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TECHNOLOGY DEVELOPMENT AND NORMATIVE PROCESS MODELS

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Keywords: technology development, stage-gate, and spiral model

1. Introduction

The "fuzzy-front end" of industrial development processes has been studied from a multitude of perspectives, often with the objective of supplying normative management support. Early development require extensive experimentation and iteration to explore different concepts. This study was initiated based on a need in the studied company to implement an operational model for strategic technology development. A structured approach to down-selection and prioritization was sought. A few authors have proposed using the stage-gate model in these phases, e.g. [Cooper 2006], while others have argued against it, e.g. [Engwall 2004]. In addition, reports have been published from different industrial contexts of such implementations, e.g. [Cohen et al. 1998].

The aim of this article is to contribute experience gained from developing, implementing and using a normative model for technology development based on the stage-gate model. Additionally, a contribution is made as to how such a model can be used operationally. A modified stage-gate model is proposed where the iterative and explorative nature of uncertain technology development is considered. An empirical contribution is made regarding the dialogue that took place in the company in question when trying to balance the management need for rationality, structure and control vs. the need of the developers for exploration and experimentation.

The outline of this paper is that it starts with a brief discussion of some normative development processes found in literature, followed by an account of the research methodology, obtained results, a discussion of the results and, finally, the conclusions.

2. Literature review

Technology and its definition have been discussed and definitions proposed by a number of researchers, e.g. by Burgelman et al.:

"Technology refers to the theoretical and practical knowledge, skills, and artefacts that can be used to develop products and services as well as their production and delivery systems. Technology can be embodied in people, materials, cognitive and physical processes, plant, equipment, and tools." [Burgelman et al. 2004, p. 4]

In this sense, the technology of a corporation is accumulated and developed over time through all its operations. However, when we discuss the technology development process in this article, we mean a *directed effort* at developing new "knowledge, skills and artefacts" that, in turn, will facilitate product/process development (See Figure 1).

Over the years, the amount of literature concerning characteristics of product development, technology development and innovation has expanded. Different aspects have been researched, but the number of descriptions of normative process models for technology development is quite limited. Most often these types of descriptions come from industry as testimonials regarding implemented models and experience from using them, e.g. [Cohen et al 1998].

A common trait of technology development is its inherent uncertainty and the need for exploration and experimentation. There is a risk that by employing normative process models, one restricts creativity and the ability to explore [Benner and Tushman 2003]. At the same time, structure is needed for efficiency [Cooper 2006], as witnesses from industry show [Cohen et al. 1998].

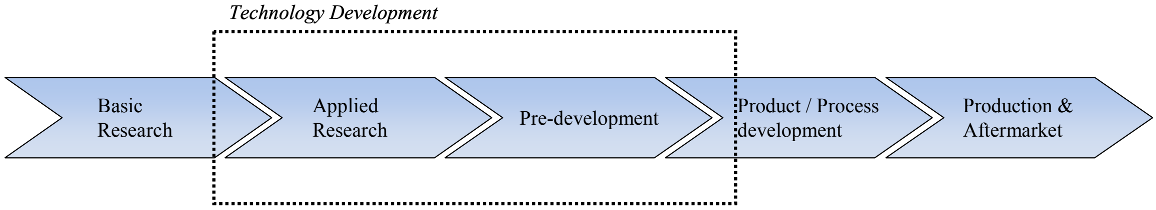

Figure 1. Technology development in the product life cycle

The notion of conducting technology development in a gated system, passing through a structured review process, has been argued by, e.g., [Cooper 2006]. He argues that since differences in character and outcome from technology and product development are so large, applying the stage-gate model to technology development means that adaptation is necessary.

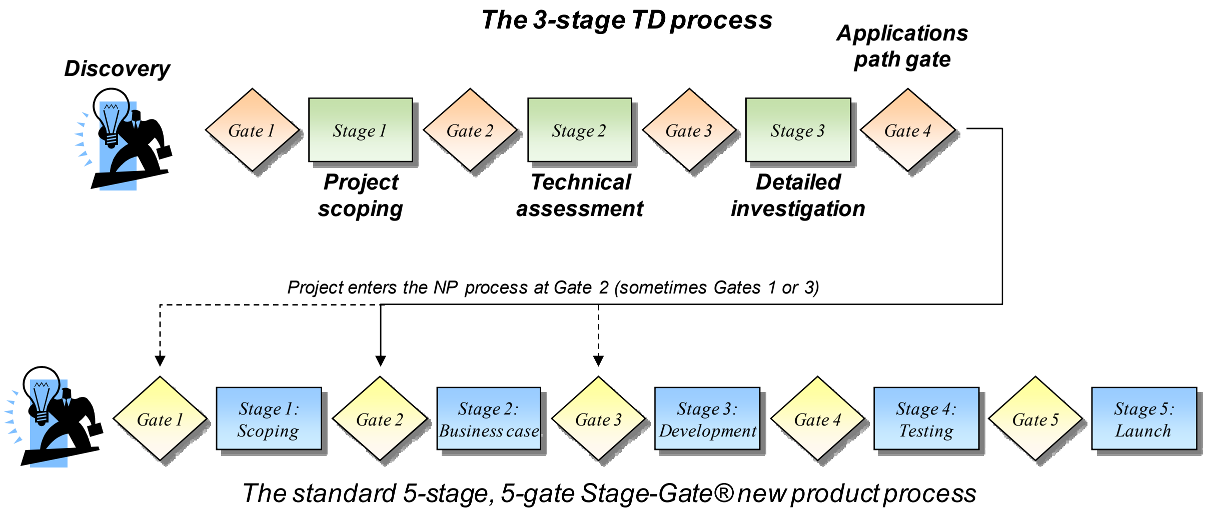

Figure 2. Stage-Gate model adapted to technology development, from [Cooper 2006]

Engwall [2004] provides a description of the history of gated development models. He describes different positive characteristics of the model that have led to its popularity, but concludes that its inherent rigidity makes it less suitable for uncertain development. He describes uncertain development as a learning process, and the normative process description should reflect this, while still respecting legitimate management needs for control. Innovation processes have often been described as iterative learning processes (See, e.g., [Rothwell 1994]).

In the past, several other authors (in addition to Engwall) have stressed the importance of greater flexibility in design processes where a high degree of uncertainty is present. Alternative models have been proposed that are claimed to better cope with development uncertainty, the spiral model being one of them [Boehm 1988]. A comparison of the spiral and the stage-gate models applied to product development has been conducted by Unger and Eppinger [Unger and Eppinger 2009]. In it, normative factors that may indicate whether a company should choose one or the other of the two models, or possibly a variation of them, were sought. Unger and Eppinger concluded that the spiral model has advantages in managing market risk and is often favoured by software companies, while the stage-gate model is often favoured by hardware companies where product integration and building prototypes are costly and difficult.

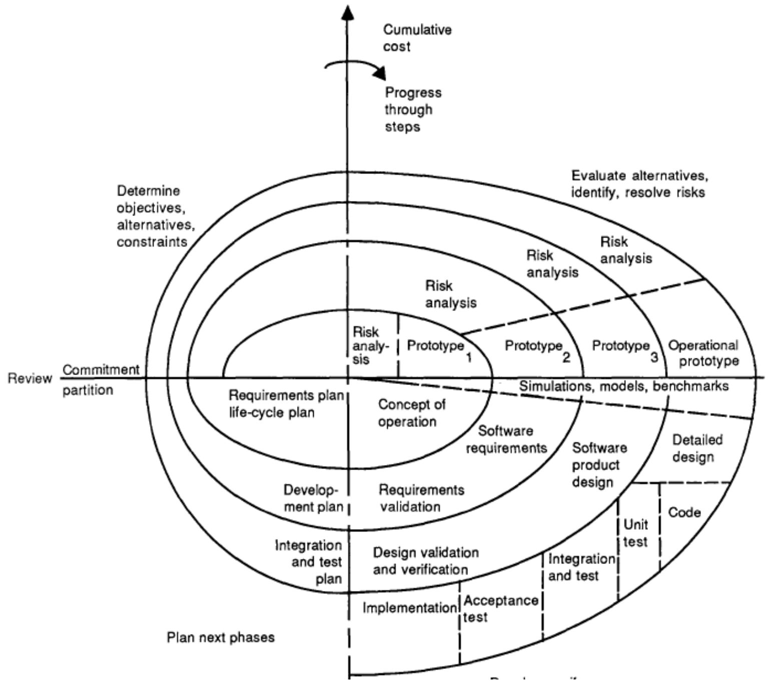

Figure 3. Spiral development process model, from [Boehm 1988]

3. Methodology

This study was conducted during a one year period, from January till November 2008, as an action research study at one industrial company in the aero-engine industry. The company is located in Sweden. An insider researcher led a group of experienced engineers in a team with the objective to formulate a normative technology development process model to be used operationally in the company. Work was conducted in a series of steps:

a) clarification of the task/problem, boundary conditions and requirements,
b) design of various models, down-selection, and detailing of a chosen model,
c) validation of the chosen model in the organization,
d) reworking after the first round of validation
e) re-validation after reworking
f) implementation in the IT management system at that company, and
g) implementation and testing in a couple of technology development projects.

Steps d) and e) were initially not planned, but were conducted as a result of step c).

Different people were involved in the different stages, but the core of the task was conducted by a team of seven to nine employees from the company, led by an insider researcher. The number of people in the team changed during the course of development, as some people left the team and others joined. The team was cross-functional, with representation from business development & sales, engineering, quality and production. Work was conducted through a series of two-hour workshops during the time period January-November 2008. Apart from these working meetings, additional workshops and seminars were held during the period, and they are described below.

Data was recorded in the form of short minutes of meetings distributed via e-mail to the participants and working material in the form of various documents, homepages, and reference material used by the group stored on a homepage dedicated to the team. The main result of the work, the normative process, has been formalised as a company routine in the corporate-wide Operational Management System (OMS). OMS is implemented as an IT solution in the company intranet. This system serves as the "law" in the company relative to which external and internal quality audits are conducted. The

material used by the group (stored on the common homepage) and the results from the work of the group form the primary data used when conducting the analysis for this article.
The insider researcher has a long history in the organisation. As leader of the group, he influenced the team, e.g. by introducing work from academia and industry relevant to the task. However, all participants were selected for their long experience and integrity, and the researcher expected opposition if he tried to push ideas that did not agree with their own views or knowledge.
The choice of research approach, action research, and the methodology followed were choices made based on the problem at hand and guided very much by the description supplied by Herr [Herr 2005]. Action research is a suitable method when trying to solve a real world problem in collaboration with practitioners. Typically, an insider researcher – insider practitioner constellation is suitable to contribute to the knowledge base on improved/critiqued practice or professional/organizational transformation [Herr 2005, p. 31]. The logic followed in the study, steps a) - g) above, agrees with the spiral of action cycles described by Herr [Herr 2005, p.5]: 1) develop a plan of action, 2) act to implement it, 3) observe the effects of action, and 4) reflect on these effects. The account of the obtained results below follows such a cycle of action.
Quality in action research has been debated for years. Herr & Anderson [Herr and Anderson 2005] discuss the topic in detail and propose quality criteria relevant to this form of research that link to the purpose usually accompanying the approach. These criteria have been used as a guide when conducting this study, and are reflected upon later in this article.

Table 1. Quality criteria relevant to action research, as proposed by Herr & Anderson [2005]

Outcome validity	The extent to which actions occur, which leads to a resolution of the problem that led to the study.
Process validity	To what extent problems are framed and solved in a manner that permits ongoing learning of the individual or system.
Democratic validity	To what extent the research is done in collaboration with all parties who have a stake in the problem under investigation.
Catalytic validity	To what extent the participants and the researcher have been open to reorient their view of reality as well as their view of their role.
Dialogic validity	To what extent the research has been peer-reviewed.

4. Results

The results from the work are presented in chronological order as described in the previous chapter, steps a-g. The learning from action research often stems from group interaction that takes place during the process [Herr 2005]. Therefore, we try to describe some of the major interactions that influenced the design of the normative process model and the rationale behind this.

4.1 Clarifying the task and boundary conditions

To clarify the task of the process team, a half-day workshop was held in February 2008. Apart from the team intended to work on the task, a number of stakeholders were invited in order to realize the intention of the workshop.
The workshop was conducted as a brain-storm relating to a series of questions. The aim was to create descriptions of the process purpose, the main output, the main input, who the customers of the process are, who the suppliers to the process are and the constraints on the process. In addition, requirements for and expectations regarding the design of the process were discussed.
Requirements for and expectations regarding the design of the process included many different aspects, e.g. the traceability of results, the management of intellectual property, needs relating to efficiency and effectiveness, the linking to customer needs and project management practices. Need for control was a strong theme in the discussion, and several aspects of this were brought up. Examples of aspects discussed included the measurement of technical maturity, the assessment of uncertainty and risk, the possibility to re-direct or stop, and the application of a stage-gate model to achieve this.

4.2 Design of various models, down-selection and detailing of chosen model

Following the first workshop, a series of meetings in the task group ensued in which a common understanding of the problem to be solved was formed. From the first workshop involving different stakeholders, it was clear that there was a request that the process should be designed as a stage-gate and that Technology Readiness Levels (TRL) [Mankins 1995] somehow should come into it as a measure of the readiness of the output from the process. At first, an effort was made to map the "real" process. Trying to map it onto the stage-gate model was done in order to visualize deliverables from the various stages. That effort, however, was abandoned since it did not really reveal what is unique for early technology development. Rather, it became a very general description of "development". An alternative approach was chosen where, through brain-storming, the team generated different process models. Input to this brain-storming was supplied first of all by the impressive experience and knowledge concerning technology development in the group. Models from literature and other industry, including the stage-gate of Cooper [Cooper 2006] and the spiral model of Boehm [Boehm 1988], also provided input. Afterwards, the generated proposals were discussed and compared relative to how they represented the actual conduct of technology development and how well they satisfied the strong request from the stakeholders to apply stage-gating and TRL.

Two main candidates materialized. One was very similar to the one proposed by e.g. Cooper [Cooper 2006] (here called "Candidate 1"), while the other was more iterative in nature, with a strong resemblance to the spiral model [Boehm 1988] (here called "Candidate 2"). (See
Figure).

However, one difference between "Candidate 1" and Cooper's model was that the model generated by the group contained six stages and gates, while Cooper's model contains three stages. The main reason for this difference was that the group chose to link the process model closely with the TRL scale such that each stage corresponded to one TRL level. Six stages became the result from the simple "rule-of-thumb" that TRL 6 should be reached prior to application in product or process development.

One main difference between the spiral model and "Candidate 2" was that the generated model assumed six loops through the spiral, one loop per TRL, while the spiral model of Boehm was open-ended. The number of turns in the spiral from Boehm is typically decided, for example, by when a sufficiently good product has been reached, when the market situation says that a product has to be released or simply when the company runs out of development funding.

When comparing the two models to criteria a) (representativity of the real technology development process), and b) (application of stage-gating and TRL), Candidate 2 was chosen by the team as baseline concept. The reason was simply that the team felt this model agreed better with how uncertain development involving extensive experimentation and exploration is conducted.

4.3 Validation of the model in the organization

The chosen baseline for the normative process, Candidate 2, was modelled in a test version in the IT system OMS where it eventually was intended to be implemented. This version was submitted in early July to some of the key stakeholders for review. Some members of the process team that had formulated the model also presented the result in some of the stakeholder groups that later would be the main users of it. A deadline to deliver a formal response was set at mid-September. When evaluating these responses, it was clear that they differed quite a lot. In general, engineers and junior managers responded that they liked the model and felt it agreed with real technology development. At middle management level, however, responses were not as favourable. In these cases they felt that this proposal was too complicated and that it did not show the overall development logic. Furthermore, they felt it deviated too much from the model used for the later development stages of "Product Development," and they wanted to see a better fit. "Product Development" is modelled as a classical stage-gate model. Having a similar way of modelling technology development would favour and simplify communication in the company, and they strongly urged the team to reconsider and instead implement "Candidate 1."

This strong criticism from middle management sparked an intense debate in the process team. The team was not happy about abandoning their baseline concept. Eventually, though, the team decided to do it, since process implementation very much would rely on middle management and that the model would meet middle management needs. After all, the model should be implemented primarily as a tool to support "Operational Management."

4.4 Implementation in the IT management system at that company

During the period September-November 2008, the process model based on "Candidate 1" was developed in its first version 1.0 and implemented in OMS. However, the solution finally chosen was actually a combination of the two candidate concepts. When viewing the process at the first level of the IT solution, the classical stage-gate model with six stages comes up (See Figure).
However, when you "click" on one of the stage boxes, the activity flow proposed in Candidate 2 comes up (See
Figure). The same flow is found in four of the six stage boxes, TRL 3-6, while stages TRL 1 and 2 are simplified versions of the same flow. The philosophy represented in this model is simply that *when technology development is conducted, activities are repeated, but the generated output contains a larger amount of detail with higher level of concretization for each stage*. This is a similar philosophy that can be found in the spiral model. This philosophy is also found in OMS when you look into the gate boxes. In those, a "TRL Checklist" can be found that is a list of questions that should be asked at the gate reviews. These questions are identical for all gates. The only difference between the gates is that the quality of the delivered answer is expected to increase regarding level of detail, accuracy and concretization. This will build reliability and validity in the process. The "TRL Checklist" defines not only the questions to be asked, but also the expected quality level of the answer at every TRL gate.
The second major principle of the model is that the *process can call itself in a recursive manner*. When a new technology is being developed, new problems or needs will be encountered that were not anticipated. This is inherent in a highly uncertain development process. To solve these problems, additional new sub-technologies may have to be developed. To develop these new sub-technologies, the modelled normative process is used, thus the recursive philosophy.

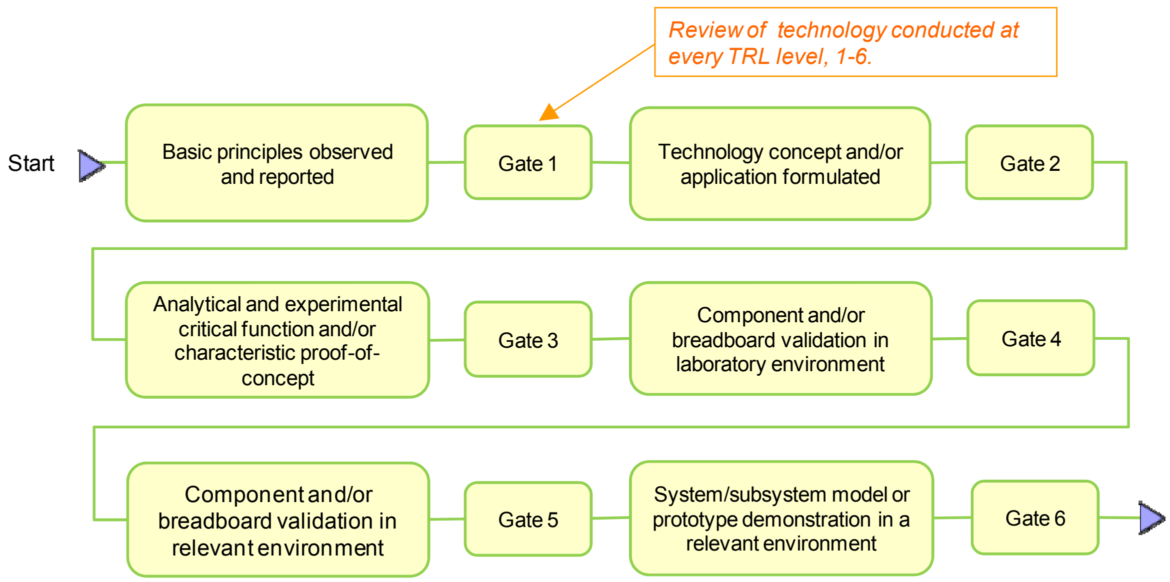

Figure 4. The first level of the process "Develop Technology" in the Operational Management System (OMS)

4.5 Implementation and testing in technology development projects

The process model was implemented and officially released in the Operational Management System of the company in November 2008. Gradually, during 2009, different technology development projects have implemented and begun to use the process, and some "how-to-do" experience has been gathered, as well as benefits and challenges with it. The insider researcher who led the process team, has during 2009 participated in a working group that has focused on the issue of "How do we implement and make use of this normative model in our projects?" The team consisted of five project managers under

whose leadership some of the major technology development efforts in the company were being conducted. Some experience from using the model, as well as good practices, emerged during the year. The results presented below are preliminary at this stage since work is on-going. More details and more conclusive work is expected to be presented in forthcoming articles.
The individual projects are usually confronted with a task involving a high degree of uncertainty. Iteration between customer/company needs, potential design solutions (product/process concepts) and technologies is conducted more or less continuously during the technology development process and a "technology tree" is gradually built.
The projects have adopted a practice where they describe the technology tree in a simple file as a list of technologies pursued. Different levels of technology readiness may have been achieved for different sub-technologies, which is indicated with links to supporting documentation. This description of the technology tree is updated as the project progresses and adapts to changing circumstances caused by, for example, new customer needs or new learning occurring in technology development. The description gives an overview of the overall status of development.
Separation is made between technical reviews conducted at the level of the individual technology tracks pursued in the "tree," technical reviews conducted at the integration level and the gate reviews.
Some conclusions can be made from learning gained from this first year of testing the process:
Advantages

- Achieved results and challenges are expressed explicitly and adjustments to meet product/process plans can be made pro-actively.
- Clear structure makes it possible to better link to overall strategies and to adapt to changing circumstances.

Disadvantages/difficulties

- Risk of burdening projects with too much administration. Management has to show restraint and find a reasonable balance.

In general, the organisation appears quite satisfied with the model at this time, and is working diligently to implement it broadly in the company. A number of improvements can clearly be made to simplify its use, and work is underway to realise some of these.

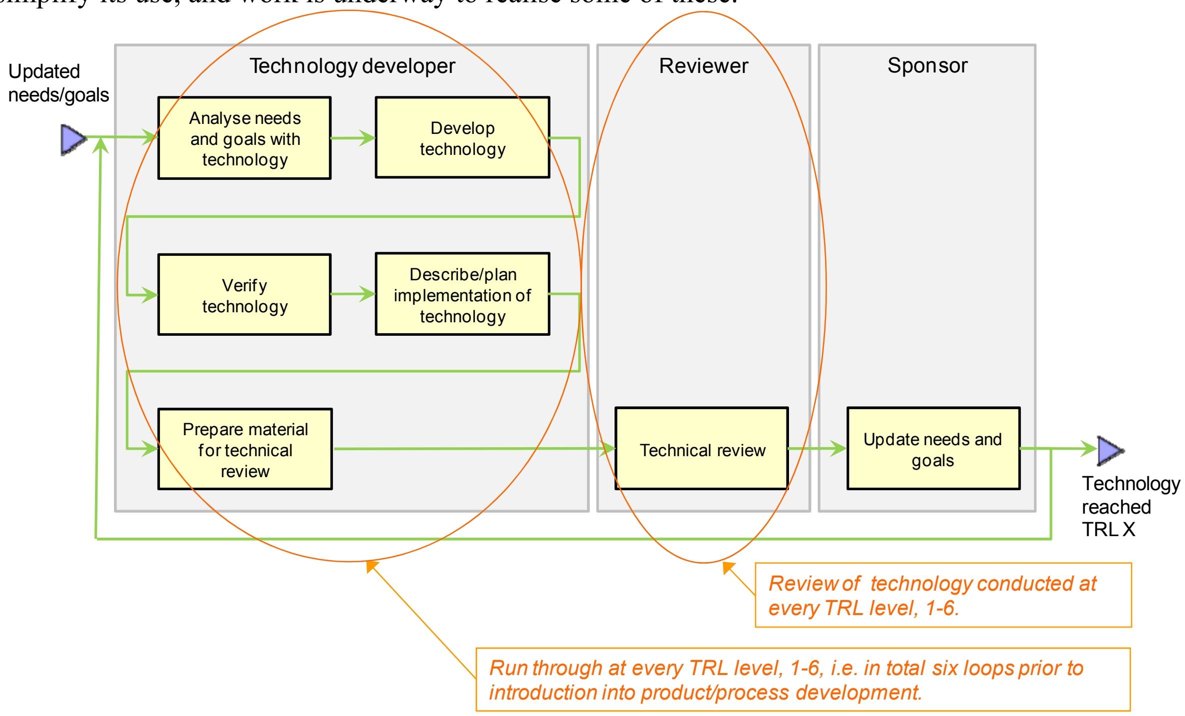

Figure 5. The second level of the process model, "clicking" one of the stage boxes

5. Discussion

5.1 Discussing the results

The aero engine industry carries a lot of the traits of the 5th generation innovation process of Rothwell [Rothwell 1994]. Innovation and development is done in industry networks and partnerships. Technology development is distinctly separated from product development, for rational reasons of risk mitigation. New product concepts, engine architecture and facilitating technologies are developed in large collaborative research programs. Engine demonstrators are particularly important as a common focus where new technologies are demonstrated and tested prior to the development of an actual product. Within the phases of technology development, and in particular the early, immature stages, the experimentation and testing of different new ideas and techniques needs to be done to feed the innovation process. In product development, the industry partners commit themselves with large sums of money and personnel, and risk-taking is not advisable during those stages. That is why such a clear distinction is made between technology and product development.

The implemented model has been heavily influenced by the stage-gate model of Cooper [Cooper 2006]. It has also been heavily influenced by the practical experience in the company of applying this type of model to product development. Adapting the model to the TRL scale is not a new idea, but has been done earlier in other aero-engine companies. The process team knew this. The spiral model [Boehm 1988], when presented to the process team, was received with enthusiasm. The model was not previously known to the team (except for the insider researcher who introduced the model). However, there were statements from experienced technology developers, such as "That is exactly how it is done in reality. We explore a concept, learn, and adapt in a new learning cycle where the concept is modified." Even though this was a spontaneous reaction, the spiral model in the form described by Boehm is not directly applicable. Physical prototypes of a product are not developed and produced. The "prototypes" in the early stages are rather concepts, virtual models of a product or process, that the team uses as a focus for defining the requirements on, and need for, new technology.

The implemented normative model in the company appears quite simple, with the sequential stages and gates. Iterations are represented in the level below the sequential description through repetition of activities and questions asked. However, the main iterative character is not found in the model description, but rather in its use. It is stated that the model should be used recursively, where the technology tree is successively built as the organisation learns, each "leaf" in the tree following the normative process. In Engineering Design theory, iteration has been described for product development. Reflecting on the "real" technology development process and the growth of the "tree" to e.g. C-K theory would probably be valuable, but is left as future work. There are, however, different purposes when developing a product and when developing technology. Returning to the quote from Burgelman et al. [Burgelman et al. 2004] in the beginning of this paper, the "knowledge, skills and artefacts" focused on in technology development can be put to good use when developing products, which usually is the very reason for developing them in the first place. In effect, what has been attempted in this work is to merge iterative innovation process description with normative management models. The stage-gate model has many advantages. Examples include clarity in logic and communicative power. However, it describes iterative learning poorly. By combining this model with iterative elements, we believe that more realism can be brought into the gates, facilitating a better dialogue and decision making process. To show this, however, requires further research, which is also planned as a part of this research project.

5.2 Discussing the quality of the research

When discussing the quality of this research we return to the criteria presented in Table 1.

Outcome validity has been realised through a model implemented in the organisation in question, and initial positive experience has been fed back to the researchers and the group that proposed it. The organisation continues using and developing it.

Process validity has been realised through the design of the study with a series of reflective workshops and seminars.

Democratic validity has been ensured through the cross-functionality of the working group and the efforts made to validate the normative process with key stakeholders.

Catalytic validity is not as obvious. On one hand, the company and the working group have been open to new ideas and also changed company practice based on obtained results. However, it could also be argued that the intervention of middle management in the concept selection shows the contrary, an unwillingness to change. Ultimately, the arguments from middle management were deemed valid in the process and, therefore, carried weight in the selection. Whether this was a good concept choice remains to be seen in the continuing use of the model.

Finally, *Dialogic validity* has been ensured primarily by involving an external researcher when reflecting on the work and also through seminars held at both the research department and another company. Furthermore, presenting this paper results in peer review.

In our opinion, generalization of our results is not possible because the study was conducted in one unique context. However, transferability is facilitated by the rich description of the case and the process for reaching the normative process model.

6. Conclusions

The concrete result from this action research study is a model to be used for technology development, primarily as a management tool. The model reflects the ambition to achieve a balance between management needs of simple, clear logic which is easy to explain and relate to, and the developers view of the need for extensive experimentation. Results from an earlier descriptive study showing that technology gradually expands in the maturation process into different sub-technologies with increasing levels of detail and concretization had an impact on this mixed model. This is in particular reflected in the formulation of the gates and the recommendations regarding how to use the model in operations.

A first version of the normative process model has been tested in the company involved in this study. Preliminary results are positive, primarily through improved transparency in on-going activities, and because actual status is clearly expressed and brought forward so that proper corrective actions can be made. Still, further improvements of the model are necessary to have it run more smoothly, some of which are foreseen to be implemented during 2010.

Finally, the main contribution of this work is the experience gained from an effort to apply the stage-gate model to technology development and to marry the management perspective with the developers' perspective in a normative development process.

Acknowledgements

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