Managing Risk in the Introduction of New Technology in Products

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Abstract. In this paper interviews with staff involved in product development from four different companies is presented. The objective is to find out how the companies manage the technical risk of introducing new technology in products and how they prepare for meeting changing requirements from customers. The companies originates from aerospace, automotive and production engineering. Based on the results of the first study, a case study was carried out at the aerospace company. The studies shows that, the introduction of new technology varies with the risk of failure in the validation of the products. Companies that easily can revert back to the former technology is more risk taking. The types of products and the companies' place in the supply chain has an impact on technology introduction and requirements handling. The companies have strategies for developing requirement specifications prior to the start of the project. This is most elaborate at the aerospace company where a thorough concept evaluation clarify possible variations in requirements.

Keywords. Product, technology, development, platform, complexity

1. Introduction

Companies in industry can gain a competitive edge by continuously and systematically investing in technology development in strategic areas. It is however a challenge to introduce the new technology at the right time. Too early means that the technology is not ready and can fail in service and too late means that competitors have reached the market already.

In this paper it will be investigated how four different companies handles the risk of getting in the situation that novel technical solutions are used in products before all major uncertainties around them have been resolved and how they handle fluctuating requirements in the product development process.

A novel technical solution can give the company's products increased performance and lower price. It is therefore tempting to present the novel technical solution in business negotiations with the costumers albeit perhaps only the function has been demonstrated for the technology alone and not as a part of a complete system. If the new technology becomes part of a product development project with fixed time and budget limitations, the company must be certain that it is possible to integrate the new technology in the complete product or alternative have a backup plan should the new technology fail.

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By interviewing 2-4 persons, ranging from designer to manager, in four companies, the company product and technology development strategies are investigated. The interviewees have been selected so that both the overall and the detailed view is represented, often a designer and the CEO or the head of the engineering department depending on the size of the company. The initial study has been followed up by a deepened study at the aerospace company.

The companies are first and second tier system suppliers or OEMs within production system equipment, automotive, and aerospace industry. They all manufacture and integrate technology into their products, and at the same time being affected by fluctuating requirements and stiff competition.

The term “risk” both involve identifying the hazards and threats as well as handling all the possible consequences in that the event should occur [1]. In this paper the risk referred to is that un-ready technology is incorporated into the products. The handling of the possible consequences is not discussed in the paper.

In past research a large emphasis has been put on splitting technology development (TD) from product development (PD) in order to decrease risk as stated by Lakemond et al. [2]. This splitting of TD and PD is important due to the difference in prerequisites, technical maturity, time horizon, need for competence and deliverables from the two processes. However, challenges in how to manage the interfaces between the two emerges. TD aims at developing knowledge, skills and artefacts in order to enable PD, Högman and Johannesson [3]. Deliverables from TD can also be a demonstrated feasibility Nobelius [4] or a technological platform as stated by Cooper [5]. It is further described by [5] that TD is important for a company’s long-term growth but it is however often not sufficiently prioritized and represents only a small portion of the total effort of a company.

TD is in need of both structure and flexibility due to the uncertain and often complex nature. This is described as mechanistic (formal) and organic (informal) methods by Olausson and Berggren [6]. In [3] the terminology product platform and technology platforms are used. The technology platform contains of all the knowledge and methods needed for the design and manufacturing of the products. The products are referred to as the product platform. The use of a technology platform is recommended for a company in the low volume, high technology segment. The technology platform consists of design concepts and methods on an abstract level since a component based platform is not applicable for such a company.

Depending on the system architecture as elaborated by Maier [7] the character of the products and systems can be either integral or modular. An integral product is one where many functions has been built into the components whereas a modular component is when the functions have been located in modules that can be replaced. It seems that modular products will not be as optimized as integral, Celona et al. [8].

PD is defined as transforming a market opportunity to meet the need of a customer and strategic goals of the company. This is done through a set of coherent activities that interacts with each other as described by León and Farris [9].

A strategy in PD that has shown to be effective is the product platform approach. A product platform can be defined on different levels ranging from a fully specified generic component to more abstract descriptions containing knowledge, people and relationships. Two product platform approaches is proposed by Simpson et al. [10]:

(1) The module based or configurable platform, is supported by a well-planned product architecture where modules can be assembled into a finished product and in that manner create a product family;

(2) The scalable or parametric platform allows for a certain amount of shrinking and stretching of design parameters in order to create a product family.

Depending on how the product platform is constituted, four types of variant specification systems are identified by Hansen [11]: (1) Engineer to order, (2) modify to order, (3) configure to order and (4) select to order. The types can be seen as levels denoting the amount of engineering needed to deliver a finished product where engineer to order is at the highest level requiring the most engineering work. A risk in platform architecture is the trade-off between increased development efforts related to the initial platform and the uncertainty whether the right platform is chosen in order to develop a sufficient number of product variants to gain back the extra expenses, Halman et al. [12]. Another trade-off when choosing the product platform approach is the one between commonality and performance as elaborated by Martinez-Larrosa and Siddique [13]. However, a proposal for a knowledge platform is given by Johannesson [14] who also states that the question is not whether to invest in a platform, but how to design it. The knowledge platform is built by reusable knowledge that has been gained through the different development processes.

Another view that aims towards making the PD process more effective is Lean product development (LPD). The true origin of LPD is debated [9], and Khan et al. [15] but most authors couple the theory to the way that Toyota develops automobiles as stated by Ward [16], Morgan [17] and Kennedy [18]. A central term used within the LPD-context which is emphasized by the research community, is value. It is crucial to only engage in activities that adds customer value, other activities are waste [17]. Other important factors related to LPD are: front-loading the PD and work with several solutions while keeping the design space as large as possible (Set-Based Concurrent Engineering); use of a chief engineer and continuous improvement. The knowledge value stream, aiming at capturing and reuse knowledge regarding markets, customers, technologies, product and manufacturing capabilities, is central in LPD [18]. The author continues to emphasize the importance of generalizing knowledge in order to make it flow between projects such that knowledge in an organization increases the value.

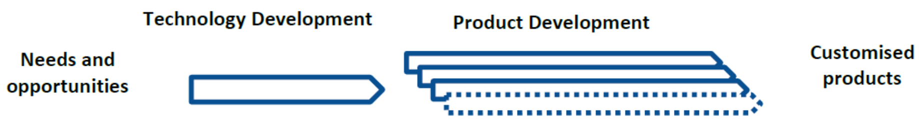

Figure 1. The process from market need and opportunities to customized products.

In Figure 1, a simplified process chart is shown, illustrating TD, PD and the interface that appears between them. The interface between the two needs to be managed in order to couple TD and PD. For example Nobelius [19] emphasizes three dimensions related to the integration of TD and PD: Strategic and operational synchronization, transfer scope and transfer management. According to [2] insufficient support for effective interface management is given in literature. The author also states that the transfer of TD to PD must take place in a physical hand over and an understanding of each other’s work must be developed.

2. Interviews in four companies

In this study four companies have been interviewed in order to receive their qualitative view on how they engage in TD, PD, the interface between TD and PD, and how they handle fluctuating requirements. The four areas have been chosen since they are of importance for the companies in the study as well as the project that this paper is a part of. The interviews have been conducted at the companies using the same questionnaire in all interviews. Two to four persons, on different levels in the organization, have been interviewed at each company. The questions have been asked in an open ended manner and the answers can be viewed at as qualitative. The aerospace supplier have been more thoroughly investigated in an extended study accounted for in chapter 3. Follow up interviews were made and one staff from the university followed the daily work for about 2 weeks in the fall of 2014.

The answers to the questions are summarized in the subsequent sections 2.1 – 2.5. First, the companies are briefly presented below:

Company 1 (C1) employs approximately 150 people totally in Sweden. However, the investigated organization employs approximately 70 people and act in the product and production development. The company is an OEM supplying directly to the final user of the products. The final users are exclusively companies. C1 is therefore a Business to Business (B2B) supplier.

The studied organization of company 2 (C2) employs approximately 300 people and act in the automotive industry as an OEM and a first tier supplier. The company employs approximately 3000 people worldwide. Some of the C2 production is sold directly to retail and consumers and some of the production is sold to car manufacturers. C2 is therefore both a B2B and consumer supplier.

Company 3 (C3). The company employs 10 000 people worldwide in different branches. Approximately 600 people are active within the investigated organization which is in the automotive sector. The company is a first and in some cases second tier supplier. C3 is strictly a B2B supplier

Company 4 (C4) is a second tier B2B supplier in aerospace industry involving structural and mechanical parts in jet aircraft engines. The studied organization employs approximately 2000 people and is part of a multinational company employing approximately 44 000 people.

2.1. Technology development

This section will provide an understanding of how the companies C1-C4 follow the emergence of new technology on the market and how they develop their own new technology and represent it for integration into products.

C1: The company does not separate TD from PD. However, the way that C1 handles new technology is by being up to date with manufacturing and material technology as well as being aware of the emergence of new technology from their suppliers. By keeping up to date on new technologies C1 can incorporate them in new products as needed. The risk of introducing the new technology is never bigger than it can be handled in projects with a customer and a set delivery date. This is accomplished by the fact that all new production lines are tested and tuned in, first at the company’s test facility and then on site at their customer’s. If the new technology is not performing according to specification, it is always possible to revert back to the former solution. The company does not provide any documentations or guidelines supporting TD, except for a preferred supplier document.

C2: In company C2, a process for TD is used. When starting a TD project there is already a target product with a specified deadline for market introduction. C2 aims at, in addition to this, also have general technology development without targeted products. 10% of the product development team is dedicated to technology development. The developed technology is then used in the different TD projects. They have frequent contact with inventors, toolmakers and industrial designers.

The company's TD process model is a light version of the PD process, containing only three gates instead of five. TD projects are initialized by product managers and may involve e.g. patents, choice of materials, customer needs and market.

It is important for the company that the employees continually update their competence and that they know what happens on the market.

C3: TD at the company can be based on individual ideas, market or even suggestions from production. The company promotes new ideas and provides support for applying for new patents and rewards granted patents.

Moreover, visiting exhibitions and bench marking against competing supplies can give new insights and initiate a TD project. There is a dedicated team of two staff that works exclusively with TD. These are senior designers with more than 15 years each of experience in the company. The marketing department perceives signals (from e.g. conversations with customers) about what will be required of future products and put them into a roadmap for the future product portfolio. The road map for renewal of product portfolio and strategic initiatives is issued by the steering committee that also takes the go or kill decisions in the gates/meetings.

C4: The company has two time frames (short time and medium time) for TD projects. The company applies TD into method engineering, production process engineering and integration engineering. The result of the TD is amended to the company's technology platform after a thorough verification process. It will result in design concepts, manufacturing methods and methods of making engineering calculations and other well documented and verified methods for the design and manufacture the products. Due to the nature of the aerospace business it is necessary to have a verified method for all activities. In the TD, all knowledge needed for the creation of the product platform is created and is meticulously documented.

One important part of the TD is conducted prior to receiving orders from customers is to build knowledge around future design concepts. This will strengthen the companies in explaining the benefits of the new design concepts to the customers and to answer requests for quotations. Usually, a specific product is considered when applying TD. TD can be either corresponding to business units' requirements, or providing solutions for gaps and deficiencies in manufacturing methods. Several dedicated team works exclusively with TD.

The company has an elaborate process for developing new concepts and finding in an early stage how the parameters of the conceptual designs will affect the performance of the products from several different aspects. This is done by numerical design of experiments. By doing extensive numerical experiments, predictions of requirements fulfillment is made. This is described further in chapter 3.

To summarize, both C1 and C2 develop new technology as part of the business models with the customer, albeit C2 has a small portion of "free" TD. The strategy for C3 and C4 is instead to prior to the negotiations with the costumers, have the new technology sufficiently ready to be confident that the technology can meet all functional requirements and that an integration on system level will be possible. The benefit for the customers is an increase in performance and / or a reduction in price compared to the former technology.

2.2. Product development

This section provides the background on how the companies organizes their PD. It elaborates on how the PD projects are initiated and how they are conducted. It also investigates how general and knowledge gained in former projects are re-used in the PD projects and how this is related to the product platform.

C1: The PD processes for C1 is similar to C2 with a few differences. Market research is not part of the process. The concept phase is divided into idea generation and concept development. No formal gates exists, except for acceptance between concept development and PD. C1 sees themselves as a service company that can offer to develop products according to the wishes of the customers as well as the production equipment for the manufacturing of that product. In this way they become an “all inclusive” company that can offer both the product and customized production system to produce the product. The product platform can be said to be constituted of the knowhow and the modules and components used for manufacturing the customized production equipment. The PD deliverable is a specification of product and the manufacture equipment, all within the same company. However, the most common project for the company is setting up or improving production lines for existing products. Taking on both product and production line is still only a small part of the business.

Experience is passed on through different documents (e.g. CAD). When problems or questions arise, the customer can often get in contact directly with the designers. This supplies the designers with first-hand information from the customers.

C2: To support the PD process, C2 has developed four different project types. The company has one full featured five gate development process consisting of the following phases: Market research, concept phase, design phase, production engineering and production. The three other project types are lighter versions of the full featured one. C2 develop their product platforms as general as possible. It is very important for C2 to make sure the platforms are scalable, ensuring that they can fit in products from different customer segments. The product platform at C2 is realized through modules and shared components. They try to keep the number of variants as low as possible. C2 has policies for capturing the experiences in several documents, but still some information is lost. Therefore, it is emphasized by the company that new engineers works and learns from the more experienced ones. A project documentation called “lessons learned” is used. It aims to document the main issues that have been encountered during the projects such as problems, obstacles, tricks, and pit-falls to be avoided.

C3: The product development process at C3 is initiated by an inquiry from the customer. In a role called “Knowledge Owner” (KO) i.e. a senior designer with long experience of the type of product, determines if the technology exists, analyses requirements and searches for already available products within the platform to solve the problem. One or several proposals are then given to the customer in different price ranges.

At C3 the PD process aims at front-loading the projects. The development model is a stage gate model containing four stages much similar to C2. Market research and concept development however lies within the first phase. The PD process aims at including a reflective activity where documents called Knowledge Briefs are created and refined carrying lessons learned, problems and inventions. This document can also contain descriptions ranging from general technology platform knowledge to specific component knowledge component. The Knowledge Briefs are stored in a separate section of the PLM system where only the KO can access them.

In order to streamline the handling of the platform there is a set of basic components in the platform that can be adapted to the case at hand. Efficiency of the platforms are also achieved by dedicating one person per platform, the KO, who answers questions from the marketing department concerning the platforms ability to adapt to customer specifications. To be able to answer such questions, various descriptions are used in the knowledge briefs. One example is trade-off curves. The trade-off curves show the relations between important design parameters to support the KO in determining the capability of the platform to adapt to the specific case. The knowledge briefs are foremost available to the KO, whereas all other product specifications is accessed through the PDM systems.

C4: The company uses a gated process for PD with two main parts: Plan product (develop new technology or product) and go on to executing what has been planned. The phases are much like the ones of C2 and is well described in the company organizational system. The company has three different platforms: A technology platform, product platform and a manufacturing platform, which are all constantly being developed. C4 views a platform as an explanation model that contains a set of rules and standardized methods used in the development process. The platform is different from the one used in the automotive industry (C2 and C3). There are no product versions. Instead, the platform is continuously evolving so that the latest technology most often is the used. At times even parts that has been in service are brought in and re-manufactured to an upgraded version. Further, no product structure from the former design is re-used, only the knowledge on how to create it. Therefore, the product platform cannot be said to consist of physical components, but rater methods on how to perform the activities leading to a new product.

After the TD, one or a few product concepts that have been thoroughly analyzed (see section 3) are used as a starting point of the PD process. At this stage there is a customer for the product, which was not the case in the TD. The CAD-models and engineering calculations from the TD is not reused. Instead, the results are replicated with more detail and higher precision to verify that the assumptions made in TD where correct.

All the critical issues around the concepts were resolved during the TD. This means that the PD phase contains a few minor unresolved issues and can therefore be planned time and cost wise with good precision.

After making the precision engineering calculations and the detailed design work, physical prototypes are manufactured and a series of tests are performed to obtain the airworthiness certificates of the product.

There is an internal web for the sharing of documents in preparation and a version controlled database (PDM) for keeping track of all documents produced in the early development process. The company uses a wiki that is editable by anyone in the company. The information in a wiki is unverified and is not allowed to be used directly. However, it helps informally spreading and storing knowledge and experiences that can be further developed into approved methods if successful. The wiki applies both in TD and in PD.

Like in technology development companies C1 and C2 have similar ways of conducting product development. Likewise C3 and C4 have similar processes. The product platform in C4 stands out in that one cannot say that it is based on former products. This distinguishes C4 from the other three companies since they have a product structure that can be re-used. Company C1 does also start the product development by investigating how much of the former product structure that can be reused. However, they do not have predefined product structures like C2 and C3. Instead, C1 searches the documentation from former projects using smart search algorithms to find the information.

2.3. The interface between TD and PD

At some point the technology is considered mature enough to be used in actual products. What is then the delivery from TD to PD i.e. what format and requirements for documenting the result of the TD? How may the result of the TD be used in actual products? These questions will be answered in this chapter.

C1: This company has no documented strategy for technology development except for keeping up to date with sub-suppliers, and therefore no interface can be identified. However, when the company accepts projects involving new technology it is integrated in the PD project directly without differentiating the two activities.

All components purchased from suppliers have been tested and are accompanied with comprehensive documentation. It is mostly standard production equipment components such as sensors and pneumatic cylinders.

C2: One aim of the TD project is to clarify when a technology is ready to be implemented. The result is embodied in a prototype together with associated process and tooling information and cost estimations. In addition, anticipated advantages and disadvantages coupled to the new technology is handed over to PD. Other deliverables from TD can be in the form of CAD-models, trade-off curves, guidelines, “lessons learned”, product structures and text documents. The company does not draw a sharp line between TD and PD. It is therefore difficult to clearly distinguish between TD and PD activities at company C2.

C3: A new technology shall be verified by design verification (DV) in order to meet the sufficient readiness level and in order to be implemented in customer projects without major risk. In addition, FMEA is used to assess and control the risks. The decisions on which verified designs created in TD to release for use in PD are taken at steering committee meetings.

The criteria for DV can be hard to decide since the technology and sometimes the area of application is new. Since no prior experience on the type of product exist, new tests and criteria need to be developed. These tests and criteria gradually evolve with increased product experience.

The result from TD is described by drawings and test results and is embodied in a prototype. When TD is done, the result is handed over to PD together with an open issue list on how to best proceed with the PD project. There is room for varying risk-taking when transferring new technology from TD to PD depending on how important the deal is to the company.

C4: In company C4, as described in section 3 a central part of the TD is building knowledge around the concepts, but there are several other interfaces between PD and TD. This has previously been described in (Högman, Bergsjö et al. 2009) and is part of a constantly ongoing quest for finding new manufacturing and inspection methods. When these are found to have reached a sufficient Technology Readiness Level (TRL) on the NASA developed TRL scale, they are amended to the set of approved technologies and are negotiated for using in current and future manufacturing processes. The TRL scale comprises 9 levels where levels TRL3 and above means that a proof of concept has been found analytically. Still, the component has not been proved to work in the relevant environment. TRL6 and above means that the component has been proved to work integrated in its context. Resent developments in systems engineering has found that the TRL scale does not to a sufficiently take the system integration into account London et al. [20]. This is becoming increasingly important with the increasing system complexity.

C4 also actively collaborates with universities for finding, spreading and documenting new knowledge. In company C4, there is a strict line between TD and PD: A new technology shall be verified by reaching the TRL6. The company has well specified criteria that should be met for a technology to be approved. Examples of deliverables from the TD is property models, trade-offs, guidelines, processes, lessons learned and instructions.

2.4. Managing risk

The risk for company C1 is that the production volume of the ready production line does not reach the target. One part in the line may be unreliable and cause frequent stops. This is especially likely if the lines contain automation equipment not previously tested. Still, C1 operates in a level of competition on which they do not have to accept projects that involve risk related to untested technology. It is possible for them to try out technology in agreement with the costumer as a part of the deal. For the time being, C1 do not have to compete with other firms offering more efficient automation solutions what involve technical uncertainty.

The risk that company C2 faces is that the requirements from the market are misinterpreted. Only part of the business of C2 involve a counterpart to negotiate with. When selling directly to consumers and retail, they have to interpret the expectations of the private consumer themselves. A new invention from a competitor can easily overthrow the sales forecast. As for requirements emerging from laws and regulations there are standardized test, making it easier to assess whether the product will fulfill the requirements or not.

Company C3 acts as a sub-supplier in the very competitive automotive industry. Cost is very important for the customers. Therefore, C3 must constantly struggle to make inventions that can reduce the price of the products and at the same time provide the same or more functionality. For C3, the risk is selling not sufficiently tested technology for the sake of getting important contracts. The company hopes to finish the technology development during the PD project. However, there can be unforeseen problems with the technology that cannot be rectified within the time and budget restrictions of the PD projects, thus C3 has to reduce the profit marginal on the deal to in worst case negative values.

C4 cannot afford to act in the same way as C3. An aircraft is a very complex system where hundreds of sub-suppliers have to make a very complex system integration. There is little room for changing technology in a late stage. Further, the penalties of delaying the total aircraft project due to selling unverified technology is considered too big. Therefore much effort is put into verifying the technology so that it performs as intended when it is finally integrated in the aircraft.

Company C4 is the least risk taking when it comes to new technology. They do not consider it an option to develop new technology within the scope of a PD project. In this respect the two automotive companies are more risk taking. Company C1 is an OEM directed partly towards end consumers and can therefore set the time of product release themselves and does therefor not have to have a sharp line between TD and PD.

2.5. Managing fluctuating and conflicting requirements

For all four companies the requirements do change during both PD and TD. They meet upcoming changes in different ways. This section elaborates on the nature of the fluctuations for each of the companies and how they work to meet them.

C1: During PD, C1 emphasizes that they view the requirement specification as a living document that tends to change. The company work with sets of solutions in parallel and they do not see vague requirement specifications as a problem, rather an advantage in that they can assist the customer in developing a requirement specification and thereby guide the customer towards preferred solutions.

As prescribed in Set-Based Concurrent Engineering, the company likes to keep a large design space in order to learn about the product and then get a steady convergence of solutions. Sometimes the requirements can be conflicting e.g. weight/stiffness or number of units/price. They use a system where they divide the requirements into three groups: desirable, must and no requirement. The balancing of demands is a challenge. The project manager is in charge of the requirements and is responsible for scrutinizing them in an early stage. Sometimes a requirement can be planned to change in the future. For example, a desired requirement can be planned to change to a must later in the project. Moreover, if there are no requirements, C1 will specify what to deliver. That is, the customer is actively helped in formulating the requirements. Without a complete specification of the requirements company C1 will not proceed with the business negotiations with the customer.

When the product is handed over to the machine manufacturer i.e. those who are building the physical production lines within the company, the requirements are frozen. Until then the engineering department has had the possibility to affect the requirements in an early stage.

C2: The most common sources of requirements changes come from market, customers, law and environment (in falling order). C2 keeps track of the applicable standards and how they will change in the near future. Since C2 is an automotive company, the standards mostly concern road safety regulations on different markets. It is possible to get some information on upcoming changes and amendments by for example following the work in the EU. This also applies to upcoming environmental regulations.

The company also actively participate in standard organization committees in order to influence new issues of standards.

The company has gates in the development process to ensure that subjective requirements are turned into objective and quantifiable requirements during TD, prior to PD. To detect and resolve conflicting requirements which often are matters of cost, quality and time, C2 use group meetings to set priorities together with project managers. However, the project team can often handle the situation right away. At times projects are re-started or a parallel TD project is started to allocate resources for solving problems related to conflicting requirements.

C3: The most common changes of requirements apply to performance, cost and environmental requirements. It is more common that requirements are added than removed, in such case a negotiation about the cost takes place with the customer.

To detect conflicting requirements C3 uses a requirement verification sheet (RVS) at the beginning of the product development projects. The RVS is intended to identify conflicting requirements in an early stage and to judge the validity of the requirements.

It is most common that changes of requirements occurs at the beginning of the projects, and when test data is available later in the projects.

C4: Early in the development project C4 receives a list with requirements from the customer that are not ranked according to requirement importance. C4 sees a problem and emphasizes that balanced requirements are important to not cause loops in the development process. The company is very aware that changes in requirements will occur, but as long as a robust design is created it is not a problem, especially since the trade-offs are clearly investigated in the concept studies stage, that is the pre-business multi objective analysis of conceptual designs. C4 tries to foresee what requirements will change by looking at the requirement history from earlier projects and adapt the designs to handle changes in a good way.

A source of changing the requirements is the OEM making changes on the top system level often affecting temperatures, loads, adjacent systems and interfaces.

The requirements are in all four companies used to steer the PD and all are elaborate in quantifying the requirements and follow their fulfillment during the process. Only C1 states that they formally freezes the requirements, meaning that changes will be rejected after this time. For the other companies it is a negotiation in which they must try to compensate themselves for the cost of implementing the changes without compromising the level of service towards their customers.

The three business to business companies C1, C3, C4 have a counterpart who follow the requirement fulfillment, whereas C2 more freely can interpret the market requirements.

2.6. The proposed model

Chapters 1.1-1.5 has elaborated on the companies view on TD, PD, risk taking, and varying requirements. In the table 2 on next page the important findings concerning these four aspects are summarized.

Table 1. Summary C1 – C4.

Company	Role	TD	PD	Interface	Risk	Requirement
C1	OEM, B2B	Part of PD	Based on former projects	No sharp line between PD and TD. New technology tested directly in PD projects.	No risk. The competition allow technology testing in PD	Frozen requirements before setting up production lines. Extensively aid costumer in requirements formulation.
C2	OEM Consumer / retail and B2B	Part of PD, 10% separate process	Component structure based	New technology verified by working prototype.	Similar to C3 as sub-supplier. Has to find market needs as an OEM.	Free interpretation of market req. Follow and influence standard development.
C3	Sub-supplier B2B	Separate process	Component structure based	Formal DV needed before release to PD.	Risk taking to stay competitive when introducing new technology	Process for detecting conflicting requirements. Negotiations with customers on requirements.
C4	Sub-supplier B2B	Separate process	Verified knowledge based	New technology must reach TRL6 before release to PD.	Low risk when introducing new technology. Extensive pre-business verification.	Actively meet requirements change by multi-objective analysis of conceptual models. Negotiation with costumers on requirements.

The study indicates that the interface between TD and PD is closely related to the technical and financial risks of introducing new technology and that the risk depend on the level of complexity and integration with other sub-suppliers. If the product are modular then the result of the TD can be represented as generic components that can be customer adapted in PD. If instead the products are integral the delivery must be on a knowledge and method format instead.

Companies that have a high level of complexity and integration with other suppliers where little is known about the adjacent components needs a more formal way of verifying new technology because their exposure to risk is higher in that the room for late changes is smaller.

However, it must be noted that it is possible to have a high level of integration with other supplier’s components and still take low risk. This is the case for C1 where the other supplier's components are well documented and standardized and the products are mostly modular.

At the same time the formalization of the TD / PD interface cannot be allowed to hinder the company too much when searching for new business. In order to stay competitive they have to take risk when going forward with new technology.

All companies are aware of and can respond to the fluctuation of requirements. If the delivery from TD to PD is component based, then the possibility to handle fluctuations for these components can be determined in advance. If the TD delivery instead is based on knowledge and verified methods then instead extensive simulation have to be made for each new design suggestion in order to find how the requirements can be allowed to fluctuate.

The findings can be summarized that interface between PD and TD is adjusted according to how much technical risk the company is willing to take and the modular / integral character of the product and the companies role in the supply chain. To further elaborate on this model, a deepened study has been carried out at the aerospace company accounted for in chapter 2

3. Towards the proposed model – a case example C4

The company C4, the aerospace supplier, has the furthest developed technology verification process of the four companies. It has highly integral components and a knowledge and method based delivery from TD to PD.

To meet new requirements on for example reduced noise levels, fuel consumption and weight, the air craft engines are gradually refined and new concepts are developed and implemented. Advances in e.g. manufacturing and material technology makes this possible. Also the geometry of the engines is gradually refined as more knowledge about how the turbine works more in detail is emerging. One example is the development towards an increased by-pass ratio. The fraction of air passing by the turbine is now as much as 80%.

Further, the methods of simulating the stresses acting on the engines and fuselages has also undergone substantial development. Earlier, large safety margins had to be employed due to more uncertainty about both the load carrying capacity and the loads acting on the aircraft. Modern simulations tools has enabled more precise predictions allowing the partial safety-factors related to uncertainty in load and carrying capacity to be reduced.

To increase the performance of every new generation of engines, the manufactures need to conceive and develop new conceptual ideas which are gradually tested and verified in the technology development. The company C4 has frequent contacts with the customers and within the aeronautics community to try to get a notion on what the requirements on the next generation of aero engines is expected to be. This is done long before there is a designated customer for the new engine.

Based on the assumed future requirements, early sketches and CAD-models are built and evaluated among others methods using computational fluid dynamics. In the following chapters the activities adding to the technology and product platforms will be described.

3.1. Steps in the development process

Figure 2 on the next page shows the different steps.

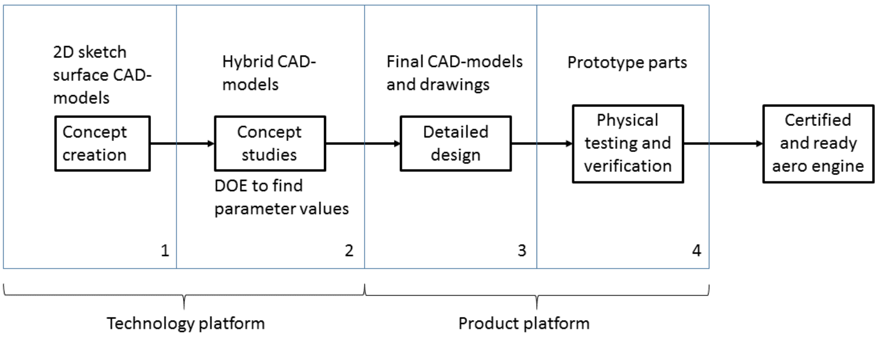

Figure 2. The development process.

After that the concepts have been created and analyzed from an aerodynamically point of view in the first stage (1). In the second step (2), the CAD-models are rebuilt in a Siemens NX centered environment. In this environment, the CAE system Siemens NX has been amended with in-house created scripts and programs to automate different tasks. The functionality of the software has also been extended to do specialized tasks that are needed for the conceptual studies.

From 2D-sketches and surface geometry in the first stage, the CAD-models are rebuilt for the concept studies in stage (2) as hybrids of solid and surface geometry. These CAD-models are detailed, yet preliminary and are used in the concept studies for studies of the effect of parameter changes on the aerodynamics, structural, thermal and manufacturability properties of the engine parts. Examples of parameters in the CAD-models are dimensions, angles and plate thicknesses.

As example of structural, among other things, the safety factor against buckling is studied. By thermal properties are meant that, the engine parts are subjected to highly varying temperatures of a repetitive nature. The temperature distribution is determined and together with structural stresses this can cause fatigue in the structure. A standardized flying cycle is used to assess the expected life of the parts.

The assessment of the manufacturability involves determining how accessible the geometries are for welding and inspection i.e. reachability studies. In the aerodynamics parameters like pressure loss is studied.

The different possible combinations of parameters and there effects on the performance are presented to potential customers to decide on which parameter sets gives design solutions that would suit the customer requirements best. It will make clear the possibilities with the concept allowing the company to react quickly on requirement changes.

When a customer has been found, the next step, (3) in figure 2, is to design the engine parts more in detail. Now, since there is a designated customer, more precise geometry from other suppliers will be available. Since it in the concept studies step was not known which engine the parts would go in the surrounding geometry it was based on discussions with potential customers and best guess.

With the adjacent geometry known and precise data available, detailed 3D-CAD models and engineering drawings are created as well as precise simulations of the expected behavior of the components. Detailed production planning such as simulating and deciding on the paths for robotic welding is carried out.

The simulations also involve taking into account the effect of the production process on the predicted life-time of the parts. One example is the effects of the welding on the stress state in the material. In practice, the sequence it not so ordered as depicted in the figure 2. Some of the detailed design work is done in parallel with the studies.

After the detailed design step, actual physical components are built. These are tested and verified, first on stationary and then flying test-benches and finally on the ready aircraft.

3.2. Conceptual studies in the work-bench

The primary objective of the concept studies is gaining a thorough understanding of the effects of changing the different parameters. In order to do so CAD-models with varying parameter setting are generated and evaluated. A large number of experiments are carried out and therefore, the procedures needs to be quick and run automatically in order to give a manageable calculation time in order of hours up to a few days.

First, a number of different sets of parameters are generated using methods to fully cover the intended design space. For each parameter-set the corresponding performance is calculated.

The below table 2 shows the principle inputs and outputs for the calculations. The inputs are shown on the left side of the table and the results on the right side.

Table 2. Concept evaluation.

Inputs					**Results**		
Design Case	Param. 1	Param. 2	Param. n		Manufactu.	Life expectancy (h)	safety factor
0	15	1	0.2		Fair	480	1
1	12.0443	1.13474	0.253546		Good	512	1.1
2	29.7771	0.846012	0.208140		Moderate	502	1.02
3	23.2880	0.846943	0.122419		Bad	498	0.99
4	27.74241	0.584011	0.135881		Excellent	500	1.03
5	18.1911	1.560024	0.300154		Fair	478	1.2
..							
128							

First, a number of different sets of parameters are generated using methods to fully cover the intended design space. For each parameter-set the corresponding performance is calculated.

The parameters (param. 1 –n). in the rows are the geometrical parameters of the CAD-model. These are used to generate a CAD-model with just these values. The CAD-model is then evaluated in commercial and in-house software to predict the expected performance in structural loads. The actual FEA calculations require long time, therefore a response surface approach sometimes have had to been employed.

For evaluating the manufacturability, in-house programs have been created. The results shown in the table 1 are examples, since the actual interpretation of the results are more complicated.

Row zero is the base-line i.e. the current concept by which the increase in performance can be compared.

For each parameter-set (row) the CAD-models needs to be regenerated, the geometry meshed and the results must be recorded. There must not be any combinations of parameters that causes failure in the generation of the CAD-geometry or in the meshing. Much effort have therefore been put into developing methods of achieving the necessary robustness of the CAD-models to secure that they can be regenerated with all possible combinations of parameter settings.

Among the generated solutions, knowledge on the response of parameter changes can be extracted. For example, the sensitivity of each parameter can be studied. The result may be that some parameters show a high correlation and can therefore be merged and new experiments can be performed with more insightful parameter sets.

The experiments are refined until a good insight in the response of the concept has been obtained.

Graphical visualization of the generated data, for instance trade-off curves, can be generated and used to better visualize which trade-offs that can be done.

4. Discussion

The definition of TD differs between the companies. When starting a TD project in C2, there is already an end date for the PD project, i.e. the TD project has a fixed time frame. C3 on the other hand has a vaguer time frame and no designated customer for the TD project. Instead, the company tries to foresee trends and customer needs in order to develop products for the future. C1 makes no difference in TD and PD. If new technology is needed it is integrated in the PD process or bought from a sub-supplier. For C1 the risk of introducing new technology is low since it is possible to revert back to the former technology if the new technology fail in testing. This would not have been possible if the motivation for developing a new product would have been an increase in performance or reduction in price. Reverting back would inevitably have meant failure of meeting the requirements. Further, companies C3-C4 are characterized as sub-supplies. Reverting to the former technology would likely have meant no possibility of system integration with other suppliers.

C4 has the most elaborate view of TD among the four companies. A technology platform is the base of the TD and consists of all methods and verified design solutions for developing products. C4 also is also able to place the methods in the TRL scale in order to assess when it is ready for use in products, reducing the risk of failure in product verification.

A similarity among the companies is that there is always a product in mind when starting a TD project. It can be seen from the interview study that the companies integrates TD in PD to different extents, e.g. C4 totally separates TD from PD resulting in low risk for the PD projects. This is an important strategy for C4 since the number of system interfaces and product complexity is high. This strategy might however increase the technology’s time to market. However, as has been reported in news media in the case of Boeing 787 is that if the ready aircraft does not pass the testing and verification phase, long costly delays can be expected.

In this way C4 is more aligned with the theories of [1], [18]. Opposite to C4 is C1 that integrates TD in PD. This increases the risk in PD projects, however the time to market for the developed technology is decreased. An explanation for why it is possible for C1 to integrate TD in PD is a lower number of interacting systems and interfaces and that they integrate mostly standardized components.

The companies all have a well-defined and similar processes for PD, yet at varying degree of complexity. A common strategy in the companies is to use a platform approach to some extent. In order to make use of a platform approach, the platform can be defined on different abstraction levels. In Figure 3 below the companies are roughly placed according to the abstraction level of their product platform.

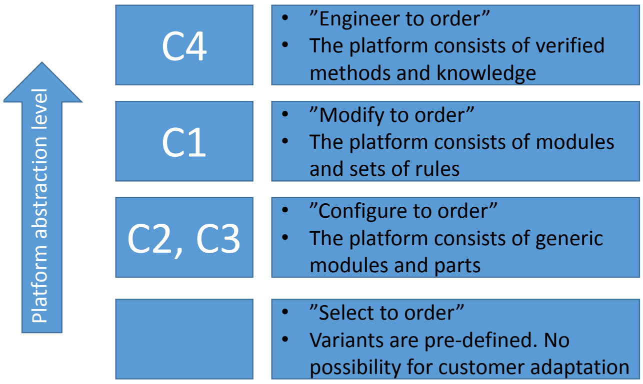

Figure 3. Categorization of platform abstraction level in the studied companies.

The types of variant specifications, according to [10] are also coupled to the abstraction level of the platform. It should be noted that each company has characteristics that can be coupled to several of the variant specifications types, however in the Figure 3 they are placed on a level resembling them the most. The company C1 is the most difficult to place since the technology platform consists of documented former cases. Some reusable "modules" are found and there are also some "rules of thumb" that the designers can apply when architecting the production lines.

Factors that increases the need of a higher platform abstraction level is: small production volumes, high product customization, high product complexity and level of integration. Then it follows that the higher the abstraction level of the platform, the more engineering efforts needs to be done to deliver a product. Moreover, the higher the abstraction level of the platform, the more the companies tend to describe it as an explanation model and a knowledge repository rather than made up by physical components.

According to [11], [12] there are trade-offs to be considered when engaging in platform development. Two of the companies have engaged in a component based platform, C2 and C3, these trade-offs were however not mentioned by the studied companies. Instead platform development is something that is considered to be a tacit strategy. C4 has a platform description on a more abstract level described in literature by [13]. However, it must be remembered that C4 has a clear product platform in that earlier products constitutes a base-line from which the improvements are made. Many of the design solutions are also carried over to the next engine. It differs in that C4 has an extensive knowledge base in the technology platform, thus the former geometries are not just copied. A thorough understanding of how and why the components works have been developed.

The difference in integration results in different deliverables from TD. E.g. the TD at C2 and C3 aims at realizing the new technology in a physical prototype and documents, when C4 aims at describing new methods and instructions. In C4, physical prototypes does not appear until towards the end of the product development in the final verification step. This is due to the high cost and complexity of the products.

Company C1 integrates TD in PD and therefore no handover or interface can be identified.

All companies in the study are faced with the challenge of requirements change. However, the view of requirements differ between the companies. In the case of C4, many sub-suppliers contributes to the final product and therefore precise information about adjacent systems are needed when developing the final product, the term requirement freeze is used.

Earlier, in the negotiations with the customer, C4 is well prepared for requirements changes.

C1 has a more dynamic view of the requirements and sees a large design space as an advantage. That way of working, including developing sets of solutions, enables a steady convergence and ends up in building knowledge of the design, according to the company. C4 is the only one of the four companies that mentions having a strategy for using a robust design in order to withstand changes in requirements.

For the project that this paper is a part of, Figure 4 below serves as a model for the interface between TD and PD.

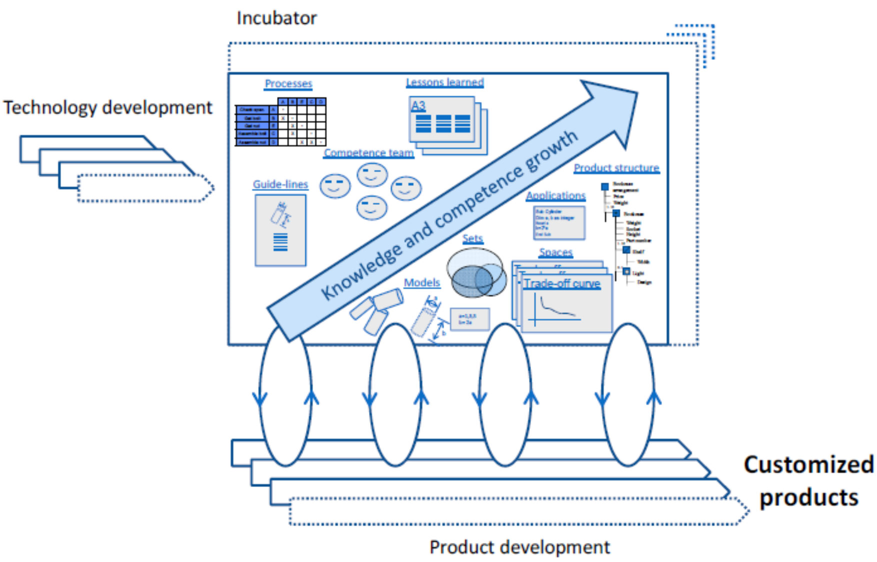

Figure 4. Proposed model of the interface between TD and PD.

The figure describes how TD is separated from PD and how the deliverables from TD builds up a platform where the technology is described and can be adapted to fit the different PD projects. The representation of the technology i.e. the delivery from TD to PD is represented on different formats of varying abstraction ranging from concrete generic components and component structure to abstract knowledge represented as competence teams. The PD can then use the platform for creating customized variants. The platform also contains the maintained knowledge that is continuously developed in the company projects. This knowledge is stored in different formats. Some of it is close to the product structure. Thus it can be said to belong to the product platform. Some of it is stored in trade-off curves, guidelines and A3 and are then part of the technology platform provided that it has been verified as part of the approved technologies.

The efficiency of the proposed platform is coupled to its ability to adapt, how well it can handle fluctuating requirements and how effectively variants can be created from it.

5. Conclusions and future work

This paper has investigated how four companies define, use and adapt their product platforms in order to enable effective technology and product development as well as managing risks in the transition between them and at the same time being able to handle fluctuating requirements.

There are three major observations:

- Complexity and level of integration of the products determines the interface between PD and TD.
- The permissible fluctuation in requirements can be determined in an earlier stage when the product structure is modular.
- When the products are closely integrated with other suppliers in complex ways, the company's has to formalize the verification and validation process to a greater extent to reduce risks.

The companies agree on that platforms can be identified in their organizations even if the scope and extent of them varies.

The companies can likely benefit from a strategy of developing their platforms for increased productivity and risk and requirements handling. This paper is part of an externally financed project running over 3 years. The next step will be finding criteria to determine how well the current platforms are performing and then refined and possible alternative ways of representing the product and product knowledge will likely be developed in the scope of the project resulting in recommendations for the companies how to build and manage their platforms.

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References

[1] I.L. Johansen and M. Rausand, Foundations and choice of risk metrics. *Safety Science*, **62**, (2014), 386-399.

[2] N. Lakemond, et al., Interfaces between technology development, product development and production: Critical factors and a conceptual model. *International Journal of Technology Intelligence and Planning*, **3**(4), (2007), 317-330.

[3] U. Högman and H. Johannesson. *Technology development practices in industry*. in *ICED 11 - 18th International Conference on Engineering Design - Impacting Society Through Engineering Design*. 2011.

[4] D. Nobelius, Managing R&D processes - Focusing on technology development, product development, and their interplay. *Doktorsavhandlingar vid Chalmers Tekniska Hogskola*, (1842), (2002).

[5] R.G. Cooper, Managing technology development projects. *Research Technology Management*, **49**(6), (2006), 23-31.

[6] D. Olausson and C. Berggren, Managing uncertain, complex product development in high-tech firms: In search of controlled flexibility. *R and D Management*, **40**(4), (2010), 383-399.

[7] M.W. Maier, *The art of systems architecting*. 3. ed.. ed, ed. E. Rechtin. 2009, Boca Raton, FL: CRC Press. 2009.

[8] T. Celona, C. Embry-Pelrine, and K. Hölttä-Otto. *Are modular products larger than integral products?* in *Proceedings of ICED 2007, the 16th International Conference on Engineering Design*. 2007.

[9] H.C.M. León and J.A. Farris, Lean product development research: Current state and future directions. *EMJ - Engineering Management Journal*, **23**(1), (2011), 29-51.

[10] T.W. Simpson, Z. Siddique, and J. Jiao, *Product platform and product family design: Methods and applications*. Product Platform and Product Family Design: Methods and Applications. 2006. 2006.

[11] B. Hansen, *Development of industrial variant specification systems*, in *Department of Management Engineering*. 2003: Copenhagen.

[12] J.I.M. Halman, A.P. Hofer, and W. Van Vuuren, Platform-driven development of product families: Linking theory with practice. *Journal of Product Innovation Management*, **20**(2), (2003), 149-162.

[13] J.A. Martinez-Larrosa and Z. Siddique, eds. *CAD support for product family design using parametrics, mating relationships, and modularity*. Advances in Concurrent Engineering, ed. B. Prasad. 2002. 535-543.

[14] H. Johannesson, *Emphasizing Reuse of Generic Assets Through Integrated Product and Production System Development Platforms*, in *Advances in Product Family and Product Platform Design*, T.W. Simpson, et al., Editors. 2014, Springer New York. p. 119-146.

[15] M.S. Khan, et al., Towards lean product and process development. *International Journal of Computer Integrated Manufacturing*, **26**(12), (2013), 1105-1116.

[16] A.C. Ward, *Lean product and process development*. 2007, Cambridge, Mass.: Lean Enterprise Institute. 2007.

[17] J.M. Morgan, *The Toyota product development system : integrating people, process, and technology*, ed. J.K. Liker. 2006, New York: Productivity Press. 2006.

[18] M. Kennedy, *Ready, set, dominate : implement Toyota's set-based learning for developing products and nobody can catch you*, ed. K. Harmon and E. Minnock. 2008, Richmond, Va.: Oaklea Press. 2008.

[19] D. Nobelius, Linking product development to applied research : transfer experiences from an automotive company. (2004).

[20] M.A. London, et al., Incidence matrix approach for calculating readiness levels. *Journal of Systems Science and Systems Engineering*, **23**(4), (2014), 377-403.