different LC technology which could not be used for the Reactive Spotlight. Because other projects were not granted, no research capacity was available to work on DPS technology. In order to solve this issue several project proposals were suggested late 2009. However, these project proposals were rejected by Philips Lighting and Research.

Current status of the Reactive Spotlight is that pilots are being set up with the developed product samples. Performance of products samples was slightly improved (but still far from optimal) by including two LC optical elements in the engineering samples. Decision on transfer of the concept to Philips Lighting business was planned to be mid-late 2010 (i.e. go / no go decision).

Although the Reactive Spotlight was a niche application with a strategic fit with the Philips Lighting venture, the maturity of the product and more specifically the LC technology was low. Because of the low maturity and the fact that no significant improvements in technology were going to be undertaken, it was decided late 2009 to also work on another concept. In this second concept a standard application, namely accent lighting was targeted, because it fitted the current business and products of Philips Lighting. The most mature LC technology which can be used for beam-manipulation is selected to lower the technical uncertainty. Of course product development is needed to get the concept to the market, but at least the LC technology targeted is already commercially available in high volume at a low price (used for a non-lighting application). In addition, the concept is selected such that it has a high compatibility with the new range of luminaires which will be introduced mid 2010 onto the market. The aim of developing this second concept, which has a good fit with the standard lighting business, has a high compatibility with the new standard product to be launched and could use the most mature LC technology, is to increase the chance of a transfer to the Lighting business late 2010.

3.4.3 R&D projects overview

Figure 24 schematically illustrates the overview of all the R&D projects which spanned over more than 7 years.

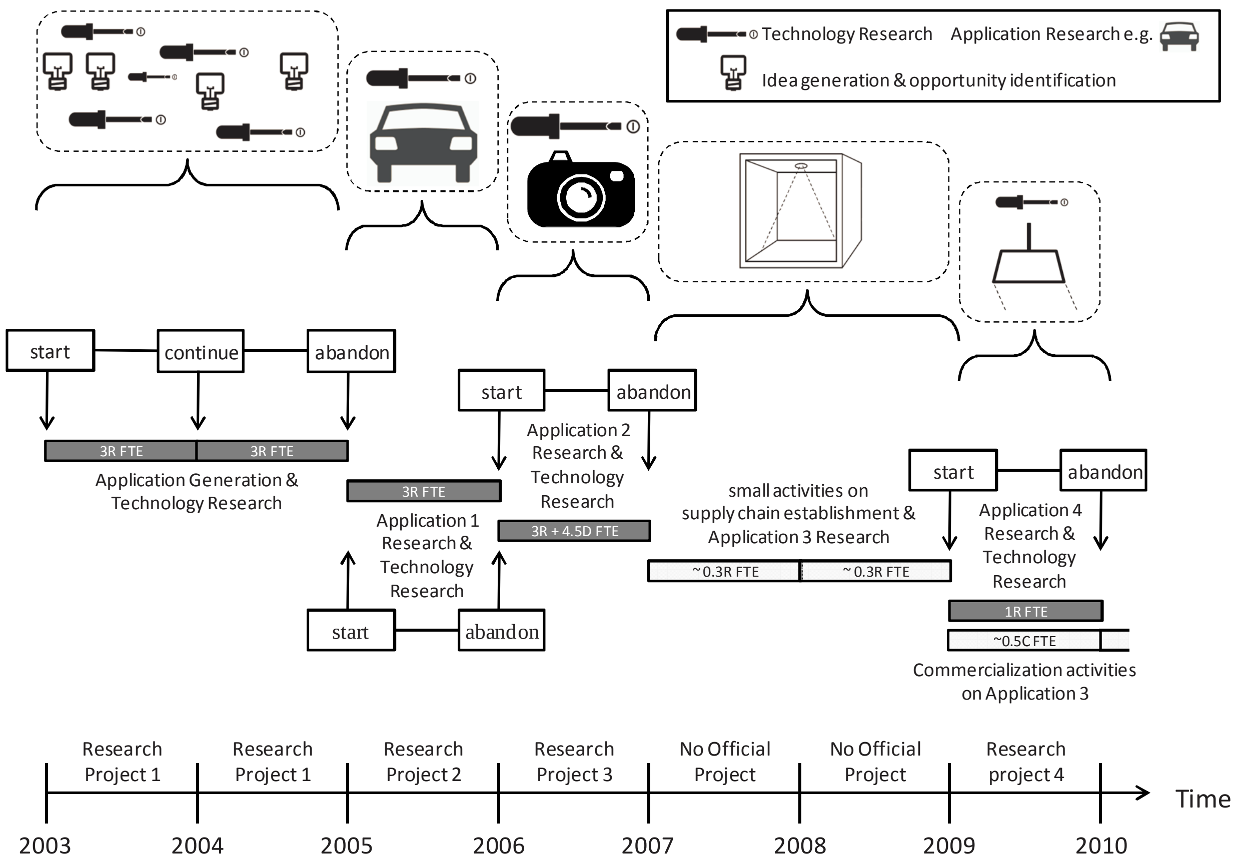


Figure 24: *Project overview 2003 - 2010.*

4. Discussion of case findings

This chapter discusses the findings of the case research presented in the previous chapter and where necessary links back to the literature. Specifically, we discuss the results according to the different phases of our case study and try to develop ideas on resolving / addressing limitations of the conceptualization of Huchzermeier and Loch (2001) identified in section 2.4. The process starts with a pre-R&D phase of developing the radical new technology and inventory (section 4.1) followed by an evaluation and application selection stage (section 4.2). The process continues with an application R&D development phase (section 4.3) showing patterns of iteration (section 4.4).

4.1 Pre-phase of developing the technology and inventory

To begin, we will focus on the first two projects (i.e. projects executed in 2003 and 2004) from our case study at Philips regarding the new lighting technology. The aim of the project in 2003 (Appendix A) and its continuation project in 2004 (Appendix B) was (1) to explore new technologies which can manipulate the light of LEDs and (2) to identify new product applications using the new lighting technology. The research projects (2003 and 2004) show important similarities to findings in the literature (*Lynn et al., 1996, 1997; O'Connor, 1998; Chandy and Tellis, 1998; Moorman and Minor, 1995, 1998; Thomke, 1998; Terwiesch and Xu, 2008; Lindkvist, 2008*; *Gruber et al., 2008; Baron and Ensley, 2006*), specifically regarding (1) divergent thinking to generate many ideas (*e.g., O'Connor, 1998*), (2) exploring and inventory of new applications/technologies (*e.g., Gruber et al., 2008*), and (3) through convergent thinking the process leads to the most interesting opportunity to pursue (*e.g., O'Connor, 1998*).

The starting point of the full R&D lifecycle is a novel idea or technology targeted for a specific market. Ideas generally originate from a brainstorm session, so-called deep dive study, Friday afternoon experiment or just from an ordinary R&D project executed by engineers and scientists.

The initial R&D projects (2003 and 2004) started with a divergent process to generate many and a wide range of new ideas in terms of technologies and applications. Our case study showed the generation of new materials and devices as well as new lighting products and accessories by searching in many directions. Such an early search of a useful application is a type of deliberated pragmatic approach in which much flexibility is needed. The case study showed that in a non-linear way various concepts were explored which were highly uncertain and outcomes unpredictable. New identified product applications were entirely new products and did not fit the existing businesses and product lines. These case findings are analogous to ideas described in the literature such as the process of divergent thinking (*O'Connor*, *1998*), statements that new product forms resulting from new technologies often do not fit existing market demarcation lines or product categories (*e.g., Lynn et al., 1996, 1997*) and similarities to other comparable trial-and-error kind of approaches (e.g., *Moorman and Minor, 1995, 1998*).

The process for projects one and two (i.e. projects executed in 2003 and 2004) continued by exploring and inventory of the radical new lighting technology which was a technology driven process. The first two projects showed an unsystematic approach of identifying and scanning various different new technology-application combinations. Our case study illustrated that NPD characteristics such as product performance, development costs and time were unknown and not specified (e.g. see project proposals) as the radical new lighting technology was still in an embryonic stage. The initial two projects of our case study did not include any commercial activities. Because the product applications generated did not fit existing market segments and product categories, market requirements and payoff were too difficult to estimate. Case findings suggest that in case of a radical innovation it is desired to first reduce the high technical uncertainty, in order to understand the technology, reveal its feasibility and to come up with additional new product applications. Our case results are in line with findings reported in the literature including insights regarding market opportunity identification for new technologies (*Leifer et al., 2000; Baron and Ensley, 2006; Gruber et al., 2008*), the technology push orientation for radical innovation (*Schumpeter, 1942*) and that it is hard to predict the market for radical innovations as the market and the technology is ill-defined and evolving (*e.g., Lynn et al., 1996*) and therefore not an issue during the early stages of a radical innovation R&D project (*O'Connor, 1998*).

Subsequently, later stages in the initial project followed a convergent process in which alternative applications and sub-technologies were briefly studied, selectively developed (e.g. by making demonstrators/prototypes) and tested, and led through analysis/evaluation to a single or a few most interesting opportunities. Similar findings are also reported in the literature such as the convergent thinking process and the experimental orientation in the phase of developing a radical new technology (*Lynn et al., 1996; O'Connor, 1998; Leifer et al., 2000).*

The process is schematically illustrated in Figure 25. Any decision to invest in basic research for a new technology is based on the notion that several applications are possible that also have market potential. Such evaluation of applications and market opportunities is more a scan than based on thorough and detailed market research. For instance, no market assessment or NPV calculations were made during the first two projects.

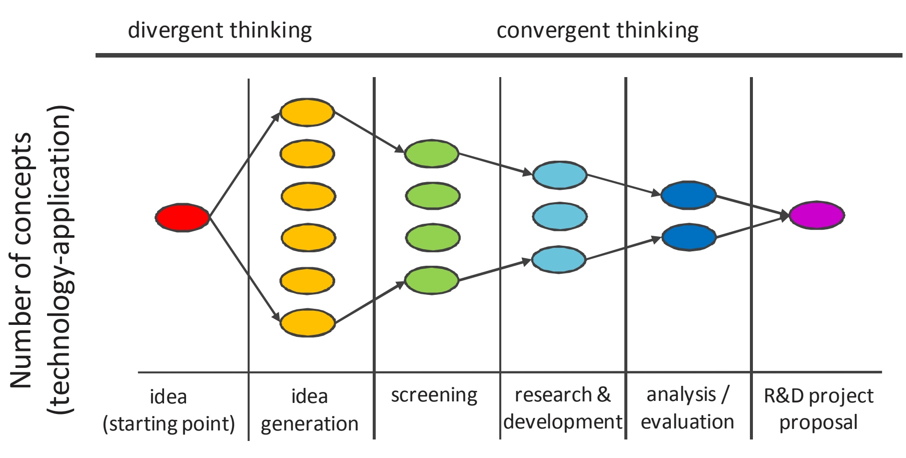


Figure 25: *Divergent and convergent thinking process (adapted from Lynn et al., 1996; O'Connor, 1998; Leifer et al., 2000).*

The phase of general investment in the new technology opening up roads to different applications (as shown in our case study) is absent in the conceptualization of *Huchzermeier and Loch* (*1999, 2001*). They start from a single application that was chosen. Hence, *Huchzermeier and Loch* (*1999, 2001*) omits this initial phase of the technology innovation lifecycle. From their examples it is clear that the application and technology is a given. Their conceptualization seems to address incremental product innovation rather than radical product innovation. These findings suggest the need to add a pre-R&D project phase to existing models of e.g., *Huchzermeier and Loch* (*1999, 2001*) and *Huchzermeier* (*2009*). Our findings further reveal that the early search of a useful application is a type of deliberated trial-and-error approach and dominates the beginning of the radical new technology for application development process. This is a line of thinking embraced by e.g., *Moorman and Minor* (*1995, 1998*), *Lynn et al.* (*1996, 1997*) and *O'Connor* (*1998*).

4.2 Evaluation and selection of application stage

The previous section showed that in the pre-R&D project phase different applications for the radical new technology were identified, because the new technology may serve a variety of different applications. Each application is linked to a different sub-technology dependent on its requirements which becomes clear through experience. Of course, it is possible that more than one sub-technology may serve the same application. Dependent on the number of applications and sub-technologies identified a set of options is defined as illustrated in Figure 26. Figure 26 shows an example of a set of 6 options which are identified and preliminarily researched in the pre-R&D project phase. Each option is a combination of a sub-technology targeted for an application in a certain market. It goes without saying that two sub-technologies or applications can be considered as well, i.e. selection of at least two options which keeps your options open. Of course, also a complete new market may be identified for the new technology, but this is out of the scope of this master thesis. Besides the options identified in the pre-R&D project phase, it is likely that new options will arise in subsequent phases as time and R&D effort continues.

Our case study revealed a selection action. Different sub-technologies and applications were identified and Philips had the choice which opportunity/option to develop/pursue first. For instance, the project proposal submitted in 2004 showed a few of the identified new applications such as Automotive Front lighting System (AFS) and Automotive Interior Lighting (AIL). These applications were submitted as new project proposal and finally selected. Our case study further confirmed that in case of radical innovation it is desired to keep your options open. For instance, the camera lighting project showed that various sub-technologies were considered during application development. Similar findings are also reported in the literature specifically regarding multiple opportunity identification, evaluation and selection (*O'Connor, 1998; Baron and Ensley, 2006; Gruber et al., 2008*) and real options reasoning (*e.g., McGrath and MacMillan, 2000A; MacMillan and McGrath, 2002; Fredberg, 2007*).

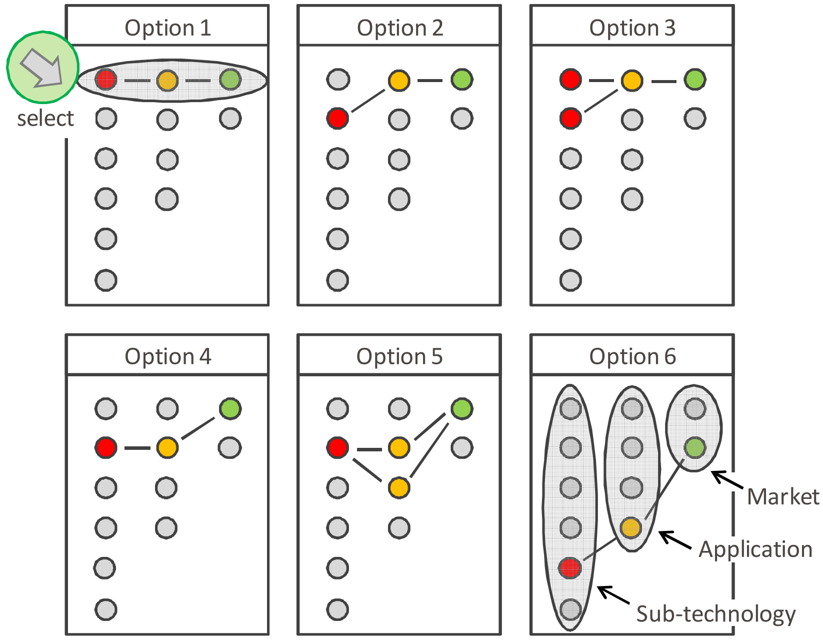


Figure 26: *Example of six out of n options for radical innovation R&D projects* (*extended from Nembhard et al., 2005*).

Each option is characterized by different amounts of project/technical and market uncertainties with inherent distributions (*Morris et al., 1991*). For example, each application requires a certain product performance and in turn a certain engineering effort, i.e. development time and costs (Figure 27). In the same way, applications identified require a certain engineering effort (development costs and time) as is illustrated in Figure 28 (*Christensen, 1992a, 1992b*).

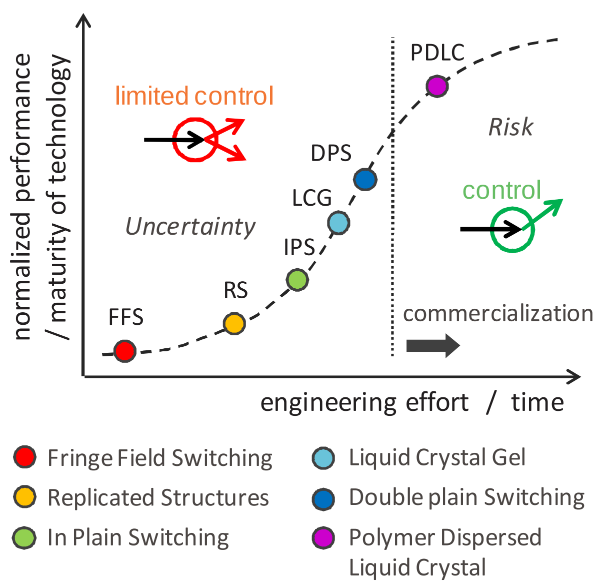


Figure 27: *Technology S-curve: Normative performance/maturity of technology as a function of engineering effort/ time for the various sub-technologies.*

The S-curves in Figure 27 and 28, displayed in similar graphs / fashion as the S-curves of *Christensen* (*1992a, 1992b*), give relative estimates about project uncertainty. However, these graphs are overly simplistic as the technology uncertainty about developing the radical new product application is rather high at the end of the pre-R&D phase and product performance, development time and cost are hard to estimate (graphs were made by the author during writing of this master thesis late 2009). In addition, as can be seen from the project proposals generated during the pre-R&D project phase (2003 and 2004) not all applications and technologies given in Figure 27 and 28 were identified at that moment which proves that besides the options identified in the pre-R&D phase, new options will arise in subsequent phases due to new investments in developing the radical new technology.

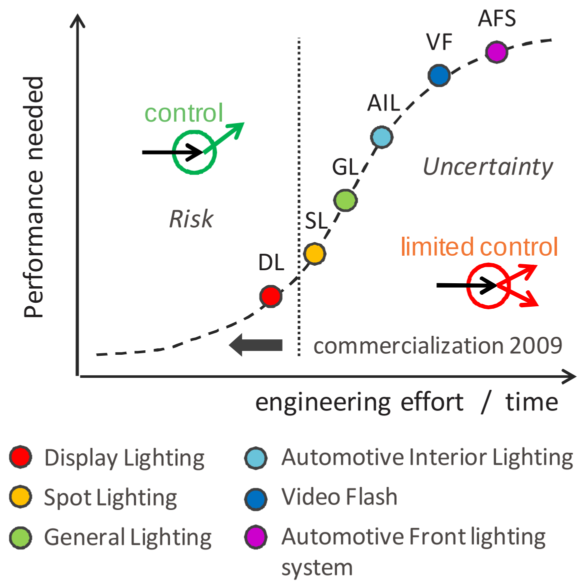


Figure 28: *Application S-curve: Performance needed as a function of engineering effort/time for the various applications.*

In short, our case study findings suggest the need to add an evaluation and selection stage to existing models of e.g., *Huchzermeier and Loch* (*1999, 2001*) and *Huchzermeier* (*2009*) as this selection action is absent in these models. This selection action shows similarities to the qualitative orientation advocated by the soft real options stream (*e.g., MacMillan and McGrath, 2002; Fredberg, 2007*).

4.3 Application development phase

As explained in section 4.1 the beginning of the radical new technology for application development process (R&D projects executed in 2003 and 2004) involved trial-and-error. However, as can be seen from the radical innovation projects executed from 2005 and onwards, the projects involved more systematic real options like approaches. During this radical innovation R&D phase, developments in technology, market and the risks involved became more specific and could be estimated within a predicted range. For instance, during execution of the radical innovation R&D project in 2006 insights about developments in technology became clearer over time. Substantial gradual improvements in beam width control were achieved in 2006 and final product performance could be defined and managed within boundaries. In the same way, market requirements and payoff could be forecasted. For instance, during the radical innovation project executed in 2006 market insights including market product specifications, market size, market potential and likely market acceptance became available (e.g., through OEM visits and by NPV calculations). Hence, real options come into sight and its theory can be used in managing radical innovation projects. However, our case study does reveal that the model of *Huchzermeier and Loch* (*2001*) cannot be directly applied as the model needs modifications based on different distributions of uncertainties. Variability or uncertainty in product/project and market characteristics depends on the type of innovation (radical and incremental innovation). Distributions in product performance, development cost and time, market requirements and payoff are much broader in case of radical product innovations as these products do not concern expansions of existing products already on the market (Figure 29). As can be observed from our case study, the distributions seem to be predictable, but not known.

Our case study suggests adding an additional radical innovation R&D project phase to existing models of e.g., *Huchzermeier and Loch* (*1999, 2001*) and *Huchzermeier* (*2009*) in which real options like approaches can be applied.

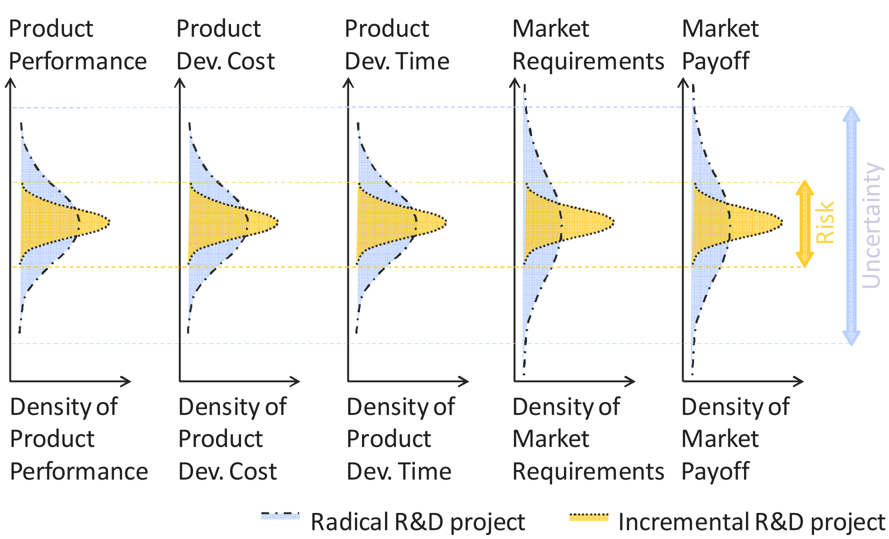


Figure 29: *Variability in project drivers for radical vs. incremental innovation.*

4.4 Iteration of application development phase

Projects executed in 2005, 2006, small project activities in 2007 and 2008, and the project ran at Research in 2009 were R&D projects which developed specific applications. The aim of these projects was to research a deviation of the radical new lighting technology targeted for a new product application. Namely, in 2005 mainly LCG technology was studied with a focus on automotive lighting, in 2006 GRIN technology was investigated (i.e. DPS, IPS, and FFS) for camera flash application, in 2007 and beyond research was conducted on DPS technology for lighting for display cabinets, and in 2009 research on LC-RS technology was executed for directable spot lighting. Early stages in the technology-application R&D projects showed that information about technical drivers and market characteristics was not available, while in later stages developments of technology, market and risks involved became more specific and could be estimated within boundaries. Another important finding is that the R&D application development projects happened to a large extent sequentially. Furthermore, our case research showed high failure rates as many of the R&D projects regarding the radical new lighting technology were abandoned. This explains the iterative behavior of subsequent radical innovation R&D projects. Our case research revealed that these subsequent R&D projects are linked with each other and are forming network effects.

This iterative behavior is also recognized in the literature (*e.g., Green et al., 1995; McGrath, 1999; Fredberg, 2007; Levardy and Browning, 2009*). The iteration occurs because of the high failure rate of R&D projects, while new project proposals describe research on deviations of the technology or same technology for a different application. Especially R&D projects on radical new technology are characterized by a high level of abandonment as many R&D projects are stopped before a radical new product innovation is launched to the market (*Green et al., 1995*). Reasons of abandonment include application needed technology performance cannot be achieved or market estimates proved to be unfavorable.

The conceptualization of *Huchzermeier and Loch* (*2001*) is limited by a single individual project, while our case study supported by the literature showed that R&D projects are linked with each other and show patterns of iteration (*Levardy and Browning, 2009; Green et al., 1995*). *Huchzermeier and Loch* (*2001*) do not address the iterative behavior of subsequent R&D projects and product network effects. As a result, for them iteration is less likely and receives little attention. This can be explained by the fact that current work (*e.g., Huchzermeier and Loch, 1999*, *2001*) is more geared towards incremental new products. Our case study findings suggest the need to add an iteration notion to existing models of e.g., *Huchzermeier and Loch* (*1999, 2001*) and *Huchzermeier* (*2009*). This notion is particularly important because it influences the value of a project and the project selection (due to the learning effect), among others.

5. Construction of conceptual framework for developing radical new product applications

In the previous section we discussed the findings of our case study. We found an additional initial phase which is absent in the model of Huchzermeier and Loch (1999, 2001). This pre-phase of developing the technology and inventory encompasses the early search of a useful application which proved to be a deliberated trial-and-error approach. After this, radical innovation R&D projects of product application developments are executed involving more systematic linear like approaches in which real options come into sight. Our findings further revealed an iterative behavior of subsequent radical innovation R&D projects which are selected by senior management. The selection action stage and patterns of iteration are also not covered by existing models of e.g., Huchzermeier and Loch (1999, 2001) and Huchzermeier (2009). In this chapter we conceptualize our findings into a framework for developing radical new product applications (section 5.6) and try to further develop ideas on resolving/addressing limitations of the conceptualization of Huchzermeier and Loch (2001) identified in section 2.4. Our model consists of a pre-radical R&D project phase (section 5.1), a real option of select action stage (section 5.2), a radical R&D project phase (section 5.3) with patterns of iteration (section 5.4) and an incremental R&D project phase (section 5.5).

5.1 Pre-radical R&D phase

Our findings of the previous two chapters suggest the need to add a pre-R&D project phase to existing models of e.g. *Huchzermeier and Loch* (*2001*) to extend these frameworks to management of radical innovations. We will denote this additional phase as the “pre-radical R&D phase”. In the pre-radical R&D project phase new applications for a novel technology or material are identified. This initial phase of the full R&D lifecycle is a convergent process which leads to a single or a few most interesting applications. We will define this pre-radical R&D project phase as “the initial phase in the full R&D project lifecycle in which new applications for a novel technology or material are generated and via a convergent process leads to a single or a few most interesting applications to be further explored with basic research.”

Definition of pre-radical R&D project phase: The initial phase in the full R&D project lifecycle in which new applications for a novel technology or material are generated and via a convergent process leads to a single or a few most interesting applications to be further explored with basic research.

Figure 30 schematically illustrates the pre-radical R&D project phase displayed in similar graphs or fashion as the conceptual model of *Huchzermeier and Loch* (*1999, 2001*).

In conclusion, our case results indicate that the early search of a useful application is a type of deliberated trial-and-error approach as information regarding developments of technology and market are not available. This phase at the fuzzy front end needs an ad hoc non-linear project management style allowing creativity to blossom and generate a wide range of novel ideas *(Stevens, 1999*). Furthermore, this approach takes into account that exceptional technological efforts are needed in this phase of the full R&D lifecycle to explore different radical new concepts of which the technology is still in an embryonic stage (*O'Connor*, *1998)*. Due to a subjective and scanning-like market, research decisions are prone to oversimplification and mistakes. The data do however, provide no detailed understanding of optimal levels of formalization and detail for this market research. However, *Gruber et al.* (*2008*) do suggest that people with entrepreneurial experience and market background are the best to make these evaluations.

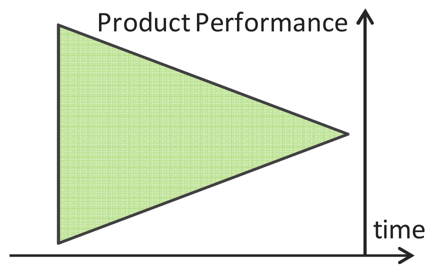


Figure 30: *Conceptual model of the pre-radical R&D phase.*

5.2 Real option of select action stage

The case study further suggests the need to add a selection stage to existing models of e.g., *Huchzermeier and Loch* (*1999, 2001*) and *Huchzermeier* (*2009*). A wide range of new applications for a novel technology or material are generated in the pre-radical R&D project phase. All applications have market potential and can be further explored with basic research. Management should assess all identified opportunities and decide which application to pursue first. However, such evaluation of applications and market opportunities is more a scan than based on thorough and detailed market research. Nevertheless, selection is a critical stage in the full R&D lifecycle and is a prime driver of new product development success. In fact, application selection is a real option which represents an additional source of option value and is a critical real option when managing radical innovation projects. To our knowledge literature so far did not consider this additional real option (*e.g., Lander and Pinches, 1998; Ollila, 2000; Huchzermeier and Loch, 2001; Borissiouk and Peli, 2002; Natarajan, 2006*). We define this real option of select action as "the possibility to select which product application to be researched and developed first."

Definition of real option to select:
The possibility to select which product application to be researched and developed first.

Again, as concluded here above, this additional real option of select action is not covered by the model of *Huchzermeier and Loch* (*1999, 2001*) because the conceptualization seems to assume that the application and technology is a given as they address continuations of existing products already on the market, i.e. incremental innovation and not radical innovation. The real option of select action (Figure 26) is valuable and should be incorporated into the conceptual framework for developing radical new product applications. The decision which application to develop first depends on various factors including the five types of operational uncertainty (*Huchzermeier and*

Loch, 2001), strategic fit with business and products of the firm, probability of market acceptance of the radical new technology which can be explained by perceived characteristics of an innovation including relative advantage, compatibility, complexity, trialability, and observability (*Rogers, 2003*) and product form design (*Rindova and Petkova, 2007*), among others.

5.3 Radical R&D phase

In the remainder of this chapter we move beyond the pre-radical R&D project phase to further develop our framework. In this section we focus on the question whether after the pre-radical R&D project phase/select action stage, real options theory can be used and what modifications are required. We draw on the Philips Research/Lighting case for our ideas and solutions.

5.3.1 Radical vs. incremental R&D projects

As discussed in chapter 4, case results showed that the early search of a useful application for a radical new technology in the pre-radical R&D project phase is a type of deliberated trial-and-error approach. After this, when executing radical innovation R&D projects, real options come into sight as developments of technology and market become more specific and can be estimated within boundaries. However, the model of *Huchzermeier and Loch* (*2001*) cannot be directly copied as *Huchzermeier and Loch* (*2001*) address incremental innovation and not radical innovation. Distributions in product performance, development cost and time, market requirements and payoff are much broader in case of radical product innovations. This means that the real options theory of *Huchzermeier and Loch* (*2001*) can be extended to management of radical innovations, but need some modifications based on different distributions of uncertainties and levels of control as will be explained further on in this section. In addition, managerial flexibility and its value depend on the type of innovation (radical and incremental innovation). Therefore, we suggest adding a separate phase to existing models of e.g., *Huchzermeier and Loch* (*1999, 2001*) and *Huchzermeier* (*2009*) in which real options can be applied to innovation management of radical new product applications. We denote this second phase in the full R&D lifecycle as the "radical R&D project phase" which can be defined as "the phase in the full R&D project lifecycle in which a radical new product application for a novel technology or material is developed and brought to the market."

Definition of radical R&D project phase:
The phase in the full R&D project lifecycle in which a radical new product application for a novel technology or material is developed and brought to the market.

Figure 31 schematically illustrates this radical R&D project phase displayed in similar graphs or fashion as the conceptual model of *Huchzermeier and Loch* (*1999, 2001*) and *Huchzermeier* (*2009*).

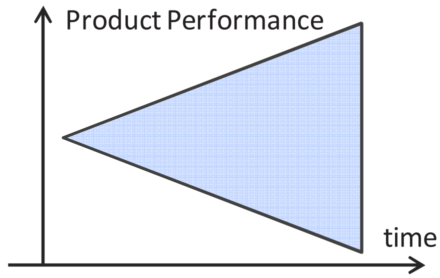


Figure 31: *Conceptual model of the radical R&D phase.*

5.3.2 Uncertainty vs. risk

The divergent findings between trial-and-error and real options approaches may be explained by the lack of sensitivity to or differentiation of radical vs. incremental innovation projects. This is because in the real options literature uncertainty is synonymous with risk, while in Finance literature two clearly separated constructs are used. In the Finance literature a distinction is made between risk and uncertainty. Uncertainty is incalculable or difficult to calculate, while risk is calculable uncertainty (*Knight, 1921*). In case of risk the probabilities are known, while in case of uncertainty they are unknown. We go along with the definitions of *Knight* (*1921*) and argue that literature on real options (e.g., *Huchzermeier and Loch, 1999, 2001; Huchzermeier, 2009; Santiago and Bifano, 2005; Santiago and Vakili, 2005; Rese and Baier, 2007; Santiago, 2008, Silva and Santiago, 2009*) do not differentiate between uncertainty and risk. In their approach uncertainty is synonymous with risk. Because project success and the individual drivers of radical product innovations are very difficult to predict, differentiation between the two uncertainty concepts is needed (*Balachandra and Friar, 1997*). In the pre-radical R&D project phase uncertainty is incalculable. In the radical R&D project phase uncertainties are difficult to calculate as the distributions are very broad. While the radical R&D projects develop through the different stages technical and market uncertainty is decreased. Later stages in the full R&D lifecycle are characterized by risk and uncertainties which can be quantified.

Figure 32 illustrates the types of uncertainty for the different phases of the full R&D lifecycle.

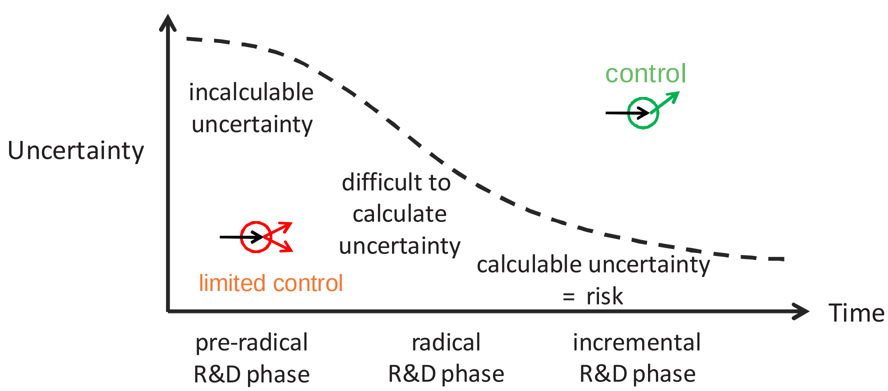


Figure 32: *Resolving uncertainty and evolvement of level of control.*

5.3.3 Level of project control

As indicated in section 2.4 *Huchzermeier and Loch* (*2001*) do not use their definitions in combination with the level of control. We argued that the use of real options and the value of managerial flexibility should be formulated according to the level of project control.

For instance, the use of the real option of improvement is rather limited in the early stages of the (pre) radical R&D phase, while this type of real option is more frequently used in later stages of the full R&D lifecycle. This finding is supported by our case study such as the improvement in GRIN LC technology over time compared to control in the pre-radical R&D phase.

Similarly, the value of managerial flexibility is reduced under conditions of a low level of project control which is often the case in the early stages of the (pre) radical R&D phase. However, if the level of control is increased, for instance when market and technology characteristics / relationships are known, the value of managerial flexibility is enhanced. Our case study showed a decrease in technical and market uncertainty, and thus an increase in project controls was obtained by supply chain establishment in 2008. A display manufacturer produced and assembled a first batch of the new lighting technology. Switchable lenses could be used in the latest identified application (Reactive Spotlight) and proved that the technology could be transferred to the business.

In general, as the uncertainty resolves in time, the level of project control is increased (Figure 32). The amount of project control in the fuzzy front end is constrained by several factors, the foremost of which is lack of control in idea generation and selection of the most favorable opportunity as markets and developments in technology are not predictable. As the R&D project develops through the different phases project control is increased as developments in technology, market and the risks involved become more specific. Furthermore, in later stages of the R&D lifecycle the amount of project control can be enhanced by having defined procedures for doing development and for instance by using growth options (i.e. real options to expand and innovate).

5.3.4 Managerial flexibility

Although the concept of flexibility is often used in the literature (*Copeland and Keenan, 1998; Rese and Roemer, 2004; Wu and Lin, 2007; Saleh et al., 2009; Huchzermeier and Loch, 1999, 2001*), the concept itself is rather immature (*Saleh et al., 2007*). The definition of flexibility depends on the context of its use and even within a single context definitions may vary or are poorly defined (*Saleh et al., 2007*). The concept itself is frequently used in combination with uncertainty as flexibility is needed in order to cope with uncertainty (*Saleh et al., 2007*). In real options literature managerial flexibility is defined as the ability to alter the course of a project in response to the most recent gathered information about project progress and market characteristics (*Huchzermeier and Loch, 1999, 2001*). As noted by *Saleh et al.* (*2007*) managerial flexibility can be used in two separated constructs: managerial flexibility per se and the financial value of managerial flexibility. We state that in the (pre) radical R&D project phase much flexibility is required consistent with an ad hoc approach. In this initial phase of the full R&D lifecycle distributions are unknown and there is very little control and therefore the value of managerial flexibility is reduced. In the later stages in the full R&D lifecycle there is a desire for flexibility but it is limited due to linear management of R&D projects using formal, systematic methodology having defined procedures for doing development. As the radical innovation R&D project develops through the different phases the value of managerial flexibility will generally increase as uncertainties become quantifiable at higher levels of control and higher investments are needed.

Huchzermeier and Loch (*2001*) neglect the fact that one possesses multiple types of managerial flexibility, such as the option to defer, expand, contract, abandon, and improve (*Wu and Lin, 2007*) in which its use depends on the phase of the full R&D product innovation lifecycle (*Katzy, 2003; Rese and Baier, 2007*). For instance, as can be observed from our case study, the real option of abandonment is frequently used in the radical R&D project phase.

Therefore we state that it is rather difficult to make a general statement about the value of managerial flexibility in R&D projects. One should at least specify conditions and the context at hand such as the phase and stage of the full R&D lifecycle including the type of innovation, the source of variability and the type of managerial flexibility, among others.

According to the findings of our case study, we conclude that between the pre-radical R&D phase and the process of *Huchzermeier and Loch* (*2001*) there is an intermediate phase which we have denoted radical R&D project phase. Systematic real options like approaches can be used or resembled in this phase of the radical new technology for application development as the uncertainty is resolved and the level of control is increased. The value of managerial flexibility increases as developments of technology, market and risks involved become more specific and can be estimated within boundaries.

5.4 Iteration of radical R&D projects

As discussed in section 4.4 our case study findings suggested the need to add an iteration notion to existing models of e.g., *Huchzermeier and Loch* (*1999, 2001*) and *Huchzermeier* (*2009*) as many of the innovation R&D projects are abandoned and as a consequence show patterns of iteration. *Huchzermeier and Loch* (*2001*) do not address the iterative behavior of subsequent R&D projects and product network effects. Their models show a focus on product project management rather than innovation project management.

The iteration in radical R&D projects is highly relevant for the value of an R&D project. For instance, if an R&D project is abandoned, not all investment costs are sunk (*McGrath, 1999*). On the contrary, in general the value of subsequent R&D projects will increase as results from one iteration are used for the next iteration (i.e. learning process). And, if a first radical product application using the new lighting technology is launched to the market, probably other applications will follow as well (i.e. network effects).

Figure 33 schematically illustrates this pattern of iteration of the R&D projects of our case study displayed in similar graphs or fashion as the conceptual model of *Huchzermeier and Loch* (*1999, 2001*) and *Huchzermeier* (*2009*).

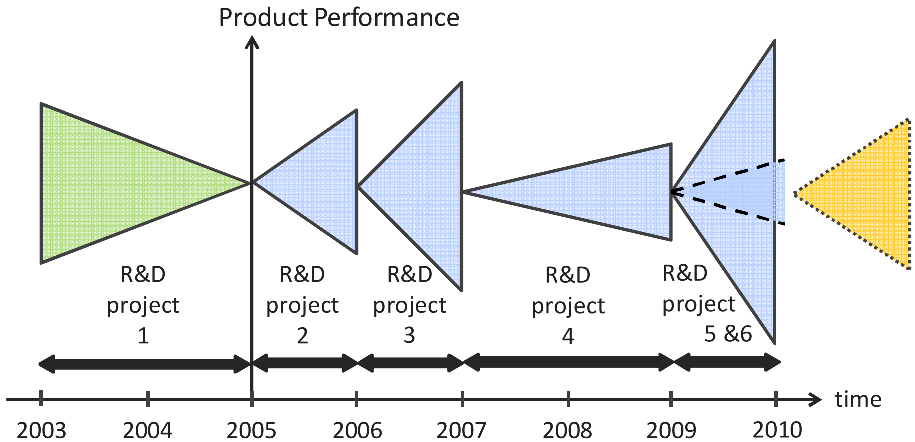


Figure 33: *Iterative behavior of radical R&D projects.*

The distributions of the projects in Figure 33 are approximations made by the author of this thesis. *Huchzermeier and Loch's* (*2001*) framework should be modified such that it includes the iterative behavior. However, as can be observed from Figure 33 and our case study it seems that subsequent R&D projects are working on deviations of the new lighting technology which are even more immature. In context of innovation management it might be suggested that one should work on a deviation of the radical new lighting technology and applications which is least difficult to bring to the market. In line with real options literature (*e.g., Fredberg, 2007*) we therefore advise to evaluate individual R&D projects as parts of a continuous innovation lifecycle. We will include this iterative behavior notion in the conceptual framework we are developing.

5.5 Incremental R&D phase

The third/final phase of the full R&D project lifecycle is the incremental R&D project phase in which the project management methodology of *Huchzermeier and Loch* (*1999, 2001*) can be fully used (Figure 33). We define the incremental R&D project phase as "the final phase in the full R&D lifecycle in which an incremental product application is developed and brought to the market."

> *Definition of incremental R&D project phase:*
>
> The final phase in the full R&D lifecycle in which an incremental product application is developed and brought to the market.

This incremental R&D phase is the conceptualization of *Huchzermeier and Loch* (*1999, 2001*) as it addresses incremental innovation. New extensions of products on the market can be managed in a linear way and outcomes optimized by quantifying risk as distributions of project drivers are known (*Huchzermeier and Loch, 2001*). For completeness we illustrate the incremental R&D project phase in Figure 34.

The value of managerial flexibility in this incremental R&D phase is high, because of the high level of project control and known distributions of uncertainties. The data of our case study do however, provide no projects which are in the incremental phase, as a first product application using the new lighting technology is not yet launched to the market. Hopefully a first commercial product using the radical new lighting technology will be available in the near future. However, other radical innovations from Philips such as LivingColors are already in this phase of the full R&D lifecycle and are going through incremental iterations at the moment.

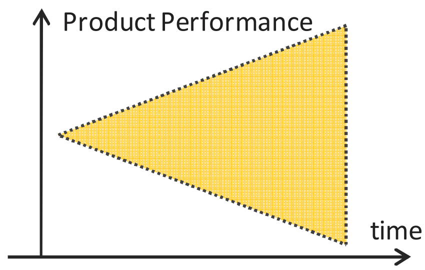


Figure 34: *Conceptual model of the incremental R&D phase.*

5.6 Conceptual framework

Based on our case study from Philips regarding new lighting technology, we found that management of radical innovations requires a mix of ad hoc and real options approaches; they coexist and alternate. The early search of a useful application for a radical new technology or material is a type of deliberated trial-and-error approach simply because risks cannot be calculated. After this, real options come into sight as developments of technology, market and the risks involved become more specific and can be estimated within boundaries. Hence real options theory can be used for developing radical new product applications but with some modifications based on different distributions of uncertainties and levels of control. Our results show that the streams seem to complement rather than substitute. Divergent findings may be explained by lack of sensitivity to or differentiation of radical vs. incremental innovation projects. Furthermore, real options literature uses synonymous definitions uncertainty and risk and lacking specifying the level of project control, which determine the degree to which real options approach can be used and extended to management of radical innovations.

According to the findings of our case study, we developed a conceptual framework for managing radical product applications consisting of (1) a pre-radical R&D phase, (2) a radical R&D phase, and (3) an incremental R&D phase (Figure 35). In the pre-radical R&D project phase new applications for a novel technology or material are identified. This is a convergent process which leads to a single or a few most interesting applications. Based on the opportunity identification radical R&D projects are executed which focus on an application. Identifying and selecting the first application of a technology is an important source of option value and is a critical real option when managing radical new projects. Because of high failure rates, many radical R&D projects are abandoned. This explains the iterative behavior of subsequent radical innovation R&D projects. After launching a radical innovation to the market, incremental R&D projects are executed delivering continuations and extensions of the radical product on the market.

We showed that distributions of the project drivers are unknown in the pre-radical R&D project phase and uncertainties cannot be quantified. However, distributions become predictable in the radical R&D project phase and as a consequence uncertainties are difficult to calculate but can be estimated within boundaries. In the incremental R&D project phase distributions of the project drivers are known and uncertainties become risks which can be quantified. Correspondingly, early stages in the full R&D lifecycle are characterized by extreme limited control, while control is limited in the radical R&D project phase, and there is much control in the incremental R&D project phase. As a consequence, the initial phase of the full R&D lifecycle requires a large amount of flexibility which is available. As the R&D project develops through the different phases the flexibility is reduced as linear and strict project management methodology is used, although in case of radical innovation still much flexibility is desired. The value of managerial flexibility is relatively low in the early phase of the full R&D lifecycle because distributions of uncertainties are unknown and cannot be calculated, and the level of control is low. As the project proceeds through the R&D lifecycle the value of managerial flexibility is increased as distributions become known, uncertainty can be quantified, and there is a higher level of control, while higher investments are needed. Table 15 summarizes our findings.

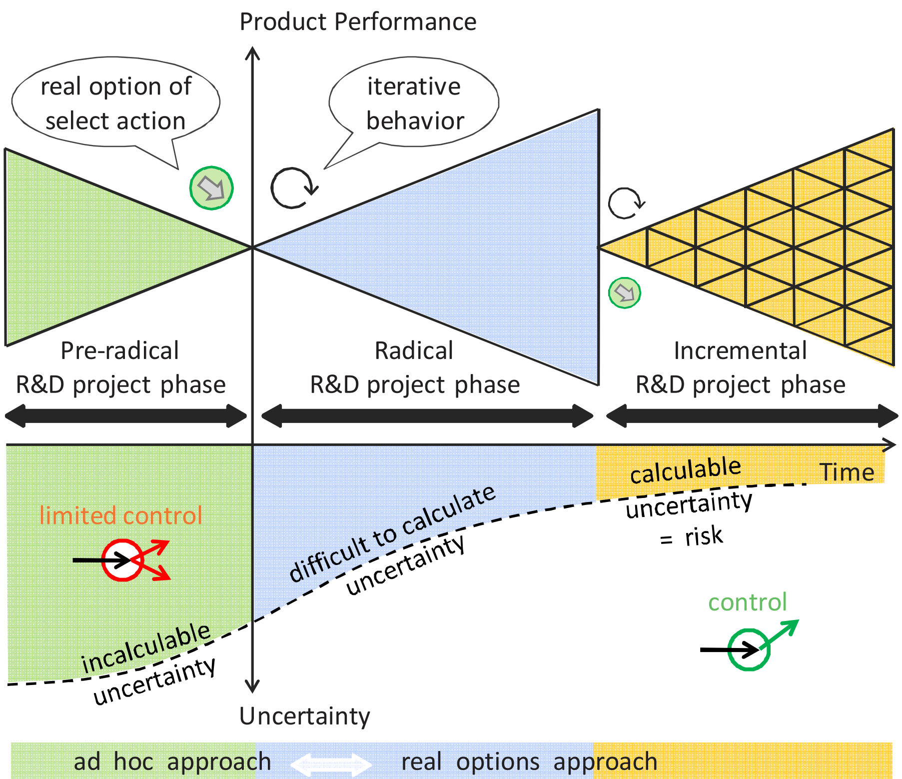


Figure 35: *Conceptual framework.*

Table 15: *Overview of findings.*

	phase of R&D project		
	pre-radical	**radical**	**incremental**
flexibility	needed & available	decreasing	limited
value of MF	low	increasing	high
uncertainty	incalculable	difficult to calculate	calculable risk
distribution	unknown	predictable	known
control	extreme limited	limited	control
approach	trial-and-error	(towards) real options	real options

6. Conclusion

This chapter concludes our work on radical new project management for developing radical new product applications. First, we will recapitulate our research questions, show our main findings and present our conclusion (section 6.1). Subsequently, we address the implications of our work for the literature and practice (section 6.2 and 6.3). We will end our conclusion by discussing the limitations of our study and indicate suggestions for future research (section 6.4).

6.1 Overview

To assure sustainable competitive advantage, firms need to bring innovative new products to the market. Radical innovations are highly desired for they have the potential to open up avenues of profitable new business. However, they are difficult to manage and very risky. The question is what can be done to manage these innovations properly?

Our literature review revealed that two contrasting views exist. First, several authors suggest radical new projects typically involve trial-and-error. Because radical new product applications often do not fit existing market demarcation lines or product categories, customer preference is difficult to forecast and market size and profitability are hard to estimate at best. On the other hand, *Huchzermeier and Loch* (*2001*) suggest managing project flexibility is well possible and can seriously reduce project costs. Drawing on real options theory, they suggest that R&D projects can be managed in a linear way and outcomes optimized by quantifying uncertainty.

The objective of this thesis was to find out which view is correct. Based on our literature study we formulated the following research questions:

1. Can radical new product applications be managed in a linear way, as suggested by *Huchzermeier and Loch* (*2001*) or is an ad hoc approach paramount?
2. Can we complement and modify *Huchzermeier and Loch's* (*2001*) approach to also address radical innovation project conditions?

We explored the degree to which real options approach can be used and extended this to management of radical innovations.

Based on a case study from Philips Research and Philips Lighting regarding new lighting technology, we found that the truth is a mix of these two approaches. The early search of a useful application is a type of deliberated trial-and-error approach. After this, real options theory can be used but with some modifications based on different distributions of uncertainties and levels of control. Our results show that the streams seem to complement rather than substitute.

According to the findings of our case study, we developed a conceptual framework for managing radical product applications consisting of (1) a pre-radical R&D phase, (2) a radical R&D phase, and (3) an incremental R&D phase. In the pre-radical R&D project phase new applications for a novel technology or material are identified. This is a convergent process which leads to one or more interesting applications. Based on the opportunity identification radical R&D projects are executed which focus on an application. The choice of which application to be researched first is an additional real option of select action. Because of high failure rates, many radical R&D

projects are abandoned. This explains the iterative behavior of subsequent radical innovation R&D projects. After launching a radical innovation to the market, incremental R&D projects are executed delivering continuations and extensions of the radical product on the market.

Early stages in the (pre) radical R&D project phase are characterized by very high uncertainty and require much flexibility. This flexibility will stimulate creativity, encourage outstanding technological efforts and fuel new opportunities. In these early phases of the full R&D lifecycle managerial flexibility loses its value because market input, such as market requirements and payoff, is not available and technical drivers are unclear and hard to manage since the technology is still in the embryonic stage. As the radical R&D project develops through the different stages the uncertainty will resolve and less flexibility is needed, while the value of managerial flexibility will generally increase as uncertainties become quantifiable at higher levels of control and higher investments are needed.

Divergent findings with the literature may be explained by lack of sensitivity to or differentiation of radical vs. incremental innovation projects. Furthermore, real options literature use synonymous definitions uncertainty and risk and lacking specifying the level of project control, which determine the degree to which real options approach can be used and extended to management of radical innovations.

6.2 Implications for literature

The findings of this study have a number of implications for the literature.

In the first place, we have reconciled the debate on the use of trial-and-error and real options approaches. We have explained how ad hoc and real options approaches complement rather than compete. This new perspective on R&D innovation project management can be a starting point for further research.

Second, we have extended soft real options stream that has focused on R&D project portfolio management to R&D project management closing the gap between hard and soft real options approach. Bridging both streams allows new research at the interface.

Third, from a theoretical perspective our findings contribute to research in the area of real options for R&D management by extending current work on real options approach for managing radical new product applications.

6.3 Implications for managers

Radical new products are important for firms as they provide sustainability for future business. However, managing R&D innovations from ideas to successful products is difficult and risky. Real options theory is seen as an important approach to manage innovation R&D projects. However, although it has theoretical strengths, its application in practice is still limited. Through this master thesis we would like to contribute to the improved management of radical innovations in the following ways:

First, one of the main managerial implications of our research is to provide a conceptual framework for managing radical innovations along the full R&D project lifecycle. Our radical new project management process is highly usable for managers in companies facing these types of projects. Our innovation process is designed to enhance the development of successful innovations.

A second important implication of our work for managers is that we emphasize the need of flexibility in the initial phase of the full R&D lifecycle allowing creativity to blossom, encourage outstanding technological efforts and fuel new opportunities.

A third key practical implication of our work is to give technology managers new insights on important aspects of radical innovation management such as the iterative behavior of radical R&D projects and the importance of the application select action.

Finally, we propose that real options approach can be used and extended to management of radical innovation. We suggest that when the distributions of the uncertainties become predictable and there is a certain degree of control, linear management and managing project flexibility is well possible and can seriously reduce project costs.

6.4 Limitations and further research

Our work has several obvious limitations including the use of a small sample size, case research conducted by a participant observer, the use of a single conceptualization, an abstract model and a single case study. We will go through the different limitations and call for further research to address these topics.

One limitation of current work is that the case study is based on only a single trajectory of multiple radical innovation R&D projects within a single organization. By having a small sample size the generalizability is somewhat limited. It would be preferable to have a larger samples size, i.e. different trajectories of related R&D projects within Philips or connected projects from other R&D based companies. Especially, R&D projects of different industries could be investigated. For instance, project management applied in pharmaceutical R&D could be different than those used by R&D managers in electronics companies. Research and product development lifecycles of the pharmaceutical industry are much longer (namely over ten years) than those of the electronics industry, and thus might need much more flexibility (*Ollila, 2000*). In addition, R&D projects executed by people from other cultures would be interesting to study because managers from companies established in a different region could have a different attitude toward risks e.g. a more risk-averse attitude (*e.g., Souitaris, 2001*).

Another limitation of the current work is that the author of this master thesis was taking part in many of the research projects. Although this will facilitate interpretation of results it can also lead to bias. By including objective documents, such as submitted project proposals and patent applications, the likelihood of bias is reduced although not entirely removed, particularly when interpreting the documents.

Our study is constrained by the use of a single conceptualization. The aim of this master thesis was to study if radical new product applications can be managed in a linear way using a real options approach or if an ad hoc/trial-and-error approach is paramount. The real options based conceptualization of *Huchzermeier and Loch* (*2001*) was used as a reference model in order to answer our research question. Based on our case study we have complemented and modified the conceptualization of *Huchzermeier and Loch* (*2001*) to also address radical innovation project conditions. However, it is desired to benchmark our findings with other real options based models because the use of different models could lead to different results.

A further limitation of the study is the abstractness of our model. Our model could have been further refined. For instance, the individual stages in the (pre) radical R&D project phase could have been further explored and extended. Particularly the real option of select action needs further attention. For instance, the selection strategy in the bowling alley idea is underexposed in the literature (*Moore, 2006*). The question which application/segment (head bowling pin) should be developed first is very relevant and is a topic to be further investigated.

So far, our model is not yet applied in R&D. Research is needed to prove the usefulness of our conceptualization.

In addition to the limitations addressed before, we believe further research is needed to strengthen our findings. Especially, research using quantitative models (i.e. hard real options) is needed such as simulations and calculations to further develop theories as introduced by *Huchzermeier and Loch* (*1999, 2001*). For instance, include the learning effect (i.e. iteration) of subsequent R&D projects in the value functions of *Huchzermeier and Loch* (*2001*). Another improvement to mature real options for innovation management can be made by further developing the soft real options stream. For instance, introduce the real option of select action in the soft real options literature. Furthermore, it is desired to improve definitions such as risk and uncertainty and the context of its use. By maturing the soft real options stream the gap between the soft and hard use of real options can be further reduced.

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Appendices

In this section, we show an overview of the different R&D project proposals. R&D project proposals A through E and G are direct copies of the proposals of Philips Research. Project proposal F shows project information of the project executed at Philips Lighting which is based on the project progress documents. No detailed project proposal of the venture project was written and submitted. Therefore the author of this thesis summarized project characteristics which are based on the initial venture plan drafted in March 2009.

In most of the appendices options are still open because they were not available at that time or not filled in. Names of responsible person or other non-anonymous information is omitted by the author of this master thesis. Unofficial projects, projects with a small activity using the new lighting technology, and projects which were submitted mid 2006, 2007, 2008, 2009, but not approved, are not listed in the appendices.

Overview of appendices:

Appendix A: Philips Research – R&D project proposal for 2003

Appendix B: Philips Research – R&D project proposal for 2004

Appendix C: Philips Research – R&D project proposal for 2005

Appendix D: Philips Research – R&D project proposal 1 for 2006

Appendix E: Philips Research – R&D project proposal 2 for 2006

Appendix F: Philips Lighting – R&D project proposal for 2005/2006

Appendix G: Philips Research – R&D project proposal for 2009

Appendix H: Philips Lighting - venture project

Appendix I: Leaflet Reactive Spotlight

Appendix A

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Appendix B

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Appendix C

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Appendix D

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Appendix E

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Appendix F

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Appendix G

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Appendix H

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Appendix I

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