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UNCERTAINTY HANDLING IN INTEGRATED PRODUCT DEVELOPMENT

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1. Introduction

Innovation projects have to face external and internal uncertainties, resulting from lacking or imperfect information on the market, customers' behaviour, competitors' moves and unexplored technological fields. Generally, the level of perceived uncertainty increases with the degree of innovativeness and novelty of the product as those projects cannot draw from past experience. A review of the prevailing literature on product development processes shows that most models exhibit some form of shortcoming in promoting radical but uncertain development projects.
Integrated product development is a widely recognized methodology for optimizing the development process. The purpose of the presented approach is to expand this method to specifically address the strategic challenges of radical innovations. Namely, procedural methods supporting such ventures should allow for a flexible process set-up while providing guidance and orientation. Furthermore, key analyses and decisions should be shifted to the front-end of the process. Marketing and technological uncertainties should also be treated simultaneously utilizing real options. According to this logic, a structured process, methodical support as well as guidelines for innovation teams are established. The work is based on a review of the current state-of-the-art and develops a model that has been derived and validated during case study research. These case studies were carried out in mid-sized companies (sales of €100M to €1000M and 100-1000 employees) active in the engineered goods sector. Moreover, the results were substantiated with third party industrial experts who did not participate in the case study but have to face similar design problems.

2. Uncertainty handling in prevailing product development models

2.1 Managerial/economic approaches

The first models describing structured development processes can be traced back to the 1960s when the NASA applied a "phase review process" in the interface with suppliers and contractors. The basic idea was to break a long development process down into discrete phases with dedicated reviews and decision points after each phase. Stage-gate models translate this idea into a process logic dividing the development process into a series of process steps ("stages") and corresponding milestone and decision points ("gates") [COOPER 2001]. Such stage-gate processes are implemented in several large - predominantly U.S. - corporations like IBM, 3M, GM, Procter&Gamble, DuPont, Corning, Polaroid and Dow Chemical. While stage-gate models allow for thorough process control and risk reduction, it is often criticized that stage-gate processes have an adverse effect on radical technology development projects [e.g. SMITH AND REINERTSEN 1992]. Stage-gate models demand for strongly linear proceedings, i.e. a project phase can only be initiated when all tasks of the proceeding steps are completed and positively evaluated. Hence, radical innovation projects as well as hardly predictable ventures, where neither a competitive environment nor a solid customer base is known at the beginning, will find little support in stage-gate models. Phased product development processes tend to promote incremental development projects because of their inherent structure and rigor, but typically fail in supporting discontinuous or radical innovation projects.

Based on a historical review of successful radical innovations, Lynn et al. [LYNN ET AL. 1996] derived the probe and learn process, i.e. a process model that aims at supporting the specific challenges of radical innovation projects. They argue for a more flexible approach and propose an iterative proceeding: Early products are introduced in test markets, and then modified according to the achieved learning and thereupon again tested on the market. This iterative experimenting loop is repeated until the necessary information is generated and the product is modified to reach its final market. While the probe and learn process led to impressive product development results in the ex post perspective, it seems less promising in an ex ante perspective when significant resources are put against a product idea. Several authors argue that aspects like project or business planning and goal stability, which are not contained in the probe and learn process, enhance the product development performance [e.g. LINDEMANN ET AL. 1998]. Overall,, the probe and learn framework is lending little structural support and guidelines to a project team planning an innovative product development.

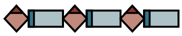
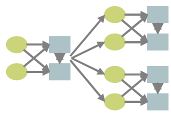
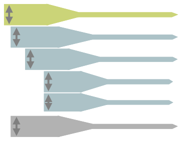
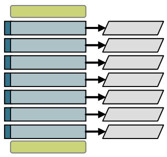
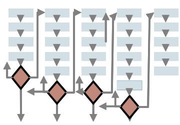
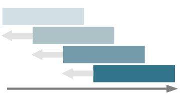
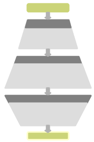
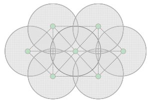
Uncertainty and risk are typically seen as challenges to a product development project. In contrast, the real option theory offers a different perspective as it values the flexibility that comes along with the liberty to alter projects. The ability to enhance, modify, put on hold or abandon the venture depending on the actual development of the uncertain variables in the project's environment is regarded as a valuable property. The core idea of the real option framework is that the holder of an option has an asymmetric risk profile, in a sense that one would only execute an option if the environment conditions turn out to be favourable for the option holder. Real options frameworks gain relevance for long lasting, radical product developments as the option value of flexibility increases with the uncertainty and length of a project. Contrary to the broad implementation in financial market, there are few implementations of the real options framework in the area of product development – one notable being the options-based proceedings in set-based concurrent engineering [GERWIN AND SUSMAN 1996]. The sparse implementation of this framework in the industrial product development reality is mainly caused by difficulties in selecting the right model and supplying it with the appropriate input data. In contrast to financial options that can draw back on a rich set of historical and current market data, real options merely rely on internally generated information which is difficult to obtain and to calibrate.

2.2 Technical/engineering approaches

Classical engineering design process models such as those pointed out in the work of Pahl and Beitz [PAHL ET AL. 2007] or Ullman [ULLMANN 2003] have led to a common view of engineering design processes offering structured support to generic development processes. They aim at a single solution that is detailed from a basic functional structure to its completed design.

The process in general and the iteration loops in particular are targeted at developing and optimizing a previously defined and specified product. This poses a significant challenge for radical innovations where the "right" product concept does typically not yet exist in the first phase. Hence, the iterative, but at the same time strongly sequential methodology offers a considerable structural support for most design problems but one that is at the same time "too linear" for radical developments. Ehrlenspiel [EHRLENSPIEL 2007] claims that the ambition to bring clarity and order into a development process appearing messy is understandable. At the same time, the strongly linear fashion of such processes yields a situation that is either not realistic or one that results in a frame too rigid for the product development team.

Andreasen and Hein [ANDREASEN AND HEIN 1987], among others, point out the aspect of cross-functional collaboration that is essential for radical innovations in integrated product development and in simultaneous and concurrent engineering models. Their work also includes theories from behavioural psychology, specifically individuals' and teams' limitations in coping with the complexity and insecurity inherent in radical innovations.

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

○ low ◑ middle ● high

Figure 1. Uncertainty handling in prevailing product development models

The Munich Procedural Model (MPM) structurally differs from the above-mentioned approaches [LINDEMANN 2007], as it does not interpret the development process as a more or less linear thread from problem to solution with iterations in between. The methodology rather consists of seven equipollent elements joined via several network connections, which allows for flexible paths reflecting jumps between different levels of completion and detail. Thus, it offers a flexible set-up that supports iterative clarification of requirements and successive resolving of uncertainties which is essential to more radical and hence uncertain innovation tasks. At the same time, the flexible set-up of the MPM may challenge users who are seeking a firmer guidance throughout the development process. Figure 1 illustrates the above-mentioned design process models and summarizes their suitability for radical innovation projects with a high level of implied uncertainty.

3. Model for Uncertainty handling in Integrated Product Development

Based on the discussion of existing product development models as well as the observation of radical innovation project teams, the following requirements for procedural models supporting projects under uncertainties can be derived:

- Flexible process set-up: Procedural models supporting such ventures need to offer the necessary flexibility for iterations, switches and jumps in the level of embodiment while providing overall guidance and support.
- Front-loading: The early phase gains particular relevance in the design of innovative products. It is characterized by a chronic lack of information and a high level of uncertainty, yet the decisions taken in the early stages have the strongest impact on the final product. Ullman [ULLMAN 2003] calls this phenomenon the “design paradox” as the design freedom decreases with an increasing knowledge of the problem.
- Embedding of options: Thinking in options essentially means the generation of several possible solutions from which an optimal one has to be chosen. Most of the engineering procedural models discussed in the previous chapter incorporate the provision of alternatives in one process step. The embedding of options serves two main purposes: Firstly, the solution space is deliberately enlarged in order to seek an optimal solution that might not have been available when following an initial idea. Secondly, through the development of options a solution space is created which helps in understanding the initial problem and independencies within solutions. This corresponds to the real options logic discussed in section 2.1.
- Interdisciplinary work mode: An integrative and interdisciplinary work mode between all technical functions (e.g. mechanical and electrical engineering) and between the technical and commercial functions is a key objective of successful radical innovations as they contain a commercial and technical part. However, today’s process organizations are often characterized by a division of labour and a strong functional specialization that constitutes a structural obstacle for a holistic commercial and technical approach in product development. In particular, the uncertainties on the commercial and technical side need to be treated simultaneously, not consecutively, and result from both areas’ need to be integrated.
- Support by tools and methods: Radical innovations with a high degree of perceived uncertainty benefit from tools providing orientation and guidance. Through established tools and methods, which rely on a stable documented base, the communication and decision making between different functional units can also be improved.

Hence, a procedural model supporting uncertainty handling in radical innovations should offer flexibility in process set-up while providing structure and orientation for the development. Furthermore, it should foster information gathering and option building while at the same time demanding decision making under uncertainty.

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

- Exploring the main fields of uncertainty through real options on the market and technology side,

- synchronizing activities on the market and technical side,
- and taking integrated decisions.

One important joint result of these objectives is to deliberately shift activities both on the market and technical side into the front-end. Here, fields of uncertainty are defined and subsequently explored through options. Following a structured idea, generation phase, possible market approaches and technical solutions towards an idea are drafted and tangible real options are thereby created. A key element of the procedural model is the evaluation and decision step, during which options from the technical and market side are integrated, evaluated and finally decided on. The latter are considered from commercial and technical perspectives and their implications and interdependencies are being discussed broadly. Following the expanded and multi-option based front-end, the development project is funnelled down to a single-option process through the evaluation and decision step. Hence, the detailed design, prototyping and 0-series ramp-up aim at the solution chosen in the evaluation/decision step. The general process logic with an expanded option-based front end and a more linear back end is depicted in Figure 2.

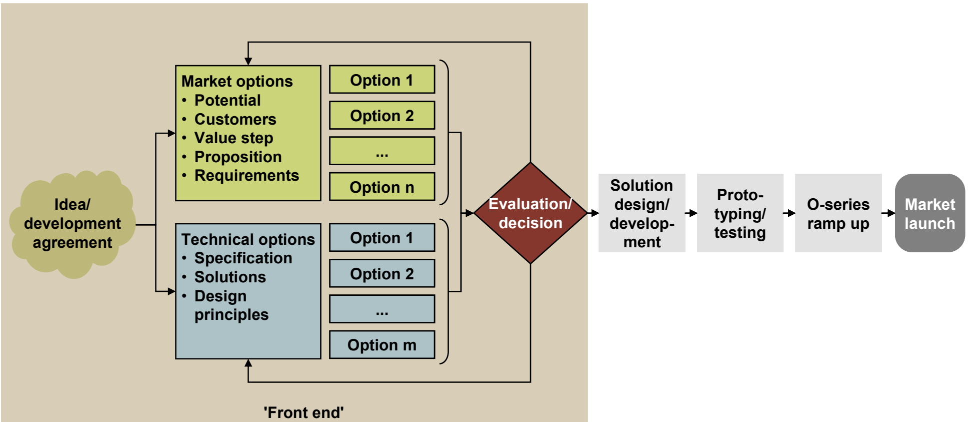


Figure 2. Process design for integrated uncertainty handling

The initial idea as well as the development stage gain special relevance, leading to a development agreement which describes project goals, resources and the main areas of uncertainty that should be investigated with options. At this point, typical procedural models coming from the engineering background underline the importance of having a complete list of specifications at the beginning of the development project [ULLMAN 2003; PAHL ET AL. 2007]. In contrast, the proposed model explicitly points out areas of uncertainties and defines "white spots" as development needs. Specifically, as an output of this phase the overall project goal is set, the project is assigned to human and financial resources, open issues are being defined, and development needs where the current know-how or existent solutions are insufficient are being named Moreover, among the list of open issues, those for which several options will be required to explore the uncertainty space can be "earmarked".

The goal to make uncertainties on the market and technology side explicit and to ensure a synchronistic procedure in both areas governs the set-up of the options generation and assessment phase. Based on the development agreement a structured options generation and analysis is conducted in this phase. Driven by the different nature of tasks, the proceedings on the market and technology show a different content. Nevertheless, the process logic enables the synchronous handling of both work streams and the integration of intermediate results. The key step in the technical work-stream is the generation and evaluation of options for each investigated technical area. As options are a suitable means to explore an uncertain space and to acquire knowledge, it is essential to create heterogeneous solution principles for each area. The proceedings in the options generation step resemble the logic of a morphological matrix, where for each subfunction displayed in rows different solutions are mapped in columns [ULLMAN 2003; PAHL et al. 2007].

On the market side, two essential tasks for the proceeding of the project take place: First, through a segmentation of the market that is addressed by the initial product idea, options on market segments are defined. Second, requirements and specifications are derived during a market analysis. These requirements then serve as basis for the evaluation of technical options. The proceedings consist of five steps, answering key questions each:

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

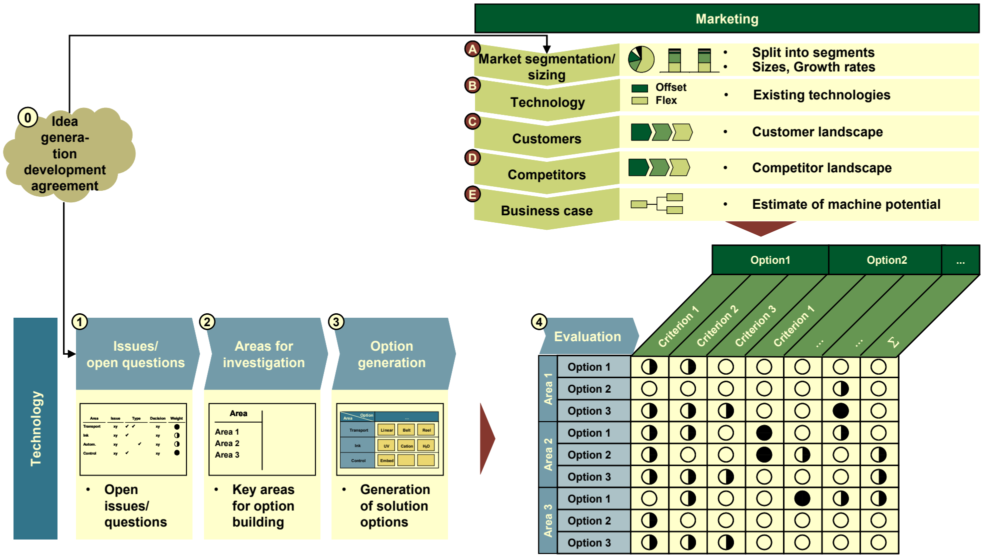
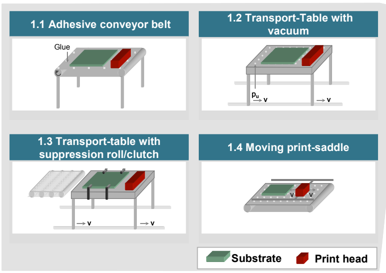


Figure 3. Options generation and assessment phase

Figure 3 illustrates the proceedings and methods in the options generation and assessment phase. The results of the technical and commercial work streams are integrated using a matrix. The areas or functions of the product including the analyzed options form the rows, whereas market options along with key requirements form the columns. Thus, an integrated view on all options and an evaluation can take place. For each function and option the fulfilment of criteria in each market option is assessed and expressed in an ordinal scaling system. Introducing a market-based weighting of the derived criteria; a score for each option representing its fit with the market requirements can be established. Using the same model but applying a different perspective yields further information on interrelations of the technical and commercial options. Summing up, the scores of the technical options for each market option provide an analytical view on which market option is best supported by the developed options. Technically, the ordinal scales used in the assessment do not allow the building of weighted sums or averages as ordinal values like the assigned score which indicates ranks but not intervals or ratios. Having the formal limitations of mathematical operations on ordinal scales and of their conclusions in mind, one can nevertheless gain valuable input for a decision problem under uncertainty: Figure 4 illustrates an example of technical options and integrated evaluation from the industrial implementation of the model. For a printing machine processing wood-based substrates, four different basic transportation mechanisms are evaluated with regard to their usage in two different market segments (laminate printing and furniture panels) along market criteria derived during market analysis In this example, laminate flooring is best supported by a moving print saddle whereas furniture panels are best supported by a vacuum-table. The circled numbers indicate the total scores regarding a technical option or a market option, respectively. Reading the matrix downwards in the columns indicates which market option is best supported by the existing technical solution options (In the example of Figure 4 the two options are equally strongly supported.)

Technical options for transportation



Extract of evaluation matrix

Technology areas and options		1. Laminate flooring: Speed	Print quality	Reliability	Σ Score tec. opt. for market option	2. Furniture panels: Speed	Print quality	Reliability	Σ Score tec. opt. for market option	...	Sum technical option over market option
1. Transport	1.1 Adhesive conveyor belt	○	○	◐	1	◐	◐	●	4		5
	1.2 Transport table with vacuum	●	◐	◐	4	◐	●	●	5		9
	1.3 Transport table with clutch	○	◐	◐	2	○	○	○	0		2
	1.4 Moving print saddle	◐	●	●	5	◐	●	◐	4		9
2. Ink	2.1 Water-based ink										
	2.2 Cationic ink										
...	...										
Σ Score market option over optimal technical solutions		◐	●	●	5	◐	●	●	5		

Fulfillment: ○ low (0) ◐ medium (1) ● high (2)

Figure 4. Example technical options and evaluation

The working mode in the front-end deliberately widens the range of solutions and thus creates a multitude of options. The evaluation and decision step at the end represent focal points where the generated knowledge is processed and key decisions are taken. In a sense, the highly iterative and broad front-end can be seen as an investment in the later development stages. While the working mode changes from a broad multi-option based mode to a more narrow single-option one with a switch from the front to the back-end, the integrative mode should be kept throughout the project.

4. Results from industrial application

Within the context of in-depth case studies accompanying development teams for two years, the discussed model for uncertainty handling in product development has been implemented in industrial settings. One project aimed at radical innovations in the industrial printing equipment market utilizing a new digital ink-jet technology. While digital ink-jet printing is broadly introduced in consumer markets, digital ink-jet printing in industrial printing systems is a novelty enabling the development of new products. The company under study had experience in the analogue photo-technology market and access to the new digital ink-jet technology but was facing uncertainties both on the market and the technology side when developing digital printing solutions. A cross-functional team with five engineers representing the main disciplines mechanics, electronics and chemistry (ink) and two experts from marketing and sales were put in charge of this project that was conducted according to the process and the methods depicted in section 3. Thus, the implementation indicates the model's fulfilments of the requirements towards radical innovation and its suitability for industrial application. Overall, the model enables a flexible process set-up and dimensioning of the technical and market work streams while providing structure and guidance to the development team. Front-loading was confirmed to be a strongly beneficial strategy as most decisions had to be made here in spite of a high level of perceived uncertainty causing the project team members to experience internal and external pressure. The model responds to this dilemma with a clear focus on the early stages and the generation of an option space on the market and technology side. Through the building of options, project members were able to learn about unknown areas in a structured way and were inclined to generate a variety of solutions even in situations where one initial solution seemed sufficient. Moreover, derived and documented options provided a base for the senior management to actually participate in the key product-related decision of a project and balancing its risks. While the presented approach cannot eliminate the immanent uncertainty of a radical innovation project, its proceedings helped in expanding the solution space and selecting an optimal solution as early as possible. Furthermore, it aligned top management, marketing and the R&D department towards joint risky decisions. Generally, the model can be broadly implemented but has limitations when a team is unable to generate a variety of solutions as the handling of market and technical uncertainties relies strongly on the development of effective options.

5. Conclusion

While uncertainty and risk are typically not explicitly modelled in product development models, the proposed approach supports radical innovation projects dealing with uncertainties from the market and technology areas. It contributes to a better understanding and coordination of market and technology uncertainties and thus generally leads to more in-depth understanding of methods supporting radical innovations. As projects which target new markets and new technologies can seldom be studied, process models for radical innovations will further benefit from their implementation in practice. In its current form, the model takes market and technology as the main sources of uncertainties. Using the described options-based approach, the model can be expanded by considering more areas that are sources of uncertainties in radical innovation projects, like sourcing, production and revenue models.

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